Risk Based Maintenance in Electricity Network Organisations

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I dedicate this work to my loving parents
Samuel Mehairjan & Chandra-Devi Kalpoe Mehairjan

Summary

Presently, the maintenance of assets is widely undergoing changes towards well-founded forms of maintenance management in infrastructure utilities such as electricity, gas and water. These are mainly driven against the backdrop of stringent regulatory regimes, ageing asset base, increased customer demands and constrained financing. Therefore, it becomes imperative for infrastructure utilities to strive towards more effective and efficient operation and maintenance approaches. In this light, new asset management approaches such as risk management are gaining more interest worldwide. In this research the focus has been on the further development of maintenance management in electricity network organisations. It covers the development and practical application of enabling factors for maintenance management such as organisation capabilities and maturity levels, structured and comprehensive frameworks for assessing maintenance policies and decision-making support tools and technologies. Thus, an integral, multi-disciplinary, approach towards maintenance management needs to be established, which is a challenge that has been taken up in this thesis for electricity network companies.

Well-founded and effective maintenance management for existing electricity network assets provides a blueprint for sustainable investments in the future. In this context, risk-based maintenance regimes are intended to ensure higher efficiency and ultimately establish a broader view on maintenance as a business function. From this research we have found that electricity network organisations who strive towards well-founded maintenance management as a business function will need to have structured frameworks in order to find efficient and practical mixes of maintenance activities beyond the sole technical aspects of maintenance. It is recommended that maintenance departments will need to function in a broader sense and move away from "silos" thinking. This requires systematically adopting multi-disciplinary organisation domains into maintenance management and the continuous measurement of the development and improvement of these dimensions by means of maintenance maturity models and maintenance key performance indicators (KPI's). Risk-based maintenance management is recommended and will need structured comprehensive frameworks, analytical tools and technological methods for developing and supporting maintenance management decisions.

In current maintenance organisations, we observe shortcoming and gaps between strategic, tactical and operational levels. In many cases, not all organisation related factors are thoroughly considered in the strategy for maintenance, which results in an unclear situation when translating these factors to maintenance concepts, policies and actions. In this research an organisation-wide (multi-disciplinary) maintenance management structure has been

introduced and evaluated in practice. In this structure the approach has been to add organisational aspects of influence, which are not confined to technical factors only. Improvements will be steered from a point of view which interacts with other non-technical, however essential, aspects of maintenance management, e.g. aspects such as, organisation & processes, information systems & data requirements, portfolio planning, compliancy, policy and criteria. A *Maintenance Management Maturity Model (M^4)* has been introduced and practically implemented. Principally, the M^4 is developed for assessing and monitoring a set of multi-disciplinary domains which are necessary for maintenance management professionalization. With the aid of this model the maturity levels have been assessed in 2012 and 2014 for gas and electricity network assets. Reviewing these maturity levels makes insightful which domains have improved or not. This approach enables continuous improvement for maintenance management organisations on strategic levels.

Evaluating our goal of professionalising management of maintenance, we have found that the adoption of systematic and methodical approaches, especially on tactical level, is essential. In this research a structured and methodical maintenance management model has been established. This model is based on the well-known *Reliability Centered Maintenance (RCM)* method which has been expanded to include and interrelate to the corporate risk management model and business values. The established model provides a method in which risk is added to the traditional RCM method in order to cope with the consequences of functional asset failures on multiple corporate business values. Once such a risk related maintenance concept is introduced, any (existing or new) maintenance policy and maintenance action can be assessed and expressed on its financial, technical and other business values such as safety, image and environmental consequences in terms of risks. This new method we developed is named *Utility Risk Linked RCM*. The method has been applied to a case study for power transformers and has been found to be a practical and comprehensive method for utility risk-based maintenance management.

The *Utility Risk Linked RCM* encompasses a comprehensive integrated approach for risk-based maintenance management. For practical robustness, we have investigated additional analysis methods and technological tools to support data driven decision-making. Statistical *Life Data Analysis (LDA)* has been applied, which forms a method to deal with the failure behaviour of assets, which is highly stochastic. We have found that failure data and in-service data of assets, when recorded, can be processed to give useful estimates of statistical failure distributions. These statistical approaches are useful for the analysis of populations of assets providing information on failure rates, probability of failures and age-based remaining life of (large) populations. This is known as a top-down approach and forms an important link between tactical and operational levels.

In the bottom-up approach the upcoming role of condition monitoring technologies, which have been provided in terms of asset management implications, has been described as well as the perception of utilities towards the adoption of these technologies. We have observed that distribution network utilities are rather reluctant regarding large scale deployment of such technologies. In many cases this is due to high initial investment cost, data interpretation challenges, unclear frameworks to relate condition data to strategic implications or the readiness and reliability of the technology itself. However, in recent years technologies have developed and are becoming financially and technically more attractive. Frameworks are needed, as has been found from benchmark surveys, to understand and interrelate the upcoming role of condition monitoring into the overall maintenance management organisation. A condition monitoring framework is developed which forms the basis for establishing condition based maintenance regimes. Such a framework can be adopted by asset management companies as a guiding principle for identifying the relationship between failure modes, ageing processes and to select amongst condition monitoring methods.

The research objective and questions, which have been addressed throughout this research, show the apparent gap between maintenance management and operational parts in electricity distribution utilities. Each research question is addressed by means of empirical research approaches which include survey studies, practical case study on implementation, data analysis methods, field measurements and development of methods based on field observation and analysis. Based on the addressed research question and the applied research methods the overall objective of this research has been addressed on aspects such as enabling well-founded organisation of maintenance management, the introduction of risk management and business values into maintenance and the application of statistical and sensor based analysis of failure behaviour of assets. Further progress can still be made in several areas and therefore we recommend future research in areas such as expanding the *Utility Risk Linked RCM* method by modelling external (third party) risks into it, which will require different sources of data. The predictive nature of risk and condition based maintenance management implied a possible new era for OPEX budget planning methods, a research area that is recommended for future work. In the quest towards advanced management of infrastructure utilities, a research recommendation is to answer the question how decisions that are made in the present time (investments, maintenance, replacements, etc.) ensure over a certain period of time the output that is expected from network companies by regulators and whether this supports, restrains or discourages investments in technologies. Research of network capacity and maintenance planning, which are nowadays separated, is needed given the increasing complexity of electricity networks.

Having concluded and said this, we want to highlight that at the moment of writing the electricity sector is amid a continuous process of quickly changing environments due to unbundling of organisations, process improvements, take-overs and mergers, partnerships, outsourcing, etc. This is due to the dynamic business environment in which electricity network businesses operate. Therefore, we want to emphasize the continual developments in the area of maintenance management of electricity networks, hence the nature of this research is an ongoing research area for coming decades.

Samenvatting

Momenteel ondergaat het onderhoud van assets in netwerkindustrieën, zoals elektriciteit, gas en water, op grote schaal veranderingen richting beter onderbouwde vormen van onderhoudsmanagement. Dit wordt vooral geleid door strengere regelgeving, veroudering van assets, verhoogde eisen van klanten, beperkte financiën. Hierdoor wordt het noodzakelijk voor deze industrieën om te streven naar effectievere en efficiëntere benaderingen voor bedrijfsvoering en onderhoud. Zo gezien krijgen nieuwe asset management benaderingen zoals risico management wereldwijd steeds meer belangstelling. In dit onderzoek is de focus gericht op de verdere ontwikkeling van onderhoudsmanagement voor elektriciteitsnetbeheer. Het heeft betrekking op de ontwikkeling en de praktische toepassing van aspecten, waardoor onderhoudsmanagement mogelijk gemaakt wordt, zoals de organisatie capaciteiten en maturiteitsniveaus, gestructureerde kaders voor de beoordeling van het onderhoudsbeleid en ondersteunende tools en technologieën in besluitvormingsprocessen. Dit vergt een integrale, multidisciplinaire aanpak, een uitdaging die in dit onderzoek en proefschrift is aangegaan.

Goed onderbouwd en effectief onderhoudsmanagement van elektriciteitsnetwerken biedt een blauwdruk voor duurzame investeringen in de toekomst. Risico gebaseerd onderhoud is bedoeld om te zorgen voor een hogere efficiëntie om uiteindelijk te komen tot een beter onderbouwde kijk op het onderhoud als een bedrijfsfunctie. Uit dit onderzoek is geconstateerd, dat het streven van elektriciteitsnetbeheerders naar goed onderbouwd onderhoudsmanagement gepaard gaat met het hebben van gestructureerde kaders om efficiënte en praktische combinaties van onderhoudsactiviteiten met meer dan technische aspecten alleen in acht te nemen. Van de afdelingen die verantwoordelijk zijn voor onderhoud wordt verwacht dat er ook met andere belangrijke aspecten rekening gehouden wordt. Dit zal bijdragen aan het wegwerken van zogenoemde “zuilen” in de organisatie van onderhoudsmanagement. Dit vereist een systematische vaststelling van multidisciplinaire organisatie domeinen in onderhoudsmanagement en de continue meting van de ontwikkeling en verbetering van deze dimensies door middel van maturiteitsmodellen en key performance indicators (KPI's). Risico gebaseerd onderhoud is aanbevolen en maakt gebruik van expliciete en duidelijke kaders, analytische instrumenten en technologische methoden voor het ontwikkelen en ondersteunen van besluiten voor onderhoudsmanagement.

In het huidige onderhoudsregime, zien we tekortkomingen op strategisch, tactisch en operationeel niveau. In de meeste gevallen worden onvoldoende organisatorische factoren meegenomen in de totstandkoming van dergelijke onderhoudsstrategieën. Dit resulteert in

een onduidelijke situatie bij de vertaling van deze strategie in onderhoudsconcepten, beleid en acties. In dit onderzoek is er een organisatie-brede (multidisciplinaire) organisatiestructuur voor onderhoudsmanagement ontwikkeld en geëvalueerd in de praktijk. In deze structuur zijn organisatorische invloed aspecten meegenomen, welke zich niet alleen beperken tot technische aspecten die onderhoudsmanagement in de praktijk beïnvloeden. Deze aspecten beperken zich niet slechts tot alleen technische factoren, maar nemen ook andere niet-technische factoren in acht. Voorbeelden van aspecten die worden meegenomen zijn: organisatie en processen, informatiesystemen en data-eisen, portfolio planning, wet en regelgeving, beleid en criteria. Om deze integrale visie en aanpak te kunnen monitoren en meetbaar te maken is ook een *Maturiteitsmodel* ontwikkeld en geïmplementeerd voor onderhoudsmanagement. Met behulp van dit model zijn de maturiteitsniveaus in het jaar 2012 en 2014 voor een elektriciteitsnetwerk in kaart gebracht. Door terug te kijken naar deze maturiteitsniveaus, kan de organisatie inzichtelijk maken welke domeinen zijn verbeterd of juist niet. Deze aanpak garandeert dat er sprake kan zijn van een continu verbeteringsproces voor onderhoudsmanagement, vooral op het strategisch niveau.

Bij het professionaliseren van onderhoud, hebben we vastgesteld dat de invoering van een systematische en methodische aanpak, vooral op tactisch niveau, essentieel is. Als onderdeel van dit onderzoek is er een gestructureerd en methodisch model ontwikkeld. Dit model is gebaseerd op de welbekende *Reliability Centered Maintenance (RCM)* methodiek waarop een uitbreiding met risico management en met bedrijfswaarden is doorgevoerd. Dit model verschaft een werkwijze waarin consequenties van falen tot op het niveau van verschillende bedrijfswaarden in acht genomen worden. Zodra een dergelijk risico gerelateerd onderhoudsconcept is ontwikkeld en geïmplementeerd, kan elk (bestaand of nieuw) onderhoudsbeleid en elke onderhoudsactie worden beoordeeld of herzien op haar invloed op alle bedrijfswaarden zoals veiligheid, imago en de gevolgen voor het milieu. Het ontwikkeld model wordt het *Utility Risk Linked* RCM genoemd. Het model is toegepast in de praktijk op o.a. vermogenstransformatoren waaruit is gebleken dat het een werkbare methode is welke zich uitstrekt tot en met op risico gebaseerd onderhoudsmanagement.

Deze *Utility Risk Linked RCM* methodiek omvat een uitgebreide en geïntegreerde aanpak van risico gebaseerd onderhoudsmanagement. Aanvullende analysemethoden en technologische tools zijn bestudeerd om te komen tot door data gedreven besluitvormingen. Statistische *Life Data Analyse (LDA)* is toegepast om de onzekerheden aangaande het falen van assets in kaart te brengen, aangezien dit een stochastisch fenomeen is. We zijn tot het inzicht gekomen, dat met behulp van storingsdata en informatie van assets die nog in bedrijf staan, er bruikbare schattingen van faaldistributies uitgerekend kunnen worden. Deze statistische rekenmethoden geven belangrijke informatie over betrouwbaarheidsparameters zoals faalkansen, kans verdelingsfuncties en leeftijd gerelateerde restlevensduur inschattingen. Dit staat bekend als een *top-down* benadering.

De *bottom-up* benadering legt vooral een focus op de rol van conditie monitoring binnen asset management en wat de perceptie binnen netwerkbedrijven aangaande deze ontwikkelingen is. We hebben gezien dat distributienetwerkbedrijven nog geen grootschalige uitrol van dergelijke technologieën toepassen. In veel gevallen blijkt dit het gevolg te zijn van de hoge initiële investeringskosten, verwachte uitdagingen met interpretatie van gegevens of de betrouwbaarheid van de technologie zelf. In de afgelopen jaren zijn er echter ontwikkelingen geweest waardoor deze monitoringssystemen financieel aantrekkelijker worden. Als gevolg van deze ontwikkelingen blijkt uit benchmark onderzoeken dat bedrijven meer willen begrijpen van de relatie tussen onderhoudsmanagement en conditiebepaling. We hebben een raamwerk ontwikkeld voor conditiebewaking, welke een basis biedt voor verdere beleidsontwikkeling. Een dergelijk raamwerk kan door asset managers als een leidraad worden beschouwd voor het identificeren van de relatie tussen faalmodi, verouderingsprocessen en voor het selecteren van conditie monitoringsregimes.

De doelstelling en onderzoeksvragen die zijn bestudeerd in dit onderzoek bevestigen het bestaan van een kloof tussen het management van onderhoud en de operationele onderdelen bij distributie netwerk bedrijven. Elke onderzoeksvraag is aan de orde gesteld door middel van empirische benaderingen zoals afgelegde enquête, praktische case studies, het methodisch analyseren van verzamelde data, veldmetingen en het ontwikkelen van methoden op basis van veld observaties en analyses. Op basis van de geadresseerde onderzoeksvragen en de toegepaste onderzoekmethoden kan gesteld worden dat de algemene doelstelling van dit onderzoek is toegesneden op de totstandkoming van een goed onderbouwde organisatie voor onderhoudsmanagement, de invoering van risico management en bedrijfswaarden in onderhoudsmanagement en de toepassing van statistische en sensor gebaseerde methoden om het faalgedrag van assets te analyseren. Aanscherpingen zijn op verschillende gebieden nog mogelijk en verder onderzoek is daarom aanbevolen in gebieden zoals het uitbreiden van de *Utility Risk Linked RCM* methode door het modelleren van externe risico's, waarbij verschillende informatiebronnen aangeboord zullen worden. Het voorspellende karakter van risico- en toestandsafhankelijk onderhoud zal implicaties hebben op OPEX budget planning en vergt onderzoek naar nieuwe benaderingen in toekomst. Inspanningen gericht op geavanceerde managementmethoden voor nutsbedrijven vergen een nadere beschouwing om antwoord te geven op de vraag of huidige besluiten (investeringen, onderhoud, vervangingen, etc.) de garantie bieden, dat de output van netbeheerders in de toekomst kan voldoen aan de door de toezichthouders verwachte prestatie. Ook is het nodig om te onderzoeken of de toegepaste reguleringsmethodes de invoering van nieuwe technologieën ondersteunen, weerhouden of ontmoedigen. Gezien de steeds toenemendere complexiteit van elektriciteitsnetten wordt ook aanbevolen om verder onderzoek te doen naar integrale aanpakken voor capaciteits- en instandhoudingmanagement, iets wat nu afzonderlijk van elkaar geschiedt.

Veranderingen in de elektriciteitssector zijn volop gaande zoals ontvlechtingen van organisaties, procesverbeteringen, overnames en fusies, samenwerkingsverbanden, uitbestedingen, etc. Dit is een gevolg van de dynamische verzakelijkte omgeving waarin elektriciteitsbedrijven opereren. Dit gezegd hebbende, willen we benadrukken dat er sprake is van een voortgaande ontwikkeling op dit gebied en evenzo van het onderhoudsmanagement van de elektriciteitsnetten. Vandaar dat de aard van dit onderzoek gezien moet worden als een doorlopend onderzoeksgebied voor de komende decennia.

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1 Introduction

1.1 Background

1.1.1 Electricity network business environment

The central theme in this thesis is the management of maintenance of assets in the electricity network sector and more specifically, on electricity networks for distribution. The concept of maintenance has existed a long time and has evolved along this period in various industrial applications as well as research areas. In the electricity network sector, maintenance is gradually gaining more interest on management level as part of an integral management aspect. This is mostly because of the changing and profoundly challenging environment in which electricity network companies have to operate nowadays. This changed environment is brought about by, for instance, the sector reform, massive uptake of distributed generation devices, disruptive changes in the control and communications equipment used in the network and increasing regulatory and funding pressure that is being placed on electricity network organisations to justify their management actions and expenditure decisions [1].

As a consequence, firstly, reliability engineering, seen from a technical point of view, took off as a prevailing discipline. Secondly, followed by the context of controlling costs, seen from a financial point of view, formed an important driver for network companies. Thirdly, a more recent development has been the progress towards a business context, seen from a social and technical point of view, as a driver to balance amongst costs, performance and risks in an integrated and documented manner. Nowadays, the management of the electricity network business speaks about asset management (physical asset management or infrastructure asset management). In figure 1, this change in business environment for network companies is illustrated with simplified decision-making chains and important steps within these chains. This change has also been described as moving the decision-making process from an investment proposal triggered process to a problem triggered process and ultimately a risk analysis triggered process, which has been reported in [2].

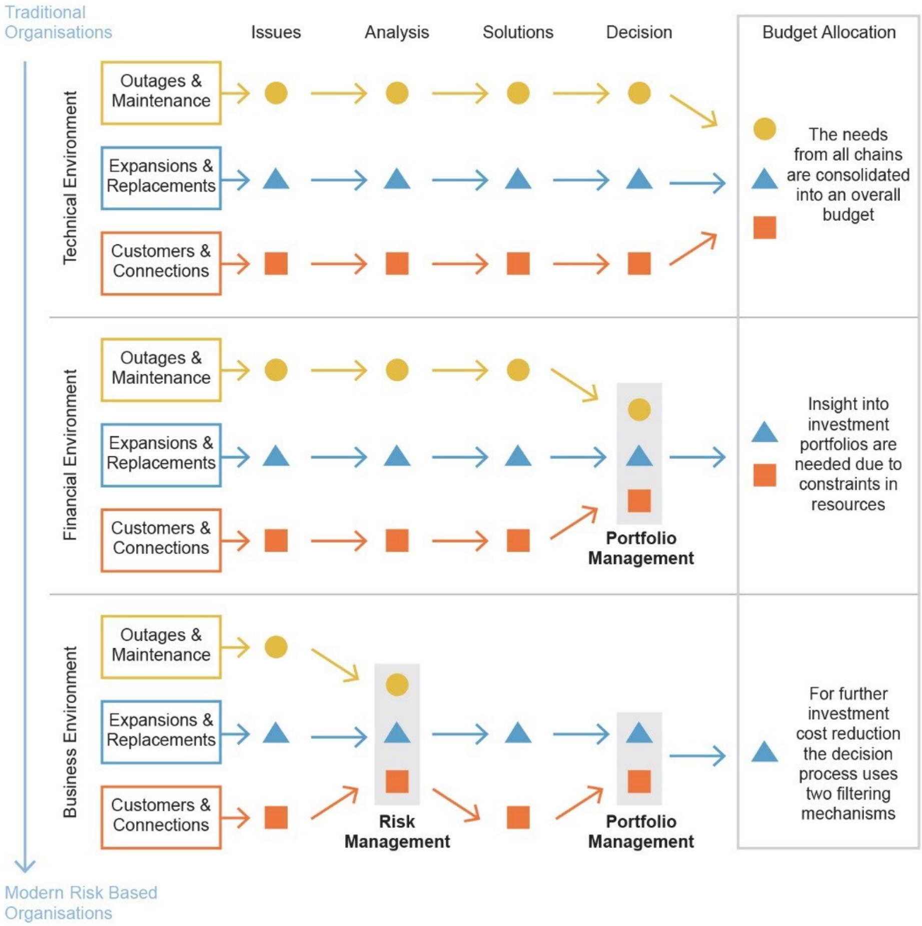


Figure 1: In traditional "technology focused" decision chains every chain defines investment needs and these needs are consolidated in the end into an overall budget allocation. Usually, only technology assessed solutions were proposed. Due to cost reductions and resource constraints, it became important to have insight of an investment portfolio. This idea of decision-making continued when network companies became more financially oriented. In the business environments (social and technical asset management environment) risk management was incorporated as an extra filtering mechanism so that technical issues for example would be assessed on their risks.

Asset management, as defined in BSI: PAS55 *is the systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan* [3].

Maintenance management forms an important part within asset management. This thesis deals with the issues surrounding maintenance management for electricity network companies. Although there are a large number of books and research papers available on maintenance related topics, however, there still remains a gap for industry-specific views on maintenance of long term assets. This thesis aims to link the general management subjects applicable for maintenance to methods, tools and technologies, which can be used for practical purposes in the electricity sector. This approach is not common, as in most available literature the focus is on one single aspect, instead of providing a broader view with practical methods. Furthermore, the majority of developed models and analysed case studies in this thesis come from real-life electricity network applications.

1.1.2 The maintenance management problem

Maintenance is not a new topic. Maintenance has existed a long time and has changed drastically over the past decades. In general, for maintenance management, the following evolution of issues has been reported:

- Not-manageable activities such as not being able to plan or schedule a maintenance task beforehand, which can be considered a necessary evil. This was, usually, seen as an unavoidable cost creator and, therefore, not manageable. This was particularly the case in the 50's. This was known as corrective maintenance or run-to-failure maintenance.
- In the 60's, many industries started to move towards preventive maintenance actions. It was argued that by carrying out preventive actions, certain failures could be avoided and that this would subsequently result in cost savings in the long run.
- The concern regarding more maintenance than required (over-maintenance) grew, and in the late 70's and early 80's interest in condition-based maintenance increased with the intention to apply this form of maintenance to assets where this was technically and economically feasible. The fact that condition monitoring systems became more accessible and cheaper also facilitated this trend.
- Recently, research attention shifted more to promote advanced maintenance management such as predictive health models, information technology, and sophisticated control and knowledge tools with the possibility to reduce the impact of breakdowns from a remote location.
- Last decades' developments are the method of maintenance where risk is seen as a guiding principle. Risk-based maintenance is seen as a state of the art maintenance regime. The risk-based approach refers to the analysis of the probability of an event (failure, or failure mechanism) occurring and the impact of the consequences of this

event on the business values of the company. This can be interpreted as a measure of risk.

The changes described here apply mostly to industrial areas such as e.g. the process industry, mechanical industries, etc. The developments in maintenance management have been less rapid for the electricity network sector, due the long lifetime of assets, the lower loading of the assets, "gold plating" of assets, redundant network design, to mention a few. In fact, it was especially the transmission network that was more mature in terms of maintenance developments compared to distribution networks (which, in the early days, mainly followed corrective maintenance). An international CIGRE survey [4] published in 2000 showed that preventive maintenance with a predetermined time interval (known as time-based maintenance) is the most common strategy (47%) for transmission networks, followed by off-line condition-based maintenance (31%). These percentages are mainly valid for assets such as transformers, lines, towers and substations equipment. For cables and control equipment, corrective maintenance was used as the predominant approach. The responses also varied between regions. Around 50% of the respondents indicated that they performed more maintenance than recommended by the manufacturers, particularly in lower labour countries.

For distribution networks, these numbers are not widely available and maintenance has been managed in a rather ad-hoc way based mainly on experience. Furthermore, and more importantly, the lack of a clear maintenance management philosophy became more visible in the distribution networks during the move from price regulation to price-quality regulation [5], where empirical studies [6] have shown that there was a decrease in network reliability as caused by an increase in the interruption frequency and average interruption duration. This was primarily the reason for the regulatory scheme to move towards price-quality regulation. Detailed information on this topic can be found in [5]. Thus, a challenge arose for the electricity distribution networks regarding maintenance management. Finding the right mix of maintenance activities for distribution network assets is a challenge for network companies due to the renewed business environment, where maintenance is not a merely technical issue any longer. Maintenance departments will be expected to function in a broader sense and move away from "silos" thinking. These days, maintenance departments are required to consider financial aspects and manage maintenance budgets. Furthermore, maintenance processes are required, maintenance and asset key performance indicators (KPI's) are needed, recourses and skills need to be managed.

Maintenance department decisions will need to reach out to strategic, tactical and operational aspects of an organisation. For example, operational decisions for maintenance concern decisions regarding maintenance tasks, scheduling and execution. On a tactical level, decisions regarding the selections of long term maintenance concepts and maintenance plans are made. More recently, strategic aspects such as organisation business values and risk management aspects are required to be taken into account in maintenance decisions, where for instance the concept of safety is vital.

Having established that these multi-disciplinary challenges must be addressed, it is expected that for a well suited organisation, techniques and tools of various nature are needed and require scientific foundation. The questions are then, what options exist:

- To develop practically applicable tools to predict failure behaviour of assets.
- To establish decision schemes for determining the right maintenance concept.
- To deploy technologies to support maintenance and ultimately, design an organisation-wide approach for maintenance management of electricity distribution networks.

The focus of the research provided in this thesis is to approach the mentioned questions from a practical and scientific point of view. It should be noted, that at the moment of writing, the electricity sector is amid a continuous process of quickly changing environments due to unbundling of organisations, process enhancements, take-overs and mergers, partnerships, outsourcing, etc. As a result, occasionally outsourced decisions require back sourcing decisions which makes the business environment very critical and unpredictable. This is due to the dynamic business environment in which electricity network business operate. This also has implications for maintenance management, for example with respect to the knowledge, resources, skills, personnel, centralization and decentralization of maintenance, etc. Having said this, we want to emphasize the continual developments in the area of maintenance management of electricity networks, hence the nature of this research is an ongoing research area for coming decades.

1.2 Research scope, objectives and questions

1.2.1 Research scope

This thesis deals with maintenance management related to electricity networks and in particular distribution networks. In general, the electricity networks can be divided into transmission and distribution. The transmission network connects generation plants and acts as an interface to the distribution network. The distribution network takes the electricity from the terminals of the transmission network to the consumers. Distribution networks can be further divided into medium voltage (MV) and low voltage (LV) networks. The LV network distributes the electricity to the final consumers. The scope of this research is to contribute in closing the gap between the technical and organisational aspects of maintenance. For the greater part, this research, its results and case studies, are drawn from experiences in the Dutch distribution network sector, with a number of international experiences from collaborations with CIGRE.

The content of this thesis is intended for a double audience, on one hand for those interested in the management aspects of maintenance and on the other hand for those interested in practical developed methods for applying maintenance concepts such as *Reliability Centered Maintenance* (RCM) within the risk management regime of the organisation, statistical tools for predicting failure behaviour and the upcoming role of condition monitoring, hence a more concept and technology oriented aspects of maintenance.

1.2.2 Research objectives

The slow development of a professional maintenance philosophy for electricity distribution network operators in section 1.1.2 is helpful in the formulation of the overall objective of this thesis. Therefore, the overall objective of this thesis is formulated as follows:

"To assess and investigate an organisation-wide maintenance management framework for electricity network companies, which includes the establishment of decision-making methods and tools to practically predict failure behaviour of assets for determining the right maintenance concept within a risk management regime including condition monitoring and statistics"

In literature, a sheer amount of information can be found on maintenance concepts to help in exploring this research objective. The aim of this thesis, with this objective in mind, is to fill the gap between organisational and technical approaches of maintenance management. In addition, the aim is to provide real-life case studies.

1.2.3 Research questions

In order to fulfil the previously mentioned research objective, a number of research questions need to answered, which will happen in the course of this thesis. These research questions are:

1. What are the organisation's supporting pillars that need to be considered when designing an organisation-wide maintenance regime?
2. How can the development (maturity model) of a maintenance organisation be modelled and measured?

3. What is required to link existing (well-developed) maintenance concepts to the overall corporate business values in order to establish a method for tactical maintenance management purposes to select amongst most effective maintenance activities taking into account the overarching risk management philosophy of asset management?
4. Which quantitative techniques, based on statistics, are applicable to adequately predict failure behaviour of assets for maintenance management purposes?
5. Which role will the upcoming development in condition monitoring systems play in maintenance management?

1.3 Research approach

1.3.1 Method of research

On account of the fact that this research attempts to bridge two research disciplines, namely from a technical and a management point of view, it is not the purpose to investigate certain topics to a level of detail as if it were the only subject in a thesis. Instead, the method of analysis has a multidisciplinary nature and the thesis is organised following an M-structure. This means that on a broad, general level, the management and organisational aspects of maintenance are elaborated (represented by the horizontal part of the M), while, in more detail, the specific maintenance management concepts, statistical analysis and condition monitoring studies are researched in depth (represented by the vertical part of the M).

The method of research applied during this research is mainly based on inductive methods. The inductive method provides a systematic approach to generalize specific expert knowledge into a framework of broader application. The inductive method involves the following steps:

- Identify and define problem areas
- Data collection
- Data analysis
- Interpretation of data
- Generalisation of model
- Validation/ verification (in field cases)

The followed research method is from a pragmatic viewpoint. The focus of pragmatism is on practical, applied research. The thesis is formulated in a way such that each chapter with the discussed topic goes through research steps/methods such as case studies, focused group research and survey research. The research consists of quantitative and qualitative methods. In line with the pragmatic viewpoint the research setting is non-contrived as the research has been done in a business and natural environment (field studies). Literature review in combination with practical working experience from within the electricity network company (DNO) and through international study committees of CIGRE provide, in many cases, the pragmatic foundation on which our methods are developed and on which the case studies are based. In figure 2 an overview of the organisation of the thesis is illustrated in the M-structure.

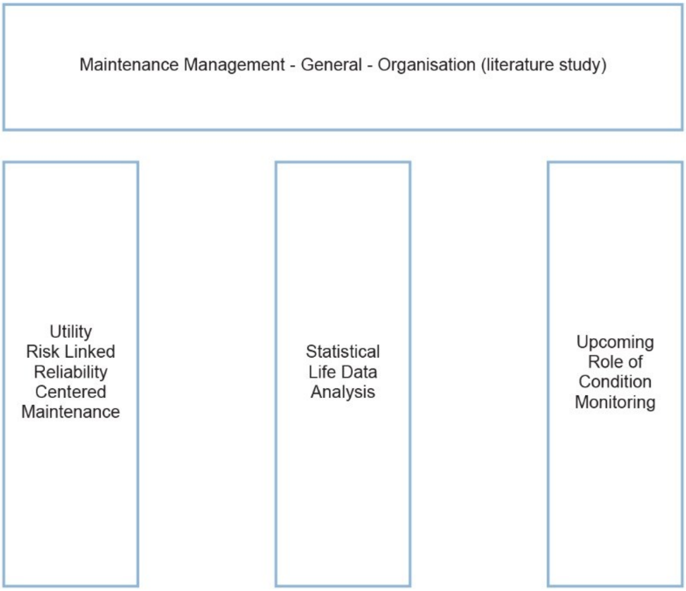


Figure 2: M-structure representing the areas of research and the method of research namely, the horizontal part of the M is based on literature study, while the vertical parts are based on developed methods in this research and for each practical case study.

1.4 Outline of the thesis

This thesis is organised as follows:

In chapter 2, asset management, risk management and maintenance management literature and general aspects relevant to this thesis are summarised.

In chapter 3, an organisation-wide approach for the management of maintenance according to corporate support pillars is described along with a maintenance management maturity model. By means of a practical implemented example the implication of this for a distribution network company is discussed.

In chapter 4, a comprehensive model is developed for risk based maintenance management. This model is called the *Utility Risk-Linked Reliability Centered Maintenance* model. Chapter 4 ends with a case study applied for power transformers.

In chapter 5, a method, based on statistical life data analysis (LDA), is described and practical aspects such a data collections, data handling, statistical failure distributions and a practical case study.

In chapter 6, the upcoming role of condition monitoring (mainly online condition monitoring) on different levels of asset and maintenance management (strategic, tactical and operational) is described.

In chapter 7, this thesis comes to a close by drawing a number of key conclusions and making recommendations for further study.

2 Asset, Risk & Maintenance Management

2.1 Introduction

2.1.1 Background

Nowadays, asset, risk and maintenance management are three types of management that are heavily related to each other. Moreover, all three of them are frequently encountered in electricity network utilities and other asset intensive industries around the world. Therefore, they need to by studied and discussed in an integrated fashion. For instance, the aspects covered by asset management can range from maintenance and renewal of specific assets or asset groups all the way to the management or balancing of financial aspects with engineering and risk aspects for a large population of geographically widespread assets. The aim of this thesis is to investigate the research objectives as given in section 1.2 for maintenance management in an integrated fashion with asset and risk management. Thus, in this chapter, the literatures covering these aspects are briefly discussed, both separately and in relation to each other.

2.1.2 Chapter outline

Firstly, this chapter starts in section 2.2 by looking at asset management in the context of a business environment for asset intensive industries. As will be seen, asset management is an *umbrella* concept that may have different meanings to different practitioners depending on their context and viewpoint. A short history and the development of specifications and standards of asset management are then provided. Section 2.3 continues with considering risk management as a decision-making method within asset management. In fact, risk management is seen as a business related managerial method for making complex asset related information understandable, comparable and manageable when interpreted as a measure of *risk*. Sections 2.4 and 2.5 cover the core topic of this thesis, namely maintenance management. An overview of literature on maintenance tasks, policies and concepts is provided in section 2.4. Section 2.5 briefly summarizes the development and evolution of maintenance management in the last decades. As maintenance management has grown to become a complex aspect within the overall business context of network companies, it is shown that knowledge of essential supporting pillars for maintenance management is required. These are discussed in section 2.5. This chapter comes to a close by drawing a number of concluding remarks and explaining the way forward for the remainder of this thesis.

2.2 Asset Management

2.2.1 Asset management as business approach

Asset management is probably one of the most debated topics over the past decade [7], [8], [9], [10], [11], [12], [13]. It has been used to label some very different processes and means different things to different players depending on where they are in the business. Even within the electricity network industry, asset management has been given a wide variety of interpretations. Indeed, within a single electricity network or power company, the interpretation may be different or change over time. Moreover, it has been recorded [7] that the scope of asset management has developed with each stage of the restructuring of the distribution network business environment and is therefore set to do so again. Asset management should not be seen as just a “buzzword” [14] management initiative. Throughout the literature, many definitions can be found for asset management. Later in this chapter, some important definitions of asset management are given.

In general, asset management is a business approach designed to align the management of engineering and asset related financial spending to overall corporate goals. The objective [15], [16], [17] is to make all asset related decisions according to a single set of stakeholder-driven criteria. The idea of applying asset management to (engineering) asset intensive industries came from the well-developed *financial asset management* community [14]. Financial asset management is defined as: *Making financial investments decisions so that returns are maximised while satisfying risk tolerance and other investor requirements.*

In principle, tangible (engineering and infrastructure) assets differ from financial assets in a way that they are susceptible to wear and deteriorate with age and can be impacted by disruptive technology developments [18]. Each installed asset is part of a larger power system and cannot be easily taken out and sold. These assets require inspection and maintenance. From this it is found that asset management of electricity networks is not identical to financial asset management. A detailed description of the differences between financial and infrastructure asset management can be found in [14].
From a business point of view, asset management has the following goals:

- Balance cost, performance and risk
- Align capital and operational spending decisions and corporate objectives
- Make fact based and asset-data driven decisions.

An organisation's asset management framework should generally include an asset management policy, an asset management strategy and an asset management plan [3], [19]. These different hierarchies come together in an integrated way in an asset management system. Each hierarchy (policy, strategy or plan) has different typical priorities and concerns with different management time-scales and levels of decision-making. In figure 3, a broad outline of the different hierarchies is provided. The accompanying levels of decision-making and time scale of concerned decision are also shown as levels of management namely strategic, tactical and operational [3], [17], [12].

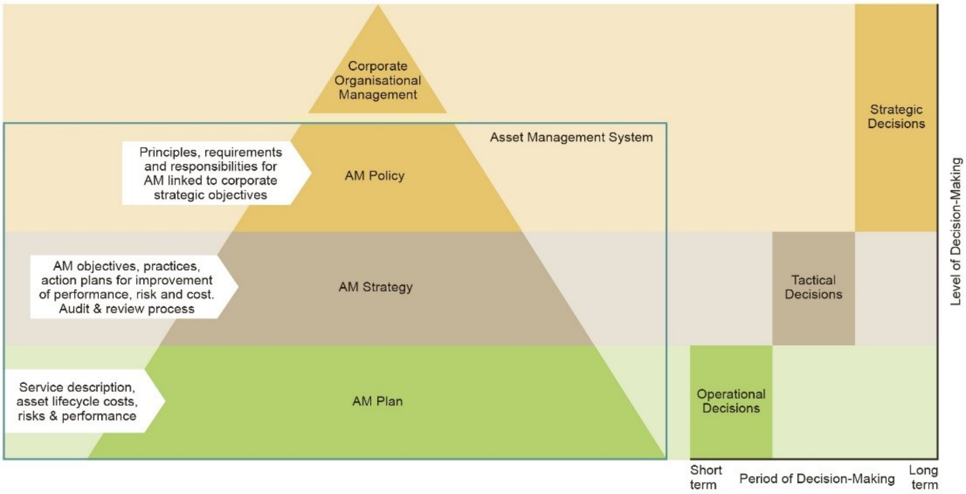


Figure 3: The hierarchy of an asset management framework as an integrated system. The asset management policy, strategy and plan are defined within a corporate organisational management framework. The levels of decision-making and management, strategic, tactical and operational levels are also shown accordingly.

At this point, many electricity network utilities have applied or are applying elements and concepts of asset management to target aspects of their business. Amongst these are for instance, [20], [21], [22], [23], [24] equipment inspections and maintenance improvement plans, condition monitoring, statistical data analysis, risk based asset replacement models, etc.

2.2.2 Short history of asset management

Although the idea of asset management seems promising for managing electricity network companies in finding the optimal trade-off between cost, performance and risk in a regulatory regime, these companies have only recently started to embrace this concept [14]. In order to understand this, it is useful to shed some light on the history of asset management. In table 1, a summary of important developments throughout the years is provided.

Table 1: Brief history of important developments in the field of asset management

Type of industry	Element of asset management	Detailed description
US nuclear arsenal (1960)	Analysis of military policy planning in a nuclear age for most efficient allocation of available budgets	
Heavily regulated industries such as petroleum refining and chemical processing	Quantitative risk management	
Manufacturing industries	Focus on optimizing process uptime and system availability	Known as *physical asset management (PAM)*
Public infrastructures such as roadways and water supply systems	Set performance measures and targets. Report actual performance against targets and add financial systems and policies	New Zealand Local Government Act (1974) Asset management requirements were expanded in 1996 to require ten year infrastructure plans that consider the costs and benefits of various infrastructure options. In order to provide consistency, the *Infrastructure Asset Management Manual* was published in 1996 by the Association of Local Government Engineers of New Zealand

In the United Kingdom (UK), asset management gained interest in the early 1990s during the privatization period. OFGEM (Office of Electricity Gas and Electricity Markets) initiated an *Asset Risk Management* Survey in 2002. In the period following this survey, OFGEM started requiring the submission of annual asset management plans from its regulated entities. Afterwards, a collaboration of OFGEM, the Institute of Asset Management (IAM) and a review panel, the *Publically Available Specification 55: Asset Management (PAS-55)* was written. *PAS 55* was first published in 2004 and substantially revised in 2008, which is elaborated in section 2.2.3.

The United States of America has also seen an increased interest in infrastructure asset management, however in a less formal way. Mainly, targeted conference and consulting services have been deployed. Here, the focus has been on the deployment of information systems that enable effective asset management such as maintenance management systems, asset databases and project ranking tools. The *Electric Power Research Institute (EPRI)* has reported an organized approach with the Nuclear Asset Management (NAM) program and the Asset Management Toolkit (AMT). Amongst the publications by EPRI, a widely used one is the *Guidelines for Power Delivery Asset Management* published in 2004, revised in 2005 and re-written in 2008 to align more with *PAS-55*.

Given the popularity of *PAS-55* and the continuing interest in asset management, and after consultation with industry and professional bodies around the world, this specification was put forward in 2009 to the *International Standards Organisation* as the basis for a new ISO standard for asset management [3]. This was approved and the resulting *ISO 55000* family of standards has been developed over a period of four years with 31 participating countries and has been published in January 2014 [19].

The field of asset management has also conglomerated with the field of engineering. Under the auspices of the *International Society of Engineering Asset Management (ISEAM)*, engineering asset management is focussing on life-cycle management of the physical assets required by private and public firms. The purpose is to make products and for providing services in a manner that satisfies various business performance rationales. In a number of reviewed publications and books [10], [11], [25], this community provides a broad view of the inter- and multi-disciplinary approach which combines science, engineering, and technology principles with human behaviour and business practice. In the *International Journal of Strategic Engineering Asset Management* this multidisciplinary practice has been extensively reported on [9].

2.2.3 Publically Available Specification 55: Asset Management (*PAS-55*)

A brief summary of *PAS-55* is given here. As mentioned earlier, in 2004, the British Standards Institute (BSI), together with the IAM released the *PAS-55* part 1 and 2, being the first internationally recognized specification for asset management [3]. *PAS-55* offers guidelines and good practices to enable optimal management of physical assets and infrastructures over their lifecycle. In order to manage the physical assets over their lifecycle, the management of other asset types (being non-physical) should also be considered within the asset management system. This way of thinking is incorporated in the *PAS-55*. For instance, for the management of the lifecycle of physical assets, a company heavily depends on the information, knowledge and financial resources. This specification provides a framework for improving the effectiveness of the lifecycle management of physical assets, especially, in capital intensive environments, such as electricity, gas & water networks, airports, railways, etc.

In 2008 the specification was substantially revised and updated. *PAS-55* has received worldwide attention from regulators and other regulated industries as a tool for integrating and improving business practices, raising performances and assuring greater consistency and transparency. Basically, the *PAS-55* advocates the removal of "silos" in companies and considers assets in "systems" instead. By doing this, a cross-functional optimization of the lifecycle of assets can be achieved as a core principle of good asset management [10]. In the Netherlands, the Energy Court has even set up a Dutch standard known as *NTA 8120* in 2009 for the management of electricity and gas networks based in *PAS-55*.
PAS-55 is published in 2 parts:

- Part 1, PAS-55-1:2008: Specifications for the optimized management of physical assets
- Part 2, PAS-55-2:2008: Guidelines for the application of PAS-55-1

The specification provides 28 requirements and guidelines for the application and is structured around the well-known *Plan-Do-Check-Act* cycle for continual improvement.

In [PAS-55-1:2008] asset management is defined as: "*systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan*". The organisational strategic plan is defined as: "*overall long-term plan for the organisation that is derived from, and embodies, its vision, mission, values, business policies, stakeholder requirements, objectives and the management of its risks*".

2.2.4 ISO 55000 series

The *PAS-55* can be seen as a groundwork which was laid in order to develop the *PAS-55* into a standard and in 2009 this specification was put forward to the International Standards Organisation as the basis for a new ISO standard for asset management. In January 2014 the *ISO 55000* family of standards for asset management was published [19]. In accordance with the *ISO 55000,* the Energy Court in the Netherlands also updated the Dutch standard to *NTA 8120:2014*. The *ISO 55000* is published in three documents:

- *ISO 55000* Asset Management – Overview, principles and terminology

- *ISO 55001* Asset Management – Management systems – Requirements
- *ISO 55002* Asset Management – Management systems – Guidelines for the application of *ISO 55000.*

In the *ISO 55000,* the most important features of the *PAS-55* are represented and expanded upon.

The features in the *ISO 55000* series are [19]:

- The alignment of the organisational objectives to the asset management strategies, objectives, plans and day to day operational activities
- The use of whole lifecycle asset management planning and cross-disciplinary collaboration to achieve the best value.
- The use of more risk management and risk-based decision-making processes.
- The enablers for integration and sustainability especially leadership, consultation, communication, competency development and information management.

As *PAS-55* was primarily focussed on physical assets, the *ISO 55000* standard has been extended to apply to any asset type. By doing this, the intention is to make asset management more general for interpretation within different asset management contexts. In *ISO 55000*, asset management is defined as: "a *coordinated activity of an organisation to realize value from assets*". Although the detailed description of *ISO 55000* is beyond the scope of this thesis, a number of relevant elements from this standard to the content of this thesis are explained for maintenance management. For instance:

- Regarding decision-making: In *PAS-55,* requirements for optimizing decision-making (between cost, performance and risks) were given. In *ISO 55000,* it is explained that clear and documented methods and criteria for decision-making and prioritizing are required to reflect stakeholder needs. This will certainly be a crucial point for maintenance management in electricity distribution networks in the future. At this moment, we have seen in many parts of distribution networks and even parts of transmission network that complete documentation is lacking regarding maintenance management spending and strategies.
- Regarding risk management: Risk management and risk-based decision making in *ISO 55000* are based on the published *ISO 31000* Risk Management. For maintenance management in general, and for maintenance management of electricity distribution networks in particular, the method of risk-based maintenance is still underdeveloped.

The discipline of asset management has, undoubtedly, shown a growth of interest internationally over last years. It has been reported in literature [26] that despite these developments there is not yet a clear and unified basis available that provides a reference across different industrial sectors [27].

In [1] it has even been reported that *"the current lack of international standards or guidelines on asset management for electrical networks will have a significant impact on the reliability and future viability of the electricity sector"*. Electricity network companies regularly adopt different approaches in testing equipment, calculating the lifetime and financial costs of various equipment maintenance options, and even reporting on the performance of their system. This is hardly intentional, but rather *"stems from a lack of internationally accepted global standards or guidelines on how to practice asset management in the electricity network sector"*. Moreover, it has been reported that *"whilst standards such as the ISO 55000 series provide general guidance on best-practice asset management procedures, they do not provide the industry-specific guidance that is needed given the operational methods and challenges of the electricity transmission and distribution industry"* [1].

2.3 Risk Management

2.3.1 Risk management as decision-making method

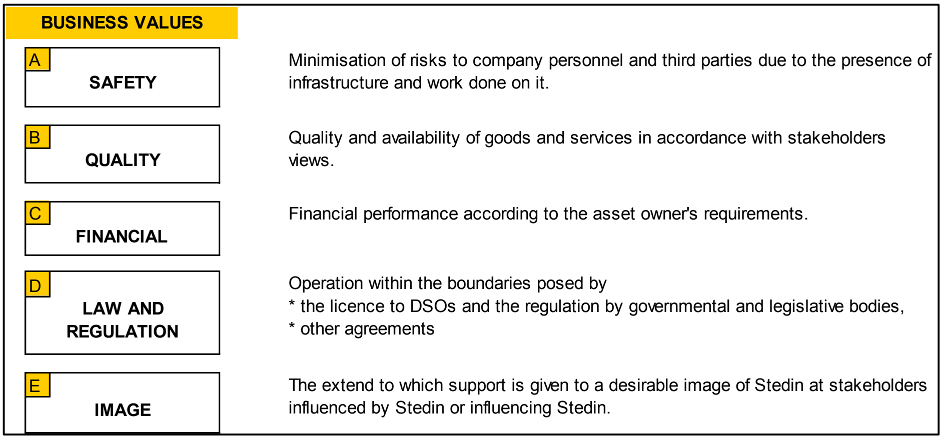
In a business environment, stakeholders and regulators expect from network companies that information is presented in an understandable way. Risk-based methods, explaining information in terms of risks and probabilities have increasingly been applied in asset management [16], [28], [29]. These methods help in expressing and presenting decisions in financial terms related to risks. As a consequence, this has forced electricity network companies to record, document and analyse data and practices in a structured way and to use a consistent and transparent method for analysis. In this context, risk management is seen as a mainstream regime to enable asset managers to translate corporate business values and requirements into a comparable, measurable and management dimension, namely *risk* [30]. Risk management can be subject to great misunderstanding, as has been reported in [12], because risk management does not that risks are deliberately accepted to meet the business objectives. The task is to identify risks within the entire business process to initiate subsequently and implement appropriate measures to manage (control) these risks.

Risk is defined as the product of the *probability* of an event and its *consequences* [31]. Generally speaking, the existence of risks implies that there is at least the possibility of negative consequences or deviations from expected values when an event has a probability to occur. Essential for risk management is that it is not just limited to solely technical risks of the network utility, but also extends to the management of risks involving the analysis of events

for a complete system (i.e. organisation, network, asset, etc.) that might have a negative impact [32]. Moreover, the management of risk involves the decision-making process of measures to assess risks and the evaluation of these measures [16].
In such a socio-technical business model, the corporate mission, vision and strategy are connected to overall corporate business values. Although every network utility may develop unique business values, some generic, and widely adopted, business values are:

- Quality (customer minutes lost / worst served customer)
- Safety (injuries to personal and third parties)
- Finance (financial consequences)
- Image (reputation)
- Compliancy (regulations and legislations)

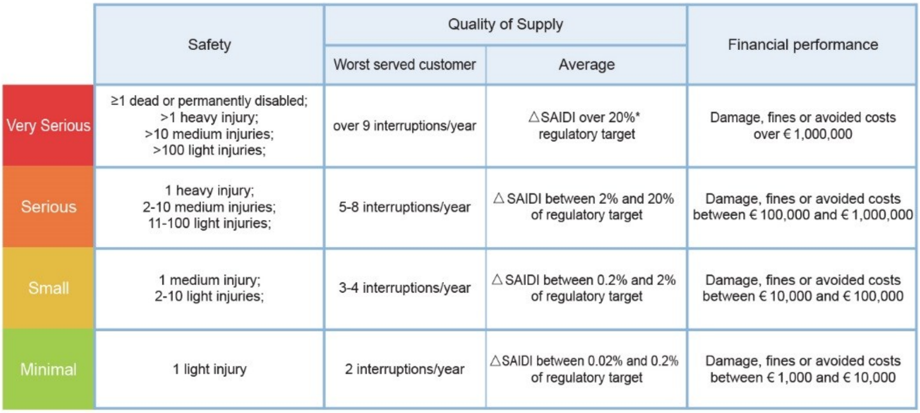
Basically, in order to pose a certain risk, this issue should have an influence on the business values of the network company [33]. Depending on the organisations management it is often useful in practice to focus on a number of these business values. For example, it is reported in [12], that risks in area of safety will not be accepted due to laws (i.e. in Germany). In appendix A an overview of different business values applicable to risk management is provided. In figure 4, the business values, as part of a risk management methodology, for a typical electricity distribution network company are shown [33].



BUSINESS VALUES	
A **SAFETY**	Minimisation of risks to company personnel and third parties due to the presence of infrastructure and work done on it.
B **QUALITY**	Quality and availability of goods and services in accordance with stakeholders views.
C **FINANCIAL**	Financial performance according to the asset owner's requirements.
D **LAW AND REGULATION**	Operation within the boundaries posed by * the licence to DSOs and the regulation by governmental and legislative bodies, * other agreements
E **IMAGE**	The extend to which support is given to a desirable image of Stedin at stakeholders influenced by Stedin or influencing Stedin.

Figure 4: Corporate business values for risk management methodology at a Dutch electricity and gas distribution company.

A risk is assessed in a way that the effect on a business value and the probability of occurrence of the effect can be scored. To ensure objectivity of the risk analysis, the probability and consequences are first assessed separately and afterwards combined to form an assessment of the risk. In order to score risks, a set of possible effects is added to each business value [33]. The effects relating to safety, quality of supply and finance are shown in figure 5.

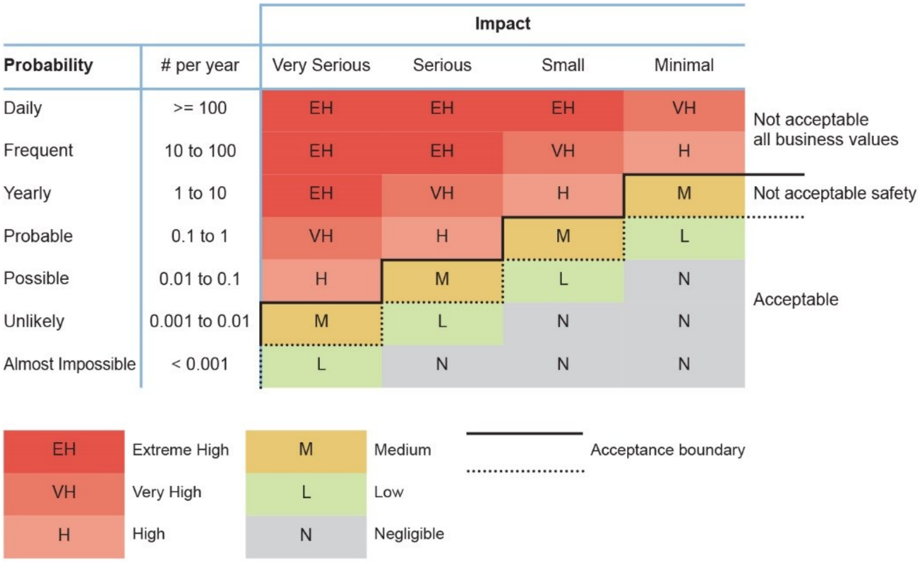


	Safety	Quality of Supply		Financial performance
		Worst served customer	Average	
Very Serious	≥1 dead or permanently disabled; >1 heavy injury; >10 medium injuries; >100 light injuries;	over 9 interruptions/year	△SAIDI over 20%* regulatory target	Damage, fines or avoided costs over € 1,000,000
Serious	1 heavy injury; 2-10 medium injuries; 11-100 light injuries;	5-8 interruptions/year	△SAIDI between 2% and 20% of regulatory target	Damage, fines or avoided costs between € 100,000 and € 1,000,000
Small	1 medium injury; 2-10 light injuries;	3-4 interruptions/year	△SAIDI between 0.2% and 2% of regulatory target	Damage, fines or avoided costs between € 10,000 and € 100,000
Minimal	1 light injury	2 interruptions/year	△SAIDI between 0.02% and 0.2% of regulatory target	Damage, fines or avoided costs between € 1,000 and € 10,000

*Regulatory system average interruption duration index (SAIDI) target 2010-2016: 25 minutes/year per customer.

Figure 5: Effect evaluation matrix for business values safety, quality of supply and finance for a Dutch electricity and gas distribution company.

After the effect has been scored, the probability of the occurrence is scored. The probability of the effects can be scored on a multi-categories scale, ranging from almost impossible (e.g. less than once in a thousand years) to daily (e.g. more than 100 times a year). When the effects scales are combined scales with the probability scales a typical two-dimensional risk assessment matrix can be used to categorize the rank of each evaluated risk as shown in figure 6.



		Impact			
Probability	# per year	Very Serious	Serious	Small	Minimal
Daily	>= 100	EH	EH	EH	VH
Frequent	10 to 100	EH	EH	VH	H
Yearly	1 to 10	EH	VH	H	M
Probable	0.1 to 1	VH	H	M	L
Possible	0.01 to 0.1	H	M	L	N
Unlikely	0.001 to 0.01	M	L	N	N
Almost Impossible	< 0.001	L	N	N	N

Not acceptable
all business values

Not acceptable safety

Acceptable

EH	Extreme High	M	Medium
VH	Very High	L	Low
H	High	N	Negligible

Acceptance boundary

Figure 6: Risk acceptance matrix, which represents the risk values, from Negligible to Extremely High. The blue lines mark the acceptance boundaries. Risks below and to the right of the lines are acceptable, risks above and to the left of the lines are not acceptable. Unacceptable risks must be mitigated to an acceptable level.

After the risk assessment, the next step is the treatment of the risk, namely the determination of alternative solutions to deal with the risk. Dealing with the assessed risk can include decisions such as accepting the current risk, take an action and invest in capacity expansions, maintenance, refurbishment, replacement or other operational procedures (i.e. restoration of outages, improved business processes, information system and data quality improvements, etc.).

Overall, risk management, as a regular business process, provides a method to identify, assess and treat an organisations risk to account for future events with a negative impact on the organisation. Furthermore, it creates an awareness of socio-technical assessed risks and possibilities to treat them. Added to this, the application of an objective risk management approach enables network utilities to have control over risks and have a common language for sharing and discussing risks between management and engineers. It is also used to quantify and support arguments for budgets and portfolio planning. Network utilities use risk management for several aspects, for example, new investment projects, expansion investments, etc.

2.3.2 Risk management standards

General risk management standards that are published are [31]:

- *ISO 31000:2009* – Risk Management: provides generic guidelines on risk management
- *ISO Guide 73* – Risk Management Vocabulary
- *ISO 31010:2009* – Risk assessment techniques

In the *ISO 31000:2009* an overview of a general risk management decision-making process is given as shown in figure 7 [31].

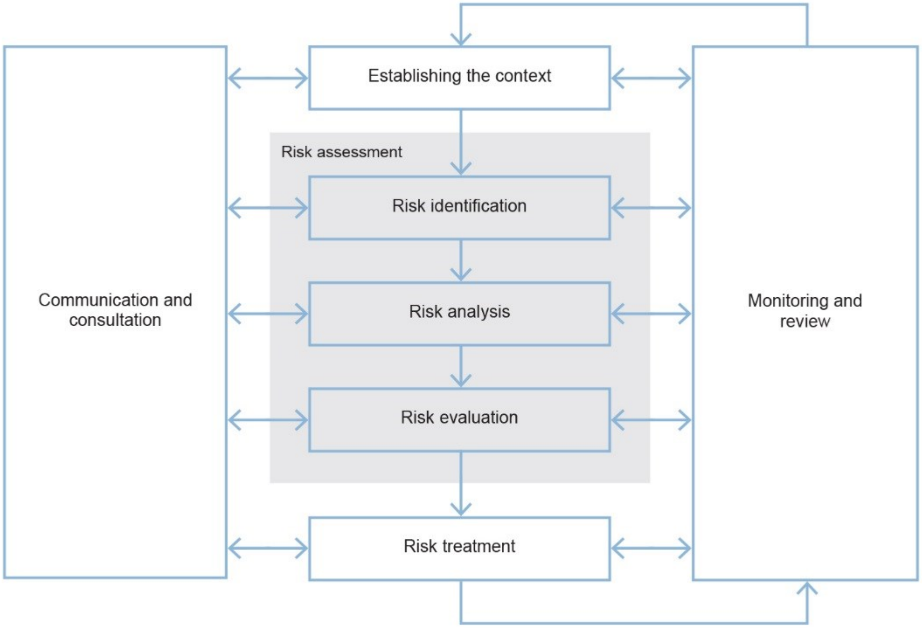


Figure 7: ISO 31000:2009 Risk Management decision-making general process [31].

In [31], risk management is described as an assessment that provides decision-makers and responsible parties with an improved understanding of risks that could affect achievement of objectives, and the adequacy and effectiveness of controls already in place. This provides a basis for decisions about the most appropriate approach to be used to treat the risks. The output of risk assessment is an input to the decision-making processes of the organisation. Risk assessment is the overall process of risk identification, risk analysis and risk evaluation (see Figure 7). The manner in which this process is applied is dependent not only on the context of the risk management process but also on the methods and techniques used to carry out the risk assessment.

In the Dutch extract of PAS-55, namely NTA 8120:2009, risk management for gas and electricity network asset management is described on the basis of the ISO 33000 guidelines. More specific industry (electricity network) related information regarding risk management can be found in [16], [30], [34], [28].

2.4 Maintenance Management

2.4.1 Definitions

A substantial amount of literature is available from various resources and industries in the field of maintenance management. A comprehensive overview can be found in [35] and [36]. There are a lot of terms used interchangeably and mixed in available literature and across the industry. Therefore, in this section, common terminology and definitions are set out which are relevant and applicable to this thesis.

In IEC 60300-3-14 of 2004 [37], application guide- maintenance and maintenance support, maintenance is defined as: "*the combination of all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in, or restore it to a state in which it can perform the required function*".

Maintenance management is defined as: "*all the activities of management that determine the maintenance objectives or priorities, strategies and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving methods including economical aspects*".

From these definitions, it can be found that in the current business environment, maintenance and maintenance management are considered as highly complex fields involving many disciplines within a company such as operations, information technology, economics, safety, risk, analytics, accounting, etc. [36].

Maintenance action/ maintenance task is defined [37], [38] as: "*basic maintenance intervention or sequence of elementary maintenance activities carried out by a technician for a given purpose*".

Maintenance policy is defined [37], [38] as: "*rule or set of rules describing the triggering mechanisms for the different maintenance actions*".

Maintenance concept is defined [37], [38] as: "*set of maintenance policies and actions of various types and the general decision structure in which these are planned and supported*".

Maintenance support is defined [37], [38] as: "*resources required to maintain an item under a given maintenance concept and guided by a maintenance policy*".

2.4.2 Maintenance action, policy and concept

In principle, two types of maintenance actions or tasks can be found. It can either be *corrective* or *preventive* [39], [40], [41], [42] and [43] . A brief description of each of these maintenance actions is given below:

- *Corrective Maintenance*: Corrective maintenance is essentially leaving all assets running until failure, and then replacing part of the assets that have failed. During the time corrective maintenance is being scheduled and performed (usually referred to "break-in", because they "break-in" to the schedule prepared), the asset is inactive. As a general rule a breakdown is often ten times more expensive compared to the situation that the failure can be identified and corrected (or prevented) in a planned and scheduled manner. Until now, the majority of components in distribution networks remain correctively maintained. However, with the adoption of AM, utilities are becoming aware of the changing requirements for maintenance [44]. Corrective actions are difficult to predict because failure behaviour is stochastic and outages in a network causing interruptions are usually unforeseen.
- *Preventive Maintenance*: The primary upgrade from corrective maintenance to preventive maintenance is by means of maintenance plans and schedules. Broadly speaking, preventive maintenance plans describe the methods of inspections and maintenance tasks which can efficiently improve the reliability of physical assets. A shift from corrective to preventive maintenance will, inevitably, require some initial investment; however, it will eventually result in moderation of the total volume of planned work and will allow for control of maintenance hours and workload. When preventive maintenance is applied on an asset item, it is called a preventive task. Subsequently, the timeline of the preventive task in an asset population is called the preventive schedule. This is why preventive scheduling will, eventually, result in arranging maintenance resources in advance, which, in turn, will considerably accelerate maintenance delivery and reduce operational costs (note, however, that an initial, increased, investment in the transition period is possible, but will decrease once in a controlled period) [44].

The European standard EN 13306:2010 shows this graphically:

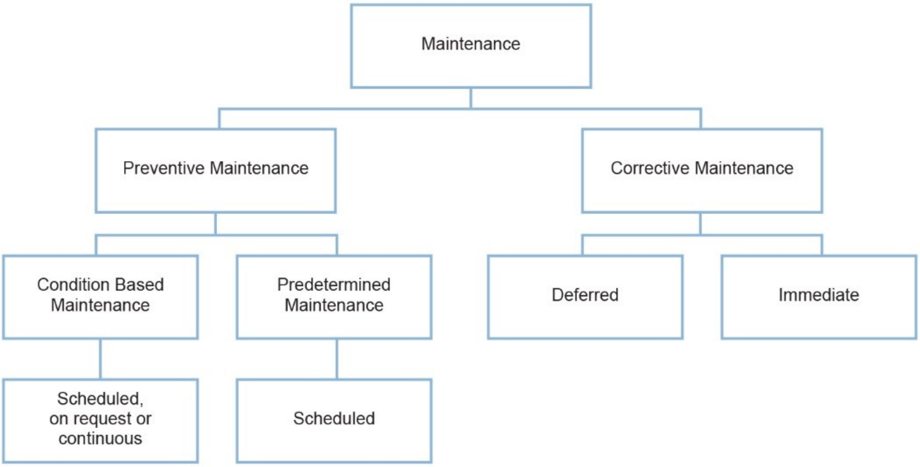


Figure 8: Maintenance methods breakdown according to EN 13306:2010.

Moreover, each of these maintenance actions or task categories can be triggered by a mechanism, which is usually denoted as a maintenance policy. Examples of maintenance policies are: *failure based maintenance (FBM), time based maintenance (TBM), condition based maintenance (CBM), and risk based maintenance (RBM).* A maintenance policy, on the basis of a trigger, determines *why* a maintenance task (corrective or preventive) is assigned [38]. A brief description of the earlier mentioned maintenance policies is given here:

- *Failure Based Maintenance (FBM)*: A maintenance action is carried out only after a breakdown. The trigger is therefore purely reactive and with FBM no planning is possible. In this context FBM requires a sound spare-parts policy.
- *Time Based Maintenance (TBM)*: A policy in which precautionary maintenance actions are carried out triggered by a predetermined scheduled interval. This is a periodic policy. The time intervals are decided according to asset type and fixed for the whole lifecycle (usually with reference to manufacturer instructions and updated with historic operational and failure behaviour). In literature, this policy is commonly denoted as a preventive policy [38]. The periodic policy can also be triggered by the use of the component, such as number of switching actions or operating hours. In general, the preventive

action coming from this policy may constitute of component replacements or may also be cleaning, lubricating or adjusting, etc.

- *Condition Based Maintenance (CBM)*: Basically, condition-based maintenance differs from time-based maintenance in the sense that a shift is made in scheduling methods, namely, from a periodic method to a "fully" predictive method. Therefore, CBM is a predictive policy. Being predictive refers to estimating the probability of failures on assets. With condition-based maintenance, an early indication of an impending failure (by applying condition monitoring, diagnostics or inspection methods) can be detected and the consequences of an unexpected failure can be avoided. CBM can use fairly low-level methods such as human senses for inspections (denoted as detective based maintenance) or deploy sophisticated monitoring and diagnostic tools (denoted as predictive based maintenance). More advanced is the use of various monitoring parameters and network condition to predict remaining lifetimes of component (denoted as prognostics or health based maintenance) [45].
- *Risk Based Maintenance*: The state of the art maintenance policy is the risk-based version, which is guided by the principles of risk management. A risk is composed of a stimulus (i.e. the root cause) and its consequences. The risk-based approach refers to the quantitative assessments of (1) the probability of stimulus (event), and (2) on business values (Key Performance Indicators, KPI) evaluated consequences. In the planning of maintenance, the stimuli are the failure modes for risk-based maintenance, which brings the term failure mode and effect analysis (FMEA). In scheduling risk-based maintenance, the potential failures on asset items are the stimuli. The probabilities of these stimuli are highly recommended to be derived from condition diagnosis (hence, the importance of the upcoming role of condition monitoring in a risk-based management regime). However, in practice, FMEA is mainly based on failure statistics if not expert judgements. The consequences of failure modes and potential failures are, if at all possible, measured with a number of KPI's, such as customer minute loss, financial loss, safety etc. These KPI's connect the operational-level maintenance tasks with high-level corporate business values. In practice, this link of consequences and failure modes through a certain KPI framework is not yet applied and most of the time not straightforwardly implementable for distribution companies. This will be discussed in chapter 3 of this thesis. Decisions on preventive maintenance plans or schedules are based on the risk register of failure modes or potential

failures. Risk register is a process to rank the expected value of risks, while the expected value is the multiplying product of probability and consequence.

In the literature, more variations of maintenance policies can be found such as *Design Out Maintenance* (a proactive policy). More literature on this can be found in [36], [38], [40].

In practice, a set of maintenance policies and actions of various types exists and requires a general decision-making structure for selecting amongst them. This is known in the literature [38] as maintenance concepts. The literature provides a wide range of maintenance concepts that have been developed through a combination of theoretical knowledge and practical experience. In [38], a summary of the most popular maintenance concepts and their characteristics are given and illustrated here.

Table 2: Summary of popular reported maintenance concepts and their characteristics [38], [12]

Maintenance concept	Description
Quick & Dirty (Q&D)	A decision chart with a number of questions on failure behaviour of assets is made taking into account the business context, maintenance capabilities and cost structure. By following the chart and answering the questions, a number of recommendations for an appropriate policy are found. Usually, companies develop tailor-made Q&D decision charts. No in-depth analyses are used in this method. It is seen as a quick method to set some priorities.
Life Cycle Cost (LCC)	This is a methodology to calculate and to follow up on the whole cost of a system from inception to disposal. All expenses for purchase, operation, and disposal of an investment, including project costs are taken into account. This method originates from the 60's and is gaining interest again. Perhaps due to the focus on lifecycles in PAS-55 and ISO 55000. The method follows a number of steps according to a detailed breakdown structure of the cost of the system under investigation over the lifetime. This method is based on a sound philosophy, however, it is both resource and data intensive. Another approach commonly used is the Total Cost of Ownership (TCO) method, which can be seen as an expansion of the LCC. In TCO calculations, expenses or indirect costs elements are added such as unproductive use of equipment, entire supply chain costs for the business.
Total Productive Maintenance (TPM)	TPM aims at getting the most efficient / effective use of equipment (Overall Equipment Effectiveness OEE). In this method, total participation (organisation-wide) is needed. TPM mainly promotes the implementation of preventive maintenance tasks based on small group tasks. This method has been successful in the manufacturing industry. It considered human and technical aspects, however, it is time consuming to implement.

Reliability Centered Maintenance (RCM)	RCM is a structured approach focused on the reliability and was initially developed for high technology and high risk component of systems (environments). It is a powerful approach based on a step by step procedure, however, it is resource intensive and time consuming. RCM will be discussed in more detail later on in this chapter as it forms an important focus area in this thesis.
RCM-based	In literature various methods / concepts inspired by RCM principles can be found. For instance, Gits developed an RCM-like concept where the focus is on technical and organisational aspects rather than on economic aspects. Coetzee states that RCM is a core methodology to ensure that an organisation can achieve world class results. However, a new RCM is proposed in this concept where quality improvement tasks, focus on most important failure modes in the company and the elaboration of task packaging are new features. Also, the incorporation of sound management principles are introduces in the implementation of RCM. Risk Based Maintenance RBM [32] is basically RCM, however, with a strong statistical background. In doing this the drawbacks from ad hoc FMEA in traditional RCM and too much of experience knowledge based on gut-feelings are reduced. In literature, RBM is sometimes seen as a maintenance policy or maintenance concept, as mentioned earlier in this section. Streamlined RCM is seen as a simplified or abbreviated version of the traditional demanding RCM method, usually promoted by industrial leaders. Nevertheless, streamlined RCM should be carefully applied in order not to lose the RCM benefits.
Customized	These concepts are usually in-house developed using the benefits of existing concepts. Examples are Value Driven Maintenance (VDM) in which the management of shareholder values are linked to traditional maintenance philosophies. Companies usually have their own, unique, prioritized method and would like to use the benefits of multiple existing maintenance concepts.
Lean Maintenance	Lean Maintenance comes from the idea of Lean Manufacturing. Lean means reassigning resources to more value-added work, eliminating all waste of work, effort and material. Lean Maintenance uses tools from the quality management field. Lean Maintenance is a proven concept in for example Toyota.

In figure 9, maintenance actions, policies and concept as related to each other are shown [38]. It is not always clear from literature whether for example a RCM related maintenance concept is a concept or a policy. There are literature sources available that state that RCM can be seen as a priority oriented policy for instance [12].

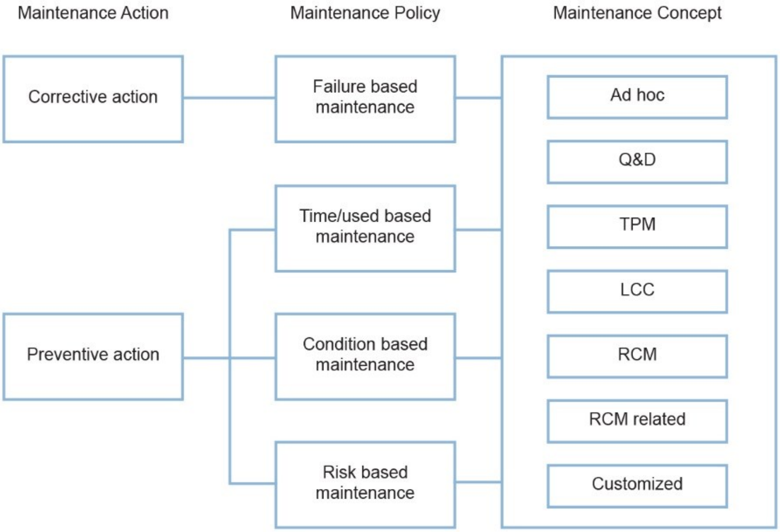


Figure 9: Interrelationship of the different definitions of maintenance action, policy and concept with each other. Two fundamental maintenance actions exist e.g. corrective and preventive. Maintenance policies are the mechanism that triggers a maintenance task, such as a calendar plan, a condition state or a certain risk level. Maintenance concepts are the previously conducted decision-making procedures or analyses that are necessary for selecting amongst a maintenance policy.

2.5 Developments & supporting pillars of maintenance management

2.5.1 State of the art maintenance management developments

In the overview and description of maintenance tasks, policies and concepts given in the previous section, it has been shown that there is a rich amount of literature on aspects of maintenance management available. In this context, we have found that maintenance management has changed drastically over the past decades. In the electricity network sector, similar developments have taken place as a result of the changing maintenance environment. Nowadays, there are different degrees of mixed maintenance tasks, policies and concept implemented in transmission and distribution electricity networks.

Although maintenance management is evolving from reactive (corrective) to more and more preventive and proactive maintenance regimes, a complete migration to a single one task, policy or concept is unlikely. In figure 10, the development in maintenance management as evolved over the past is shown [41], [32] and [46], [47]. This is, however, a general representation of maintenance management regimes and not necessarily reflects the situation for electricity networks. The developments have followed a slower pace in this sector. Mainly, as result of the long lifetimes of power system assets in relationship to the redundantly design networks, stations. Maintenance could in this sense be postponed for longer periods compared to other sectors. Due to the fact that these assets are gradually coming to the end of their technical lifetimes, maintenance management and replacement strategies are crucial aspects in management the populations of assets. Nevertheless, these trends are happening as well for transmission (started earlier) networks and more recently at a faster pace in distribution networks. The evolution in maintenance management, according to the majority of literature review, can be summarized and depicted as shown in figure 10.

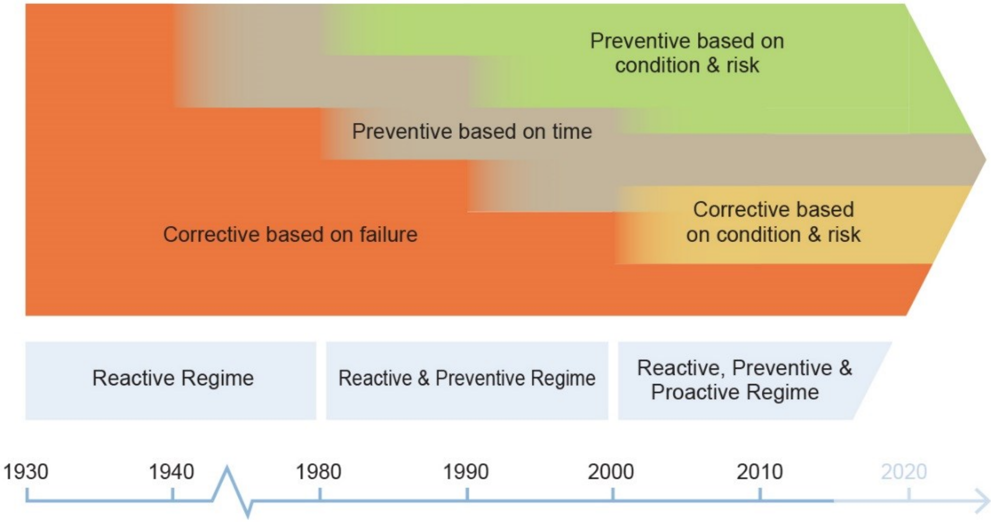


Figure 10: Maintenance evolution in policy implementation.

2.5.2 Supporting pillars for maintenance management

Obviously, maintenance management has evolved, based not on solely technical grounds, but rather on techno-socio-economic considerations. Therefore, it becomes clear that maintenance cannot be managed as a purely technical and technological function only [38]. Maintenance management has to take into account and deal with aspects such as financial insights, the management of maintenance budgets, the management of resources and skills, adoptions maintenance processes for effective measurement of the contribution of maintenance to the overall business, data and data quality, computerized maintenance management systems (CMMS), etc. [36]. Thus, maintenance management has to take into account a myriad of considerations. Having said this, literature, however, reports [36] that many utility network companies have difficulties in practice with enabling an integrated view for maintenance management. According to [36] this is mainly due the lack of essential supporting pillars for maintenance management from an organisation-wide (business) point of view. For network utilities, the essential supporting pillars to enable a foundation for sound maintenance management are [36], [48]:

- *Process management:* maintenance management based on process management is according to a reasonable strategy. It is required to have methodologies which allow clear definition of the processes, their execution and data requirements. The aim of having maintenance management processes is to improve the efficiency through the management of business processes that are modelled, automatized, integrated, controlled and continuously optimized.
- *Quality management:* In network utilities the management of quality is concerned with the quality of the service provided through the network. In general, it can be said that the performance of the quality of the service that is delivered is determined by the design, operational status or condition, proper operation and proper maintenance of the network. The level of performance to ensure proper service is achieved by having processes of continuous improvement, incorporation of diagnostic and monitoring tools, analytical methodologies and new technologies.
- *ICT management:* Because maintenance management is considering more and more information from the business environment, Information and Communication Technology (ICT) is beneficial for the optimization of maintenance management due to the proper exchange of updated information and coordination of automated procedures. The proper exchange of information and the coordination is important for maintenance management, however, interoperability among different systems (and vendors) is required to ensure this.
- *Knowledge management:* Knowledge management is the key for proper maintenance. Maintenance requires up-to-date data, information and knowledge about assets. Basically, this is needed for the planning, scheduling and execution of maintenance and the continual improvement of this process. Most of the time in electricity networks, there is a large amount of dispersed knowledge available amongst technical workers, specialists and managers.

> However, due to the dispersions or lack of methodologies that extract this knowledge, it remains unprofitable and inaccessible.

More general details of these supporting pillars can be found in [36]. In chapter 3, the implications of supporting pillars with similar characteristics in practice on the improvement of a maintenance organisation will be discussed in more details together with a case study of its applications.

2.6 Conclusions & outlook

2.6.1 Conclusions

In this chapter, a brief overview was given and an investigation of relevant literature on the underlying arguments for asset management, risk management and maintenance management was performed. Asset management is widely argued in the literature as an *umbrella* subject which can encompass many aspects for the management of asset intensives industries. In this thesis, asset management is described in the context of infrastructures or physical asset management. The history and development of asset management and the coming into being of PAS-55 specification were provided. Since 2014, asset management has been adopted in the ISO 55000 series as an international standard. This illustrates the rather recent (at the moment of writing) history of asset management and therefore an interesting field and subject for many asset intensive companies worldwide.

Moreover, the principles of risk management within an asset management oriented environment were discussed. In general, risk can be seen as a dimension which makes it possible to have a measureable, comparable and management entity, which, at the same time, is understandable and communicable to management layers for making decisions.

Subsequently, maintenance management, as the main focus area of this thesis, has been described. In line with available standards, a number of important definitions for maintenance management terminology have been given. More importantly, the context of maintenance tasks, policies and concepts were provided in detail in this chapter. Additionally, the relationships of these terms with each other were given. The chapter comes to a close with a brief review of developments in the field of maintenance management. Because maintenance management is evolving into an increasingly complex context within the business environment of electricity network companies, as suggested in literature, it is essential to build maintenance improvements on at least the mentioned essential supporting pillars for maintenance management.

2.6.2 Outlook

In the next chapter, an organisation-wide maintenance improvement plan will be addressed with the focus on the establishment of an organisation for maintenance improvement within an electricity distribution network company on the basis of the supporting pillars for maintenance management as discussed in this chapter. Furthermore, chapter 3 will also discuss the developments, on a maturity model for maintenance management and a framework for maintenance *key performance indicators (KPI's)*.

3 Organisation-Wide Maintenance Improvement Framework

3.1 Introduction

3.1.1 Background

Presently, asset intensive organisations increasingly recognize the importance of maintenance management as an important contributor to business profitability. Although rather scarcely available, data records [48] indicate that maintenance budgets range from 2% to 90% of the total operating budgets depending on the nature of the asset intensive industry. The average is around 20% for infrastructure oriented industries. Moreover, maintenance is increasingly seen as a potential source for cost savings (70%). At the same time, amongst other aspects, the availability and adoption of PAS-55 and ISO 55000 require, if not mandatory, to continuously improve overall management of assets. In the electricity distribution network sector, maintenance management is practiced on a rather traditional level. This traditional level is typically characterised by the following:

- Maintenance is often a department or function located in the final process of the main supply chain.
- Reactive management and decision-making with scarce knowledge of the adequate maintenance action and solution. Usually, based on manufacturers' suggestions and from operational field experiences.
- Self-organisations per service regions, with a meagre degree of central authority and rules which makes standardization and integration difficult.
- Absence of a unique and updated asset information and maintenance management system, consequently leading to isolated information transfer and islands of specialisations or departments.

The above mentioned characteristics tend to become more complex and difficult to manage when the population of assets are geographically dispersed and consist of large numbers of different types of assets.

In this chapter, we discuss, from a scientific point of view, important organisational building blocks for maintenance management improvement which are relevant for electricity distribution companies. This driver for improvement is the professionalization of maintenance management in order to provide:

- Improved control of the maintenance organisation with the whole of the management of organisations

- Transparency for stakeholders on the decisions-making processes
- Support for further developments of the PAS-55, NTA 8120 (and ISO 55000) to a higher maturity level

In the ideal situation, electricity network companies will be able to continuously improve and professionalize the maintenance management function with reliability and availability of the assets as the central themes. In the most advanced phase, the utility is able to set a policy for maintenance, which is based on a risk driven maintenance concept as result of a risk management approach.

3.1.2 Chapter outline

In section 3.2.1, the objectives of electricity distribution organisations for maintenance improvement on strategic level are described. A concept of a model for cyclic continuous maintenance improvement is provided in section 3.2.2. In section 3.2.3 the organisational elements that play a key role are described. In order to set the reference point at start and to be able to accurately determine the improvements, a *maintenance management maturity model* (M^4) is developed and described with results in section 3.3. Usually, decisions are taken from top to the bottom of an organisation, while, conversely, the performance reporting occurs from bottom to top. For this purpose, in section 3.4, a methodology for maintenance key performance indicators is elaborated on. In section 3.5, an outlook to the chapter 4 is given.

3.2 Objectives for maintenance improvements

3.2.1 Maintenance management decision levels

In line with the decision-making levels described in chapter 2 for asset management (section 2.2.1) and according to the well-known framework [49], we structured maintenance management decisions as shown in figure 11.

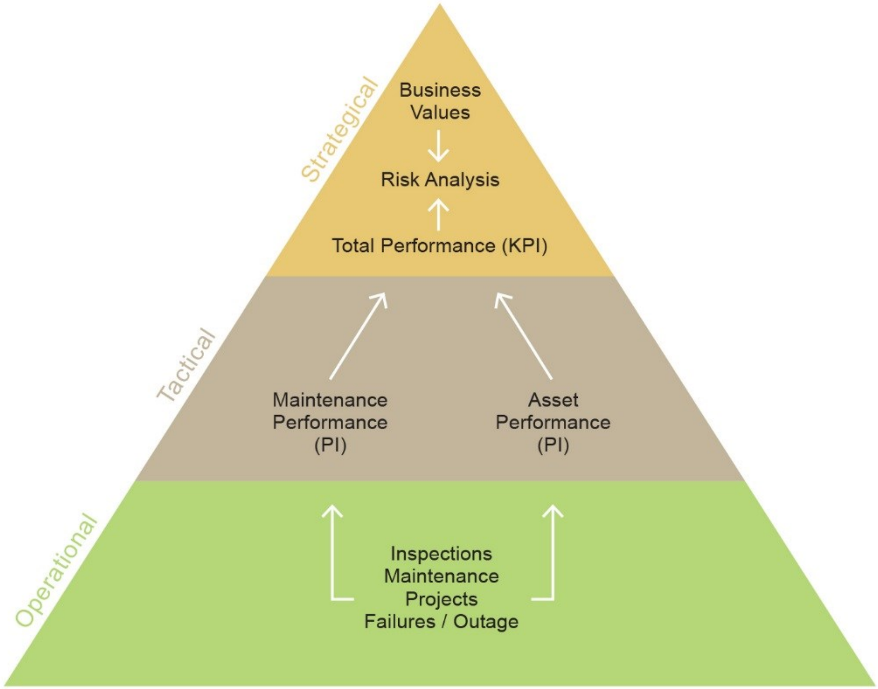


Figure 11: Maintenance management decision pyramid.

The maintenance decision pyramid shown in figure 11 shows the different decision-making levels. Firstly, at the top level, strategic decisions are made concerning large organisational risks, over a long period of time, with a wide scope, looking at internal and external aspects and in an unstructured ad hoc way. Secondly, at the tactical level, medium term, moderate risk and semi-structured decision are made. Finally, at the operational level, the plans that have been made at tactical level should be translated into workable (daily) schedules (short term decisions) and into executable maintenance tasks. In an ideal situation, along the path from strategic to operational, decisions become more structured, the information and tools to base these decisions on are improved and implemented into the organisation.

In current maintenance, we observed that a commonly noticed deviation between strategic and tactical level is the unsatisfactorily applied structured methods and tools. In many cases, not all organisation-related factors are thoroughly considered in the strategy, which results in an unclear situation when translating these factors to maintenance concepts and policies. This, evidently, leads to sub-optimal situations on all levels. On an operational level, for example, usually a gap exists with prioritizing maintenance schedules and tasks.

3.2.2 Underlying objectives for steering maintenance improvement

A maintenance improvement plan is best driven by organisational objectives and contributes to the corporate vision (strategic level). For many electricity distribution network companies, the focus of maintenance is solely on the technical aspects. However, as discussed in chapter 2, maintenance management has evolved throughout the years. Therefore, the underlying objectives for steering maintenance improvement require including not only technical aspects, but also interacting with other non-technical organisational elements. The fundamental objectives for an improvement plan are [20]:

- To improve maintenance and inspection activities.
- To have control of the said activities.
- To increase the transparency towards the stakeholders regarding certain investment decisions and capital and operational expenses (CAPEX and OPEX).
- To further develop and professionalise PAS55 and the Dutch supplement NTA 8120 to the next level (keeping in mind the ISO5500/1/2 standard which is in the making).

Typical maintenance problems experienced in the electric power distribution industry are given below [38].

- Failures are often not analysed to the extent that similar subsequent failures can be prevented.
- Often, in-depth failures investigation results are not consistently taken into account during maintenance scheduling.
- Usually, there is no structure and clear relevance between maintenance actions and organisation objectives (lacking a link with broader AM objectives). On one hand, it is, most of the time, unclear whether preventive maintenance is performed unnecessarily or not. Moreover, it is important to assess what exactly will be improved (technical goals) with a maintenance action and what the added value will be (economic consideration). On the other hand, if the effects of maintenance activities are not measurable to the organisation, it is hard to motivate current strategies or future improvements.
- Traditionally, manufacturers maintenance recommendations are accepted, without considering the operational conditions

3.2.3 Cyclic continuous improvement approach

Following on the maintenance improvement objectives and in order to meet these, the approach should have a cyclic characteristic. As a consequence, it is expected that this cyclic characteristic will guarantee that the maintenance and inspection plan will be improved continuously. In figure 12, the vision of the maintenance and inspection programme based on the principle of the *Plan-Do-Check-Act* cycle is shown.

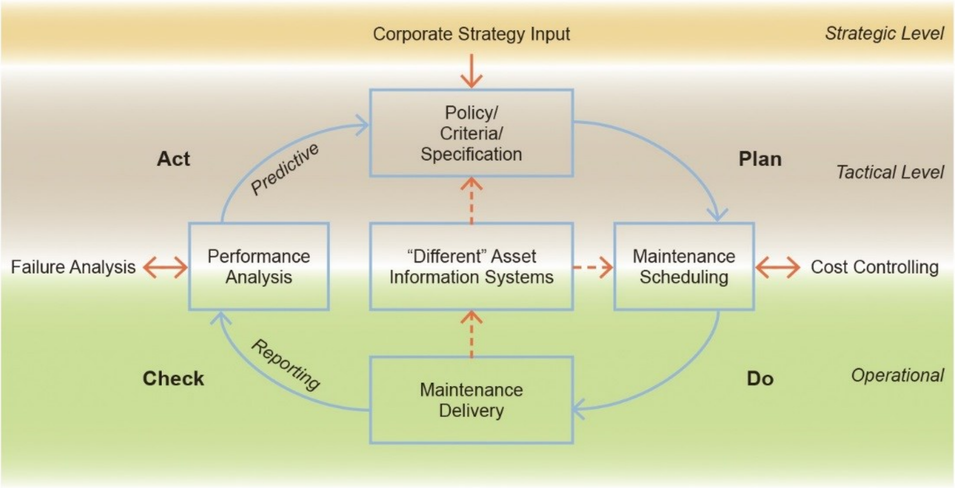


Figure 12: Elaborated vision for maintenance and inspection based on the cyclic characteristic: Plan-Do-Check-Act (PDCA-cycle).

Moreover, when each phase of the cycle has been embedded in the processes of an organisation, then the following steps will be carried out:

- ***Plan:*** A maintenance policy including product criteria and product specification will be made for short-term and long-term scheduling. After maintenance scheduling, the corresponding maintenance tasks can be prepared to be carried out.
- ***Do:*** Developed maintenance schedules are commissioned to the service provider, which will deliver the required maintenance tasks. Maintenance delivery includes the reporting of the performed maintenance actions (e.g. cost, condition, failure code).
- ***Check:*** Different levels of asset performance analysis are carried out after reporting of maintenance delivery by the service provider. The performance analysis consists of two types of analysis. Firstly, an analysis is carried out to assess the quality of the maintenance delivery (completeness, abnormalities, condition,

and other necessary findings). Secondly, an analysis of asset performance is carried out, which has a predictive characteristic and forms the basis for the Act phase (next step). The predictive analysis is beneficial for e.g. reliability trend analysis and failure forecasting. Afterwards, a separate historic failure analysis is added to the cycle giving information about failure modes, possible mitigating actions for these failure modes, the impact on larger populations, and on key performance indicators (KPI's).

- ***Act:*** In the last step of the PDCA-cycle, the asset performance analysis results are used to re-adjust maintenance policies, generate reports for the asset owner or stakeholders and regulators.

The above described cyclic maintenance and inspection improvement plan has to be broader than solely concerning about technical aspects, and extends from a strategic/tactical to an operational level (process, information systems, portfolio, performance, policy and criteria). Therefore, the maintenance management improvements must not only focusses on the technical pillar of maintenance, but also incorporates other key organisational pillars.

3.2.4 Organisational pillars steering maintenance improvement

The pillars of the organisation which are expected to have an impact on the continuous improvement on maintenance activities at a company, and which are included in this programme are:

- Organisation & Process
- Policy & Criteria
- Information & Systems
- Data quality
- Portfolio & Performance
- Transition
- Vision & Pilot (for risk driven maintenance)

In figure 13, an illustration of the maintenance and inspection matrix is given.

Taskforce	Management	Maintenance & Inspection Matrix						
Names	Names	Organisation & Processes	Policy & Criteria	Information & Systems	Data quality	Portfolio & Performance	Transition	Vision & Pilot
Asset Groups	Asset type	🔴○○○	○🟡○○	○🟡○○	🔴○○○	○○🟢○		
	Asset type	○○🟢○	🔴○○○	○🟡○○	○○○🟣	○🟡○○		

For Future Outlook

Figure 13: Overview of maintenance and inspection matrix which is used as a guidance to ensure that the improvement programme is consistently implemented across the company.

Each organisational pillar (column), which is necessary for improving the maintenance function, is linked to an asset group and its related individual asset types. From a practical case from a Dutch DNO, Stedin, typically two asset groups are taken up in such a matrix, namely electricity and gas network assets. The asset types which are included are:

- Gas Infrastructure:
  - Stations
  - Pipes
  - Connections

- Electricity Infrastructure:
  - Power Transformers
  - High Voltage Substations
  - Power Cables and Lines
  - Medium Voltage/ Low Voltage Substations
  - Medium Voltage/ Low Voltage Connections

- General Infrastructure (globally used):
  - Secondary Systems (control, protection, communication, signalling, etc.)
  - Tertiary Systems (buildings, properties, fencing, infra-related assets, etc.).

Based on this (pillar) matrix methodology for organising maintenance management, possible “gaps” between current and future maintenance management can be assessed.
As mentioned earlier, seven organisational pillars are considered (in this case), which are required for optimizing the effectiveness of maintenance related activities. Relevant

information of each pillar is gathered in order to assess the degree to which the company achieves maintenance improvement. An additional pillar named “Vision & Pilot for risk driven maintenance” shows that a risk driven approach is adopted with the aim to optimise the maintenance and inspection activities. By linking each of the above mentioned pillars (elements) to a specific asset group (electricity and gas assets) gives the degree to which the company can achieve or reaches maintenance optimisation (excellence). For each pillar, a brief description is given in table 3.

Table 3: A description of each multidisciplinary organisation pillar that is required for maintenance management improvements

Pillar	Brief description
Transition	The transition, or rather optimisation of effectiveness of maintenance towards a RCM methodology, will have an impact on many aspects of the organisation (asset owner, service provider, etc.). Gathering accurate, relevant information and communicating this to different layers of the organisation are of fundamental importance. The pillar Transition is responsible for this.
Vision & Pilot for RCM	This pillar is responsible for setting up a research and development pilot project to study maintenance methodologies based on RCM philosophy. A series of steps or levels that can be followed to implement RCM across the company where it is feasible and favourable are analysed and provided. Based on the work of this pillar, more insight on the issues that must be addressed to improve RCM implementation and achieve the maturity levels is gained.
Organisation & Process	This pillar has an important responsible, which involves defining and guaranteeing processes to ensure continuous improvement according to earlier mentioned PDCA-cycle. Moreover, the processes should be mapped with the proper designated departments and people. Especially, the inter-department part of the processes should be clearly established. Improvements, such as RCM, require organisations to have thorough insight into all the available resources, such as skills, knowledge, and discipline to perform the basic elements of the maintenance system.
Policy & Criteria	At the boundary of strategic and tactical level, the responsibility of this pillar is linked to maintenance planning. At any time, all activities of maintenance and inspection tasks should be described, recorded and implemented correctly. Added to this, as the “Act” phase of the PDCA-cycle, all new relevant information should be used to stimulate new policy, criteria and specifications.
Information & Systems	At different stages of maintenance planning, information and corresponding information systems fulfil a key role. As a consequence, the responsibility of this pillar is to describe asset information requirements of each asset type. Furthermore, this pillar will make clear whether required information is actually available and recorded in the dedicated information management systems.
Data Quality	Data quality is the degree to which data is suitable for the purpose for which it is used. This pillar should verify that the data is suitable to be used as a source of information for operational, tactical and strategic maintenance processes. The set of static and

	dynamic asset related data must be available, to the extent that valid decisions can be made within the maintenance and inspection process.
Portfolio & Performance	In an AM framework, success is measured by business performance, rather than solely on engineering and operations measures. Within the context of the improvement programme, maintenance and inspection decisions, should not only focus on financial profit, but need to consider multiple objectives. This pillar is responsible for rolling-out clear financial business rules, suitable for the operational environment, leading to a uniform way of categorizing maintenance activities. Hence, making metrics usable as maintenance performance indicators.

With this expanded view of the asset groups and organisation pillars, it is necessary to have the ability to understand the level of integration of each pillar in the complete maintenance and inspection programme. Often, within the same organisation, different levels of maturity for different asset classes or pillars are possible. At the same time, not every asset group of pillar needs to be at the most fulfilled level. In practice, we observed, that the challenge is to determine the required level of fulfilment for each pillar. For this purpose, a maturity model has been developed which provides a typical maintenance organisation with a structure to assess the current level of integration (maturity level) of each pillar and a forward-looking vision. In addition, the pillars are expected to work in unison with each other to be effective. The maturity model helps in establishing the priorities for improvements (e.g. of a certain corporate pillar) and to guide the implementation of the improvements.

3.2.5 Maintenance management maturity model (M^4)

Maturity models have, recently, been gaining more attention in the field of asset management. Initially, these maturity models have been developed following the capability maturity model (CMM), which was developed by the Carnegie Mellon University [50]. In its original design, these maturity models were aimed to assess software development projects. Gradually, its application has extended to include a wider scope such as systems engineering, collaborative processes, knowledge management and human resources. According to [51], [52], a maturity model can be viewed as a set of structured levels that describe how well different processes of an organisation are able to produce the required outcomes in a reliable and sustainable way. An overview of different maturity models which have the potential to be applied for infrastructures (such as electricity networks) is provided in [51].

Although a matrix approach as explained in the previous section seems straightforward, we observe that it is still difficult for asset intensive organisations to develop, use and control these kinds of approaches in practice. To assist the professionalization of the maintenance management process, maturity models can be used [52]. Historically, electricity network companies would consider maintenance as a merely technical function. Nowadays, maintenance is progressively seen from a holistic business point of view. Many difficulties arise because of the mix-up between different specialities, systems and cultures. Consequently, it is necessary to have the ability to clarify whether the maintenance management process is adequate. In practice, this issue often remains unresolved, yet it can actually be assessed by means of a maturity model [52], [53] . On one hand, the maturity model serves as an indicator of the current circumstances for each organisation's supporting pillar (figure 13). On the other hand, it will form the basis to compare the maturity for different asset groups with each other and it is fundamental to develop a mix of maintenance strategies depending on risks associated with the asset groups (shown in more detail in appendix B).

3.2.5.1 Development of maintenance maturity model

For the development of a maturity model, the following aspects should be taken into account [52]:

- The process and domain areas included in the model
- The nature of the assets within the organisation
- The levels of maturity measurement
- A qualitative versus quantitative approach
- The measurement method to collect data

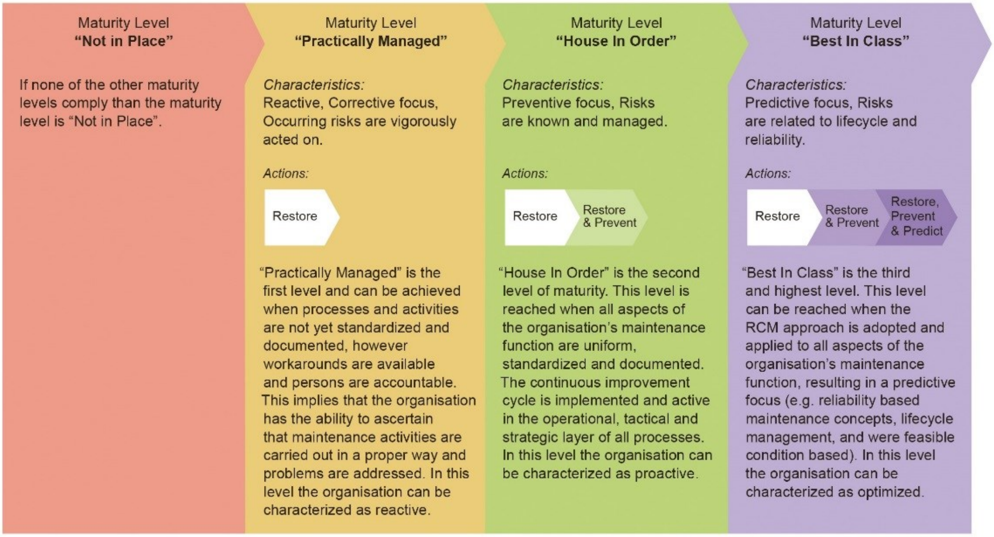
In the development of the maintenance maturity model, the domains which are taken into account are the organisational pillars which were described in the previous section. The nature of the assets within the organisation is also described in the previous section which to a great extent are electricity and gas assets. The development process that has been followed when designing the M^4 model is given in more detail in appendix B. The process of developing a maturity model for maintenance management purposes was initiated by means of an extensive strategic stakeholders brainstorming session. In this session strategic asset management stakeholders from various departments that influence maintenance management were involved. This key group identified and agreed upon a number of organisation-wide dimensions that influence the performance and further professionalization of maintenance management. Critical dimensions were then grouped into 5 domains which turned out to be the essential building blocks to develop a maturity model. Afterwards, in the development phase of the model, the characteristics and levels of the model were agreed upon. These process phases required strong commitment from all the involved parties and were achieved by extensive discussions.

The maintenance management maturity model design process consists of the following components:

- Dimension selection
- Number of levels and description of characteristics of each levels
- Description of elements of each dimension
- Description of elements and activities of each level
- Maturity level measurement process and evaluation
- Asset categories to include in the model

To be able to decide which necessary measures, activities, projects or changes should be carried out in order to achieve a desired level of maturity, it is necessary to define unambiguous levels. The levels of maturity assessment which are adopted can be clustered and explained in the following way [54]:

- *"Practically Managed"* is the first level and can be achieved when processes and activities are not yet standardized and documented, however workarounds are available and persons are accountable. This implies that the organisation has the ability to ascertain that maintenance activities are carried out in a proper way and problems are addressed. In this level, the organisation can be characterized as *reactive*.
- *"House In Order"* is the second level of maturity. This level is reached when all aspects of the organisation's maintenance function are uniform, standardized and documented. The continuous improvement cycle is implemented and active in the operational, tactical and strategic layer of all processes (see figure 11). In this level, the organisation can be characterized as *proactive*.
- *"Best In Class"* is the third and highest level. This level can be reached when the RCM approach is adopted and applied to all aspects of the organisation's maintenance function, resulting in a predictive focus (e.g. reliability based maintenance concepts, lifecycle management, and were feasible condition based). In this level, the organisation can be characterized as *optimized*.



If none of the other maturity levels comply than the maturity level is "Not in Place".

Characteristics: Reactive, Corrective focus, Occurring risks are vigorously acted on.

"Practically Managed" is the first level and can be achieved when processes and activities are not yet standardized and documented, however workarounds are available and persons are accountable. This implies that the organisation has the ability to ascertain that maintenance activities are carried out in a proper way and problems are addressed. In this level the organisation can be characterized as reactive.

Characteristics: Preventive focus, Risks are known and managed.

"House In Order" is the second level of maturity. This level is reached when all aspects of the organisation's maintenance function are uniform, standardized and documented. The continuous improvement cycle is implemented and active in the operational, tactical and strategic layer of all processes. In this level the organisation can be characterized as proactive.

Characteristics: Predictive focus, Risks are related to lifecycle and reliability.

"Best In Class" is the third and highest level. This level can be reached when the RCM approach is adopted and applied to all aspects of the organisation's maintenance function, resulting in a predictive focus (e.g. reliability based maintenance concepts, lifecycle management, and were feasible condition based). In this level the organisation can be characterized as optimized.

Figure 14: Brief explanation of the three maturity levels to assess the maintenance management organisation together with the characteristics of each level and which type of actions the utility can be related to.

In this model development the choice for data collection is realized by means of interviews and questionnaires which provide information. The advantage of this approach is that it provided the opportunity to explain the results and the elements when needed. Moreover, it can be performed in relative short periods of time.

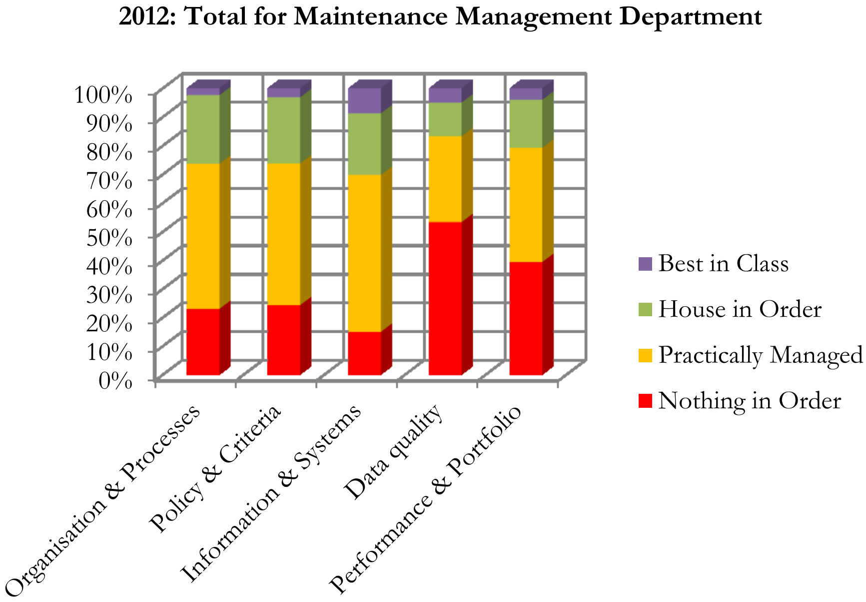
The level of maturity is determined by filling out a questionnaire, consisting of 50 questions about all aspects of each supporting pillar. The goal of every pillar (domain) is translated into a questionnaire and thus provides three possible scenarios to choose from. The scenario which reflects the most likely current situation will be chosen. Each scenario corresponds to one of the three levels of maturity. The same questionnaire can be used to determine the desired level of maturity by answering each question with the desired scenario. In figure 14, the maintenance maturity levels are summarized and explained.

3.2.5.2 Results of maintenance maturity model

The method that is adopted for carrying out the assessment of the maturity levels is based on internal interviews of the personnel that are predominantly responsible for a given asset group regarding all strategic and tactical maintenance management planning and activities. Following from the organisation-wide approach [55] these roles are known as *asset captains*. Each responsible *asset captain* is given a set of predetermined statements that are related to questions regarding each organisational domain.

The questions and statements comprise a structured collection of characteristics that are related to a specific maturity level i.e. *"Not much in place", "Practically Managed", "House in Order", "Best in Class".* Thus it becomes possible to achieve a uniform and objective maturity level and to evaluate the extent to which a specific asset group has been developed and improved for a respective organisational domain. In appendix B a summary of the number of questions per domain and the overall characteristics of these questions are provided. The assessment procedure starts with measuring the maturity level. This measurement is based on a series of predetermined questions and answers in the form of propositions, and is performed by each person which is responsible for a specific asset group together with the people responsible for the different dimensions. The questions consist of a structured set of topics that describe the maturity characteristics of an organisational dimension. By doing this in a combined setting with multiple responsible people it is strived to achieve and ensure uniformity and objectivity as substantially as possible throughout the assessments. In appendix B a flowchart of the assessment procedure is given.

The organisation-wide maintenance management improvement was initiated in 2011 and the M^4 was developed along with this as has been published in [55]. In 2012, a first maturity measurement was performed, which also forms the reference measurement against which maintenance professionalization activities and improvements can be benchmarked on their effectiveness. Additionally, this reference measurement was used to document and make insightful what the maintenance management's maturity levels were for each domain at that moment and to set a goal towards which level the organisation would mature. The goal that was set in 2012 was to completely grow towards *"House in Order"* for all asset groups and relevant organisational domains. In order to achieve this goal, a number of specific projects, actions, skills and processes were planned and given priority. In the end of the year 2014, the maturity levels were assessed again in order to evaluate the levels at that given time and more specifically to evaluate whether the goal set in 2012 was achieved or not. The results are shown in figure 15 for the total electricity and gas network and in figure 16 for the electricity network only [54] .



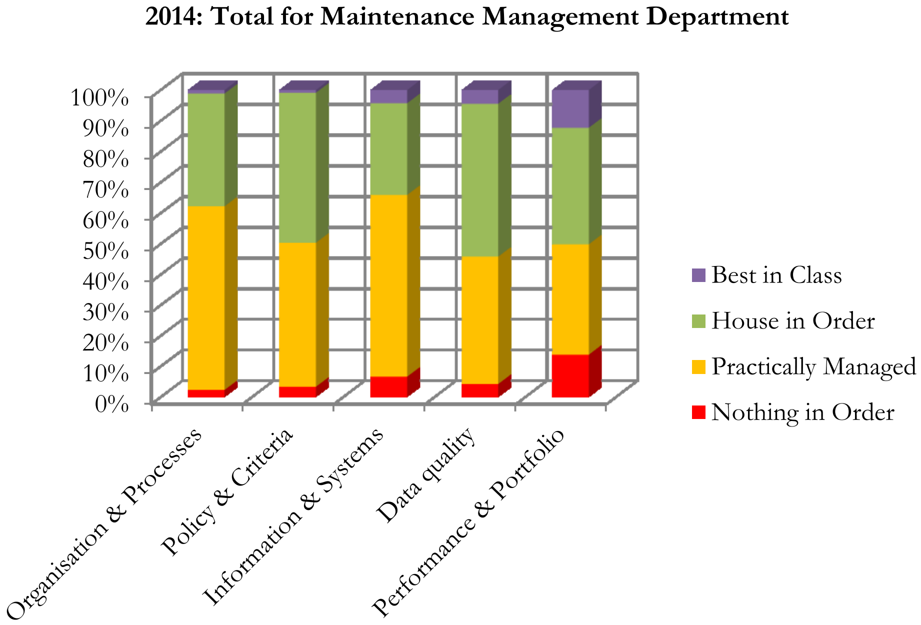
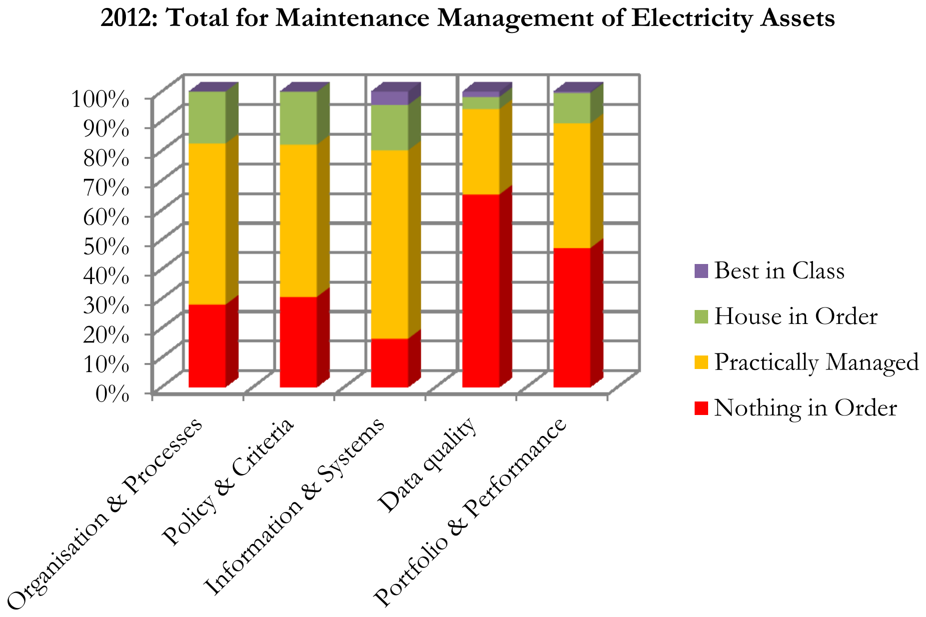


Figure 15: Summary of the total results of the maturity levels for 2012 and 2014.



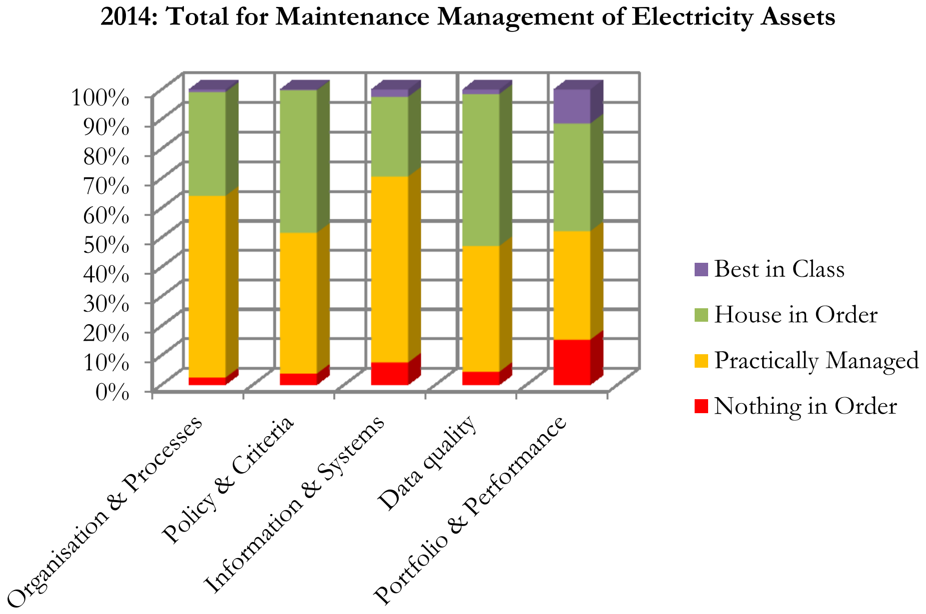


Figure 16: Summary of the total results of the maturity levels for 2012 and 2014 for electricity assets.

The changes from 2012 and 2014 have been validated by evaluating the changes by means of an internal survey studies. The same group of people are used in both measurements. Due to fact the assessment is based on closed questions that are linked to each organisational pillar the person at hand does not have the possibility to provide opinion biasing into it. Additionally the answers are fed back in a combined setting where expert interact with each other in order to reconfirm the validity.

The challenge with the application of the maintenance maturity model lies in the translation of the goals of a maintenance supporting pillar (domain) into scenarios that correspond to the three levels of maturity. In this development process of maturity levels extensive discussions and debates with experts and asset managers had to take place in order to reach unanimous definitions of the possible scenarios. These discussions were both, necessary, and inevitable, because the maturity model has to be interpreted with similar meaning by all involved users. This process has been reviewed by management teams before that the model was approved. An additional challenge experienced during the creation is the degree to which the model represents the needs and interests of all related departments in the maintenance organisation. This is demanding because of the multi-dimensional corporate objectives (pillars) [20], [54]. The maturity level assessment that was performed in 2014 and the results from this are also used to set new goals. As this assessment was the first after the reference assessment (2012), it was also found that some initial goals were probably on the ambitious side. This experience and knowledge is used to adopt a set of new goals. The use of the maturity model has shown to provide advantages in the process of setting goals, because it is able to provide a common language and it assists in sparking discussions on where the organisation stands now. Moreover, it proved means to grasp better how certain developments within the organisation that are not directly related to maintenance management might influence the achievement of goals that are set and thus the maturity levels. On one hand, the maturity model serves as an indicator of the departing point for the further development of each organisation's domain for maintenance. On the other hand, it will form the basis to compare the maturity for different asset groups with each other throughout the development path and provides the scope within which specific actions plans have contributed.

With the goal to understand the underlying aspects that had contributed positively or slowed down certain maturity growth, an internal questionnaire amongst the *asset captains* was organised. Amongst others, one part of this questionnaire focussed on what the respective *asset captains* consider as important for growing towards *"House in Order"*, while another part focussed on what it would, according to them, take to achieve the most advanced maturity level *"Best in Class"*. In appendix B overview of the main findings that contributed in the growth towards *"House in Order"* and what will contribute in the further growth towards *"Best in Class"* is given. Added to this a benchmark of this M^4 model with other available models in literature is given in appendix B.

3.2.6 Maintenance Key Performance Indicators (KPI's)

With the aid of the maintenance maturity model, a roadmap steering towards maintenance management improvement, and ultimately excellence, can be set. However, behind any improvement lies an important aspect, namely the enabling of the measurement of a certain contribution. It has been reported [36] that many *"agree on the fact that maintenance performance should be measured not only in relation to the degree of fulfilment of a certain technical standard"*, but also considering other company departments, as well as the impact on relationship with customers and other external parties. As a result, it is necessary to be able to measure maintenance management contributions. Measuring and reporting maintenance contribution can thus be defined as the management activity of regularly evaluating past performance with the aid of performance indicators (PI's). In this section, different *Key Performance Indicators* (KPI's) that can be utilized to measure the maintenance management contribution in the electricity network company are developed and presented.

According to [56] a maintenance performance measurement system generating useful maintenance indicators is required for:

- Following up and evaluating short and long term effectiveness and efficiency of maintenance management and maintenance activities
- Assessing that the maintenance process is supporting the overall corporate business objectives

A general consistent set of business indicators are reported in [57], grouping them in four main categories. For maintenance management, literature related to indicators suggests a multi-criteria hierarchical maintenance performance [56], [36].

In these contributions, various indicators are considered amongst which are:

- Financial
- Effectiveness & efficiency
- Tactical & functional
- Maintenance tasks
- Asset condition & reliability
- Costs

- Planning
- Health & safety
- Customer satisfaction
- Environment

The importance and interest in maintenance performance indicators are increasing. In 2006 the European Federation of National Maintenance Societies (ENFMS) and the Society of Maintenance and Reliability Professionals (SRMP) started with a collaborative effort to harmonize maintenance KPI's. As a reference point, the available BS EN 15341:2007 is considered. In the BS EN 15341:2007, three groups of indicators are being considered which are economic, technical and organisational. The characteristics of maintenance KPI's as introduced in BS EN 15341:2007 are:

- Simple
- Defined in a clear and unambiguous way
- Measurable on a consistent basis
- Linked on one are more factors
- Suitable in management maintenance process.

Although a rather large number of contributions can be found in literature about maintenance key performance indications, it still not yet well documented or not yet available for electricity distribution networks. Due to this, we have developed a set of maintenance key performance indicators are developed as part of the overall organisation-wide maintenance improvement plan.

3.2.6.1 Development of maintenance key performance indicators

When developing indicators, two aspects are distinguished:

- Indicators structure
- Indicator reporting structure

On one hand, according to [56], the *indicator structure* is developed from top to down, where the top indicator level must support the organisations overall objectives. The bottom indicators must support sub-processes, asset groups and single asset characteristics. In summary, the result of this approach is an indicator system where all indicators at different levels support organisational objectives. On the other hand, the *indicator system reporting structure* should follow a bottom-up perspective [56].

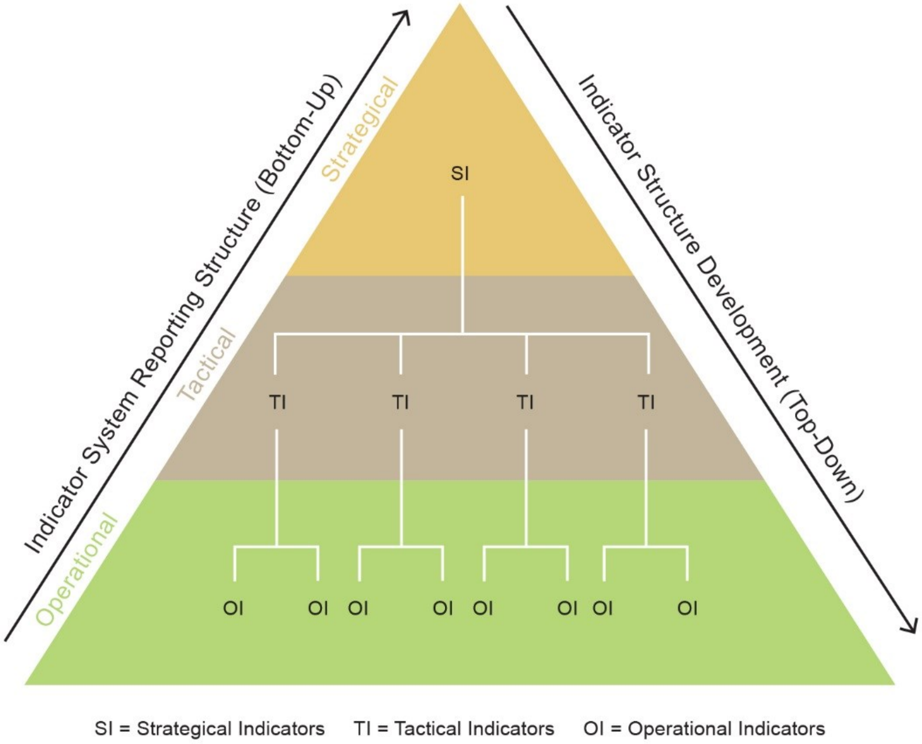


Figure 17: Maintenance key performance indicator development process and the relationship between the different indicator levels. In general, strategic indicators have a control purpose, while tactical indicators have a planning/ follow-up purpose. And operational indicators have an alarm/ diagnostics purpose.

The developed useful and suitable KPI's for maintenance management of electricity distribution networks should support the overall decision-making process. Fundamentally, for effective and efficient maintenance management, two main groups we distinguish with accompanying KPI's as shown in table 4.

Table 4: Developed maintenance KPI's for electricity network operator

Main Group	Key Performance Indicators
Maintenance Performance	1. Service
	2. Financial
Asset Performance	1. Reliability
	2. Availability
	3. Maintainability
	4. Safety

The main purpose of *maintenance performance* is to control and readjust the control of the planning, scheduling and execution of maintenance activities. While, the main purpose of *asset performance* is to monitor the condition and performance of the assets regarding maintenance. Asset performance KPI's are proposed to follow the RAMS parameters (Reliability, Availability, Maintainability and Safety) as the primary indicators. RAMS parameters are functional parameters and therefore well suited for measuring asset performance. The general definition of reliability, availability, maintainability and safety used throughout the engineering industries and quoted in literature on this subject follow the example as taken from MIL-STD-785. The definitions in this are as shown in table 5.

Table 5 RAMS parameters and their definitions for asset performance KPI's

Parameter	**Definition**
Reliability	The ability of an item to perform a required function under given conditions for a given time
Availability	Ability of an item to be in a state to perform a required function under given condition under a given instant of time or over a given time interval, assuming the external required resources are provided
Maintainability	A state in which it can perform a required function, when maintenance is performed under given condition and using stated procedures and resources
Safety	A safety state with an acceptable level of risk (with respect to injuries, fatalities, damage to public or private properties)

In the figures 18 and 19 maintenance KPI's which are developed for a typical electricity distribution network company are shown.

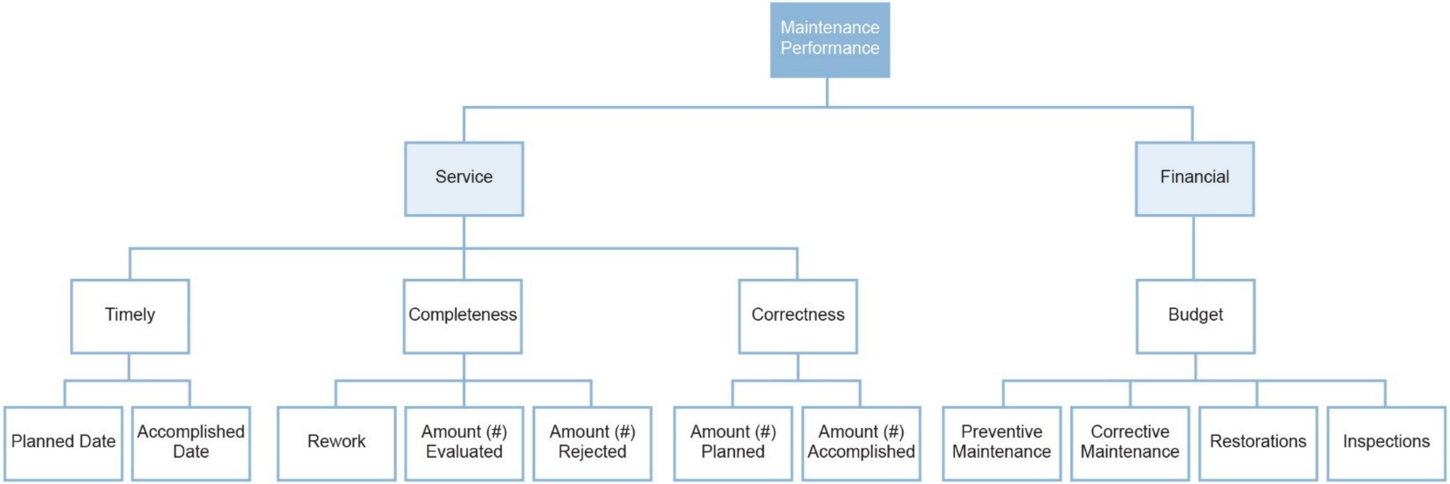


Figure 18: Maintenance KPI framework (performance tree) for maintenance performance as developed for a typical electricity distribution company. In this KPI structure strategic, tactical and operational KPI's are shown.

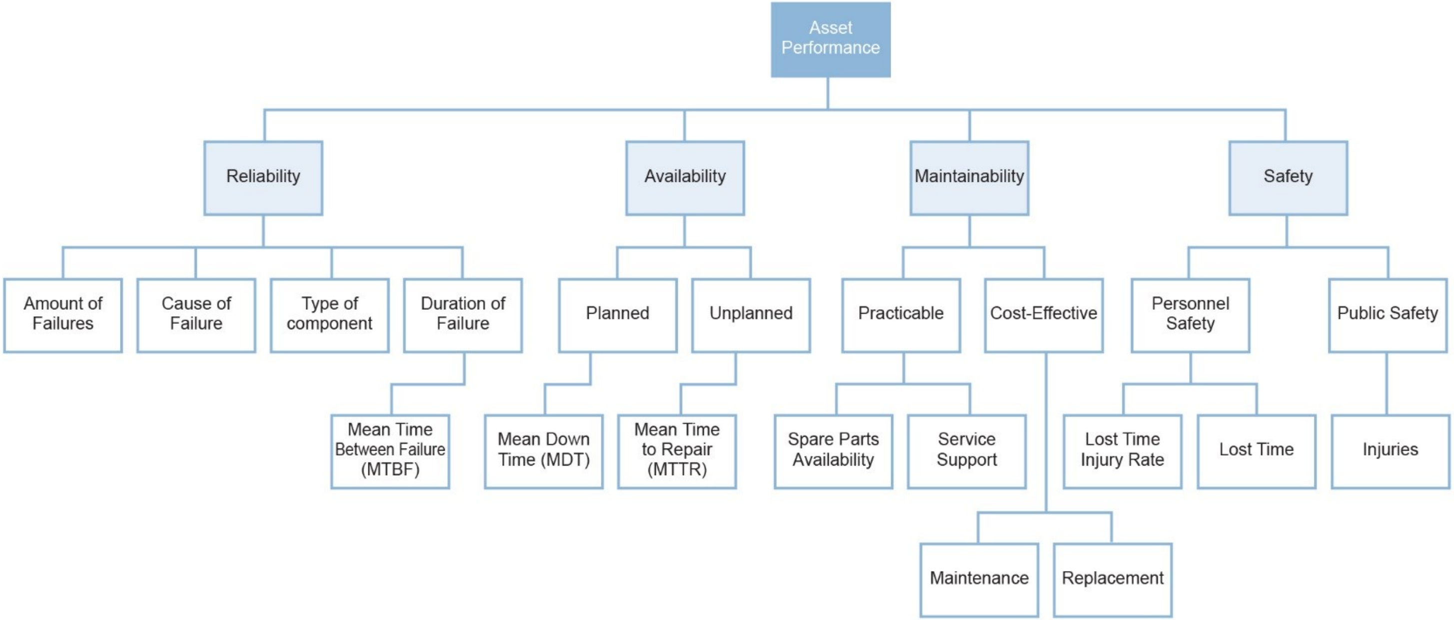


Figure 19: Maintenance KPI framework (performance tree) for asset performance as developed for a typical electricity distribution company. In this KPI structure strategic, tactical and operational KPI's are shown.

3.2.6.2 Reporting Indicators

Reporting indicators form a crucial part in the implementation of indicators in an organisation in the sense of presenting and visualizing the indicators to the users. When presenting and visualizing indicators, it is important to take into consideration the following properties [56]:

- The actual values of the indicators are not in itself intended to be direct measures of a certain aspect, such as safety, although they might infer a certain performance characteristic
- When treated in isolation, the numerical values of any individual indicator may be of no significance, however, the relevance may become when considered in the context of other indicators
- Trends of individual indicators over a period of time can provide an early warning to management to further investigate the cause of the observed changes
- Comparison of indicators against identified targets and goals may be necessary in order to evaluate performance strengths and weaknesses
- Each asset type or group of assets needs to determine which indicators best serve its needs
- Selected indicators should be adaptable for changes in processes, condition and performance assets and systems

The reporting of indicator is often visualized in diagrams, showing both indicator history and trends. Furthermore, it is common that the indicators are visualized by means of different colours depending on the actual indicator value in relation to a desired targets or goals, so called traffic lights. Basically, KPI reports vary from handwritten reports to very sophisticated computer generated reports with multiple charts and graphs.

A common way of visualizing the indicators is in the form of a dashboard. Typically, a KPI dashboard holds a summary of all KPI's on one or two sheets. The dashboard allows management to have quick access to various KPI's. It summarizes what these indicators measure, how they currently perform and whether these indicators have improved or worsened over time.

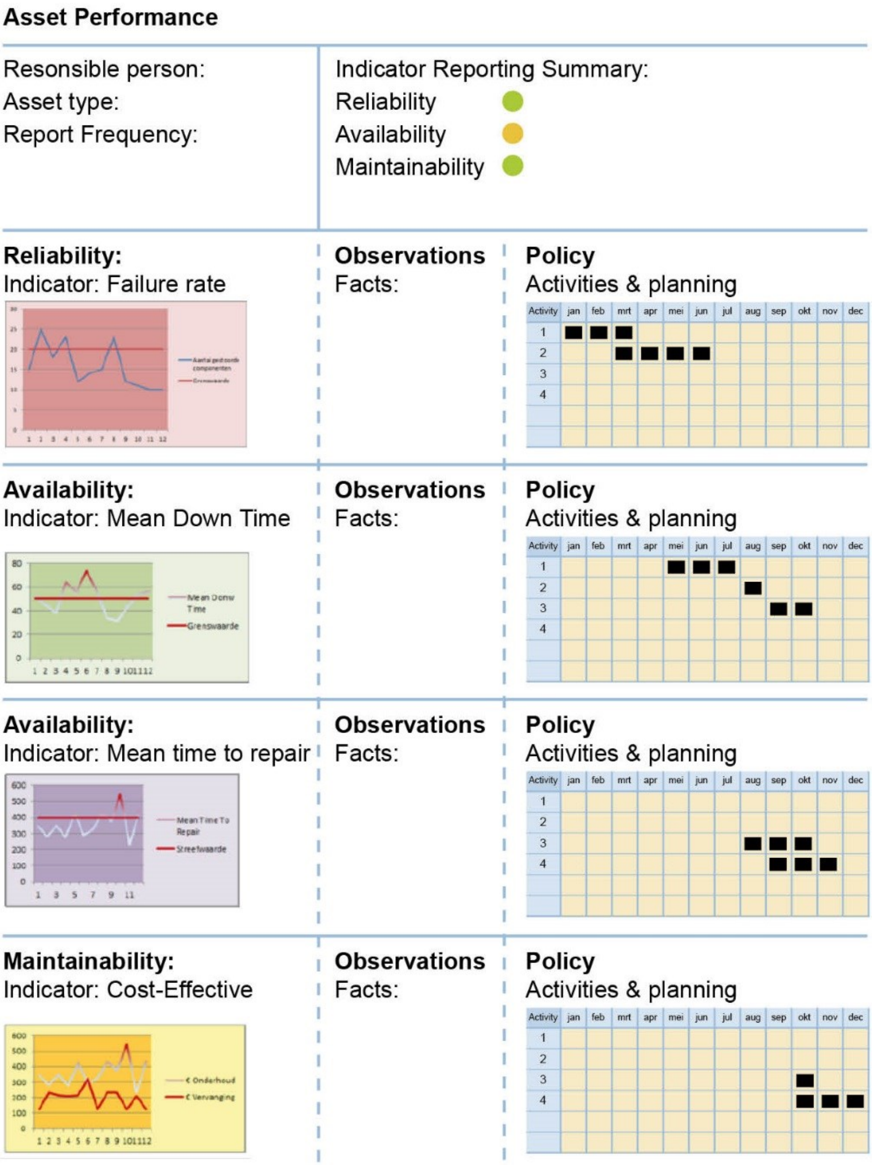
Added to this, the reporting frequency of a specific indicator is shown in the dashboard and this may vary depending on the characteristics of the indicator. For example, monthly, weekly, daily, half yearly or yearly frequencies can be shown.

In [38] KPI reporting formats are discusses briefly, mentioning a number of generic concepts such as a *System Input, Process Output (SIPOC)* model and more complex models such as the *Hibi model, DuPont model and MMT (maintenance management tool) models*. In [38] it is reported that most of the models used for maintenance KPI reporting have much in common with the *Balanced Score Card (BSC)* concept launched by Kaplan and Norton [57].

For electricity distribution network maintenance management, there are no documented maintenance KPI reporting methods found. Most commonly, system level, measuring reliability of the overall system, reporting of KPI's are found, however not specific for maintenance purposes. Therefore, and as part of the maintenance improvement objectives, a KPI reporting concept was developed aimed for maintenance management.

This reporting concept has been inspired by the *BSC* concept, which tracks the key elements of company's (here: maintenance management) strategy. Thus, including a set of measures that gives managers a comprehensive and fast view of the maintenance management. What has not been included in our reporting concept are the numbers of resource management.

An example of such a KPI reporting concept is shown in figure 20 in the form of a dashboard. In figure 20, the reporting of indicators for asset performance of a typical electricity distribution network company is depicted.



Asset Performance

Resonsible person:
Asset type:
Report Frequency:

Indicator Reporting Summary:
Reliability ●
Availability ●
Maintainability ●

Reliability:
Indicator: Failure rate

Observations
Facts:

Policy
Activities & planning

Activity	jan	feb	mrt	apr	mei	jun	jul	aug	sep	okt	nov	dec
1	■	■	■									
2			■	■	■	■						
3												
4												

Availability:
Indicator: Mean Down Time

Observations
Facts:

Policy
Activities & planning

Activity	jan	feb	mrt	apr	mei	jun	jul	aug	sep	okt	nov	dec
1					■	■	■					
2								■				
3									■	■		
4												

Availability:
Indicator: Mean time to repair

Observations
Facts:

Policy
Activities & planning

Activity	jan	feb	mrt	apr	mei	jun	jul	aug	sep	okt	nov	dec
1												
2												
3								■	■	■		
4									■	■	■	

Maintainability:
Indicator: Cost-Effective

Observations
Facts:

Policy
Activities & planning

Activity	jan	feb	mrt	apr	mei	jun	jul	aug	sep	okt	nov	dec
1												
2												
3										■		
4										■	■	■

Figure 20: Example of a maintenance KPI reporting dashboard for asset performance indicators developed as a concept for electric distribution networks.

3.3 Conclusions & Outlook

3.3.1 Conclusions

This chapter elaborated on key enabling aspects for a maintenance management improvement plan for electricity distribution network companies. In doing this, it has been concluded, that due to the evolution in asset management applications and standards, maintenance management is becoming a critical business aspect. As a result, maintenance management is under more pressure to professionalize their processes, tools and performance measurement capabilities. Nowadays, many electricity distribution network companies still lack the ability to go along with the fast maintenance management evolution. The aim of this chapter was to discuss the *management* side of maintenance, with emphasis on organisational aspects.

In conclusion, typical maintenance management improvement drivers for electricity distribution network companies are:

- Improved control the maintenance organisation with the whole of the management
- Transparency for stakeholders on the decisions that are taken
- Further develop the PAS-55, NTA 8120 (and ISO 55000) to a higher level

Furthermore, this chapter provides a broad understanding of organisational aspects which are relevant for maintenance improvement and professionalization. We found and described that the following key subjects are relevant:

- Maintenance management decision levels
- Continuous improvement approach for the maintenance organisation
- Including organisational pillars which steer maintenance improvement
- Development of a maintenance maturity model
- Development of maintenance key performance indicators

A clear maintenance management process is necessary in order to identify the key enabling organisational pillars that will play an important role in steering maintenance improvement. When the organisation has the ability to set this in a clear way, it will be able to develop, for each supporting pillar, a roadmap (maturity levels).

With the aid of a maturity model for maintenance, the organisation can look back and predict where improvement gains are feasible and required and which particular supporting pillar for a specific asset type (or group) needs attention.

With the aid of the maintenance maturity model, a roadmap steering towards maintenance management improvement, and ultimately excellence, can be set. However, behind any improvement lies an important aspect, namely the enabling of the measurement of a certain contribution. Here, maintenance key performance indicators can play a vital role. They provide means to measure maintenance management contributions. Measuring and reporting maintenance contribution can thus be defined as the management activity of regularly evaluating past performance with the aid of performance indicators.

3.3.2 Outlook

Here the importance of having a professional maintenance organisation is extensively described. However, this has been on the *management* side and related organisational aspects needed for this. In a matured state of the maintenance regime a structured and effective methodology is envisioned. In such a particular state of the art structured maintenance approach, each maintenance action (resulting from overarching maintenance concepts) can be translated into its benefits to the business values of the organisation. Indeed, capturing data, knowledge and analysis tools from each layer of the organisation in order to use this as input in a straightforward and structured method to develop risk-based maintenance concepts. In chapter 4, a method for approaching the aforementioned is developed, namely the development of a risk linked maintenance management model. This model can provide a state of the art maintenance concept, which is, ultimately, based on the fundaments of the overall corporate risk management model.

4 Risk Linked Reliability Centered Maintenance Management Model

4.1 Introduction

4.1.1 Background

Professionalization implies a systematic and methodical approach and where applicable making use of knowledge, experience and opinion. A major challenge for asset managers when aiming to professionalise maintenance management is to implement a maintenance concept which [58]:

- maximizes availability and efficiency of the assets
- controls the rate of asset deterioration
- ensures a safe and environmentally-friendly operation and
- minimizes the total cost of operation

Such professionalization can be achieved by 1) adopting a structured approach to the study of asset failure modes and 2) the systematic design of an optimum concept for inspection and maintenance. As has been discussed earlier in chapter 2, maintenance management has been through a major process of evolution. Most recently, risk-based maintenance methodologies are starting to emerge, signalling that there is new trend to use the context of risk as a criterion to plan maintenance tasks. Therefore, electricity network companies, where the decision-making process is guided by risk management, increasingly want to incorporate the concept of risk into maintenance management.

From the above it can be seen that there seems to be a need for 1) a generalized methodology that can be applied to different types of assets irrespective of their characteristics and 2) a method that is linked to the corporate risk management model. In this chapter, the concept of risk is applied to *Reliability Centered Maintenance (RCM)* and through this, a uniform systematic and methodological approach will be developed. The result, named *Risk Linked RCM*, provides a method in which risk, as a calculated dimension, is added as another functional focus of the RCM method. In this method, the traditional *Risk Priority Number (RPN)* calculation has been expanded in order to deal with the consequences of asset failure modes on multiple corporate business values (business drivers). This is necessary in order to have a realistic quantification of risk factors, which is affected by the quality of the consequences assessment and the accuracy of the estimates of the probability of failures. In doing so, the aim is to develop a practical yet sufficiently accurate method for risk-based maintenance management.

A complete and extensive description of the development of this method will be described in this chapter. Once such a risk related maintenance concept is developed and implemented, any maintenance policy and maintenance action can be assessed on its financial, technical and business values denoted in terms of risks. In order to demonstrate this, the model will be applied for a practical case of high voltage power transformers.

4.1.2 Chapter outline

In section 4.2, RCM is briefly introduced and the steps followed within a RCM approach are described. Although abundant literature has been published on RCM, a brief introduction is given to facilitate the discussion during the remainder of this thesis. Aspects related to RCM such a *Failure Mode and Effect Analysis (FMEA)* and the calculation of a *Risk Priority Number (RPN)* are described. Section 4.3 continues with considering risk management as a decision-making method within asset management and explaining the link between RCM and risk management. In sections 4.4 risk linked RCM methodology is developed, where failure modes are linked to business values through the use of risk factors. Section 4.5 applies this model to a case study of a Dutch electricity network operator for a power transformer and subsequently to manager a larger fleet of power transformers. This chapter comes to a close in section 4.6 by drawing a number of concluding remarks and explaining the way forward for the remainder of this thesis.

4.2 Reliability Centered Maintenance (RCM) Basic Principles

4.2.1 Reliability Centered Maintenance (RCM)

A sheer amount of literature is available covering the topic of RCM. The first industry to renew the widely-held beliefs about maintenance was the international civil aviation industry [42], where this framework was known as MSG-3 and outside this industry as RCM [41], [40]. The method developed by [41] during the 1980s and 1990s was aimed to enable the retrospective application of RCM, which was initially rigorous and comprehensive [59]. This approach was widely acknowledged to form the basis of applications in other industries. As we are going to discuss the application of RCM outside its initially intended context, it is essential to point out that this needs careful consideration. In the civil aviation industry, for what RCM was principally designed, any failure would be unacceptable and failure modes should be designed out. If this would be impractical or uneconomic to design out, then a RCM regime was introduced to manage and mitigate the failure modes.

When the interest of RCM shifted to the railway, water and power utilities, the fundamental difference compared to that of the aviation industry lies in the focus upon managing. In the case of network utilities, this is the management of the number, severity and risk of asset failures to a level that is acceptable to corporate business values. Apart from this, performing RCM provides a means to find a balance between the need to ensure acceptable reliability levels, while also keeping maintenance costs under control. Traditional maintenance regimes hold onto procedures that were either devised resulting from asset failures, or from manufacturer's recommendations. In both cases, the devised methods are unlikely to have been set up based on an evaluation process which recognises engineering experience and operating conditions in which the asset is performing [43]. This unlikeliness is due to the failure-based or ad-hoc driven maintenance methods that are used. RCM provides a formal and structured process to carry out a comprehensive review of maintenance requirements of each asset in its operating context. The central focus in RCM is that the intended maintenance is not to preserve the asset for the sake of preserving the asset, but rather to preserve the system function. With RCM, a thorough understanding of asset failure modes, failure causes, likelihood of occurrence and effects is achieved. Ultimately, this understanding can be used to define a maintenance task that prevents or proactively addresses the potential cause of failures such that the overall lifecycle cost of performing this maintenance task [53].

4.2.2 RCM Analysis Process

A wide variety of application forms of RCM are available. Depending on the purpose of the RCM analysis, a specific form can be used. This may range from a classical (comprehensive) approach to a more pragmatic approach which is less time consuming, because readily available information is used. In the approach, as used in this context, the RCM process includes the following steps for the system/ components under consideration:

1. Identify function
    - In this step, different asset functions are distinguished from each other regarding the level of their functioning (for example primary, secondary, etc.). A functional breakdown of the system under analysis is made in this step.

2. Identify functional failure
    - In this step, it is determined in what way a system or sub-system can fail in fulfilling its function (functional failure). In this context, failure means not being able to fulfil the function in a satisfactory way.

3. Identify functional failure cause(s)
    - In this step, the cause of each failure (failure mode) is determined by analysis. The failure mode can be of different nature e.g. normal wear and tear, human errors, manufacturing defects or wrong operation.

4. Identify the effect of the failure
    - In this step, it is determined what happens when each failure occurs (failure effect). This requires the evidence of the failure to be investigated for example effect on operation, safety or environmental hazards.

5. Identify the impact of the failure
    - This step, which is often confused with step 4, is actually used to assess in what way each failure matters (failure consequence). In general, several types of consequences are possible such as safety consequences (injuries), operational consequences (loss of service), non-operational consequences or hidden failures. Moreover, it is also possible that there are multiple consequences to the organisation. In this step, the RPN is calculated. This step is of particular importance for linking risks to failure modes and their consequences. This is elaborated on in the next section.

6. Select maintenance task
    - In this step, a task for preventing or predicting each failure (along with a time interval) is assessed. These tasks should be technically feasible and worthwhile of doing.

7. Other measures
    - When no preventive or predictive tasks can be found, other measures are investigated such as failure finding (for hidden failures), redesign or process changes. Another category which is used in the case that there are remaining (non-) operational consequences are corrective actions (run-to-failure).

These seven steps can be grouped into three main parts as follows:

- Steps 1-4: *Failure Mode and Effect Analysis (FMEA)*, which provides an initial *Risk Priority Number (RPN)* of the failure.

- Step 5: *Failure Effect Categorization (FEC)*, which provides a method to categorize the failure modes according to their effect in a uniform way. This helps with selecting an effective and proper maintenance strategy in the next step.

- Step 6: *Task Logic*, which provides, on basis of the FEC, means to define a maintenance strategy for each failure mode. Maintenance strategies such as, preventive scheduled maintenance, condition based maintenance or run-to-failure can be selected.

4.2.3 Risk Priority Number (RPN)

The RPN is a commonly applied factor for calculating the risks associated with potential failure modes identified during the FMEA. With the RPN, a numerical value is assigned to each of the following categories [60]:

- *Severity* (*S*), which is a rating for the severity or consequence of each potential failure effect
- *Occurrence* (*O*), which is a rating of the likelihood of occurrence of each potential failure cause
- *Detection* (*D*), which is a rating for the extent to which detecting the failure cause is possible.

Usually, each of the above mentioned categories are rated, for each failure mode, on the basis of the analysis of a RCM team. For this, experience and engineering judgements are used. The specific rating description, criteria and values are defined by a RCM team in order to fit the system under analysis. When the ratings have been assigned, the RPN can be calculated as follows:

$$\boldsymbol{RPN = S \times O \times D} \qquad \textbf{(1)}$$

With the purpose to calculate a RPN value for each failure, a ranking (scoring) table is usually developed and used for the severity, occurrence and detection. This will be discussed in more detail in the next section.

4.3 Concept of Risk and its Relevance to Maintenance

4.3.1 Challenges with Incorporating Risk to RCM

In section 4.2.3, it is said that the RPN is a commonly applied factor for calculating the risks associated with potential failure modes identified during the FMEA. This implies that with the use of a RPN, risks are related to the RCM process. This is partly the case. Indeed it is possible to rank and categorize failure modes with related RPN values, however, this is only possible once ranking tables are available. Usually, such ranking tables are made specifically for the RCM study and are deviant from, if any, available corporate risk models which have their own ranking tables. Moreover, the calculation of the RPN also requires the *detection* to be ranked, which is not common in risk management calculations. This is shown in table 6.

Table 6: Comparison of risk calculation methods

Risk Calculation in Risk Management (corporate)	**Traditional RPN calculation**
P (probability)	O (occurrence)
C (consequence)	S (Severity)
	D (detection)

The *probability* as used for risk management is a statistical parameter, while the occurrence as used here is a frequency of occurring failures. The difference between *consequence* and *severity* lies in the fact that the former is an objective, measurable parameter, while the latter is subjective and not directly measurable.

In order to calculate an appropriate RPN value, given that a risk model (corporate risk management) is available, the *probability* ranking and *occurrence* ranking can be used as substitutes of each other. Likewise, the available *consequences* definitions and rankings of the risk management can be adopted for the *severity* parameter for RPN calculations. Usually, slight changes are necessary in these ranking values. The only parameter that needs to be taken care of is the *detection* parameter. This can be dealt with by establishing a ranking table specific for the *detection* parameter. This can be developed based on the available methods which are possible to detect the effect of a possible occurred failure mode. Examples or directions in order to establish this are:

- Signals from primary assets to operators (e.g. trips, alarms, monitoring, etc.)
- Routine inspection rounds with a given time interval (e.g. daily, monthly, yearly, etc.)
- No detection

Once such a ranking for the *detection* parameter is established, the calculation of each failure mode can be made with the aid of the RPN calculation process.

With the aid of the RPN, the link can be made between risk management and RCM. By adopting the risk ranking, criteria and values used by risk management, each potential failure mode is assessed against the corporate business values. In doing so, the RCM analysis clearly aligns with the overall maintenance management process and is building on the principle applied in the risk management approach. While this appears to be straightforward, however, the contrary is true when applied in practice. There are, in general, three challenges that need to be taken care of when implementing risk management into RCM. These challenges are:

- The necessity of the overall group (RCM team) to understand and accept the notion of risk.
- The data availability to extract required failure occurrences (probabilities).
- The necessity to have a (sufficiently) accurate procedure for calculating the *severity* and *occurrence*

The first challenge is dealt with by involving risk management in the RCM analysis and clarifying the notion of risk to a broader audience (RCM team). Because of the difference in specialities and application of risk management, this can be an intensive and time consuming experience. It is important to stress the fact that risk is not only a theoretical tool, but has sufficient practical foundation for maintenance management analysis. In this context, the availability or development of an overall corporate risk management model is essential and provides a steppingstone to align the more practical operational and technically risk associated layers of the organisation with the strategic more abstract and business risk associated layers.

The second challenge is one which requires a pragmatic approach. It is indeed true when one states that the available data is insufficient to calculate failure probabilities individually or for populations of assets. Usually, this is true, as, traditionally, databases were designed to record asset failures and not failure modes for RCM-based analysis. The importance of quantitative calculation of probabilities is gaining more and more interest. Added to this, data records are gradually becoming more suitable for probabilistic studies. Life Data Analysis (LDA) is an example of how statistical tools and models can be applied to calculation failure probability models that can be used for maintenance, risk or replacement analysis. This will be discussed in detail in chapter 5. At this point, a practical and yet sufficiently accurate manner to deal with the challenge of lack of data for occurrences is required. With the right combination of asset experts, manufacturer knowledge, engineering judgement and scientific collaboration many failure modes and rough estimations of frequencies in which they occur can be determined in a practical way. This will be demonstrated in the remainder of this chapter. Practical experience has taught that difficulties arise when people with non-statistical background are questioned about the probabilities of failures. In order to cope with this another approach is chosen. Instead of asking what the probability of failure is, it is asked how often a similar failure mode is experienced in a given time period.

The first two challenges can both be tackled with a practical, sufficiently accurate procedure for calculating the RPN.

The third challenge is related to shortcomings in the calculation procedure of the traditional RPN approach. The multiplication of *occurrence (O)* and *severity (S)* implies that an effect and a failure mode are considered to be directly related and therefore have the same probability of occurring (e.g. torqueing of a bolt will lead to breaking of the bolt). However, the consequence of an effect and its impact on a certain business value, which is the *severity* parameter, depends on multiple variables and circumstances (e.g. position of the bolt, importance of the bolt, time of occurrence, presence of people, etc.). When multiplying S with O, we implicitly assume that the probability of the failure mode (O_{fm}) is the same as the probability of the resulting consequences and impact (S). This is not true for many practical reasons. For instance, the probability of the failure mode (O_{fm}) is based on component failure data or experience. A failure mode can have different consequences and these can also have different probabilities. At the same time, the consequences have an impact on multiple business values, which also have their own likelihood of occurring. Therefore, it is important to note that the probability of a failure mode (O_{fm}) is not necessarily equal to the probability of a consequence happening for a specific scenario ($O_{scenario}$).

We would like to stress here that the identified failure mode will not necessarily lead to a maximum effect. In other words, the discovered effect may have consequences in different degrees (scenarios) each with its own likelihood (probability). In addition, the probability and impact of the effect, depending on the scenario, will be different for each business value. Only considering the "realistic worst case" consequences during the *FMEA* process will result in a one-sided view on the impact on the business values and will be prone to scepticism. Also, sometimes the consequences in a more likely scenario have a bigger impact on the business values than the worst case scenario due to a more certain likeliness of taking place. Objectivity during the assessment of consequences is important and should, in principle, be included in the calculation efforts.

In section 4.3.2, the RPN calculation is re-examined in order to deal with this challenge. This has been done in order to develop a *Utility Risk-linked RCM* approach for maintenance management which is not only practical for real industry application, but also developed in such a way that it can be used for different types of components and with sufficiently accurate levels of risk calculation.

4.3.2 Expanding the Traditional RPN Calculation

For the said challenge an extended version of formula (1) is introduced in order to assure a (sufficiently) accurate procedure. In this extended version, two scenarios (worst case scenario and most likely scenario) for each failure mode can be employed. It is also possible to include more scenarios if that is needed. Each effect scenario can, by itself, have an impact on multiple business values. Notably, it should be clear that the likelihood of the impact will vary for each business value within the scenario. The above mentioned description is made clear by means of a conceptual overview in figure 21 [53].

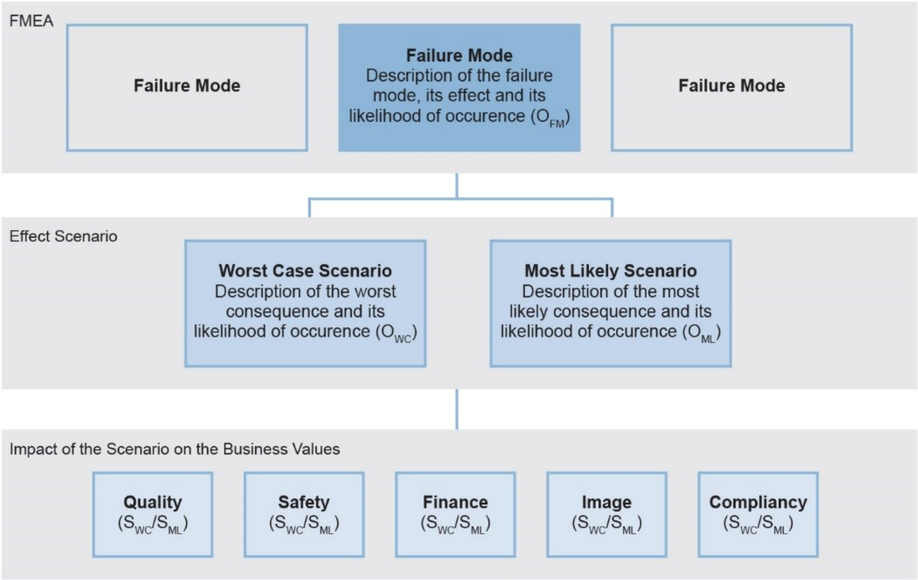


Figure 21: Shows the interrelated issue with multiple business values for two effect scenarios for an identified failure mode.

This brings us the extended version of formula (1), denoted in formulas (2) and (3).

$$\boldsymbol{RPN_{worst\ case}} = \boldsymbol{S_{WC\ (business\ value)}} \times \left(\boldsymbol{O_{WC(business\ value)}} \times \boldsymbol{O_{failure\ mode}}\right)_{\boldsymbol{worst\ case}} \times \boldsymbol{D} \qquad \textbf{(2)}$$

$$\boldsymbol{RPN_{most\ likely}} = \boldsymbol{S_{ML\ (business\ value)}} \times \left(\boldsymbol{O_{ML\ (business\ value)}} \times \boldsymbol{O_{failure\ mode}}\right)_{\boldsymbol{most\ likely}} \times \boldsymbol{D} \qquad \textbf{(3)}$$

To illustrate the use of formulas (2) and (3), a simple example is given in table 7.

Table 7: An explanatory example of how the formulas (2) and (3) are used.

The likelihood of the scenario ($O_{scenario\ (business\ value)}$) and the frequency of occurrence of the failure mode ($O_{failure\ mode}$) together form a conditional occurrence (in parenthesis in formula (2) and (3). This conditional occurrence is then looked up in a table specifically designed for the calculation of the RPN.
For instance,

- $O_{failure\ mode}$ *: probable = 0,1*
- $O_{scenario\ (business\ value)}$ *: probable = 0,1*
- *Conditional occurrence= 0,1 x 0,1 = 0,01*

Assuming that in the table (risk management table) 0, 01 is ranked as having a calculation value of 5. The value for the conditional occurrence is 5 and this will be used for the further calculation of the RPN value.

When the RPN's are calculated, each failure mode can be individually ranked from high to low risk. Moreover, the ordering of RPN's will provide a priority ranking for choosing maintenance tasks to mitigate and control the occurrence of failures or their effects. It should be noted that the calculated RPN's should not be seen as absolute values. Instead, they must be used in a relative way. The arbitrary values have no direct meaning in itself, rather its significance comes when compared to other values. Finally, it is desirable to also perform the initial risk assessment based on the assumption (or the fact) that the recommended maintenance actions have been completed. To calculate *revised* RPN's, a second set of revised ratings of *severity*, *occurrence* and *detection* for each failure mode are calculated. The *initial* RPN's can be compared to the *revised* RPN's. This offers an indication of the usefulness of certain maintenance actions and can also be used to evaluate the value to the organisation of performing the FMEA. In addition, an assessment can be made of the implications on risk exposure when certain maintenance tasks are not performed (i.e. in case OPEX budget cuts). With the expanded formulas (2) and (3), it can be found during the analysis that for some particular failure modes, the overall RPN for the most likely scenario is higher compared to the worst case scenario. This lies in the fact that the impact in the worst case scenario may be more severe, however the likelihood of that impact occurring might be lower than for the most likely scenario. This is in accordance to practical circumstances and therefore a realistic aspect that should be included in the model. By doing this the difference can be made between "what could happen" and "what actually happened".

With the ability to analyse scenarios separately and have an objective tool to determine which impact in relation to its occurrence reveals a higher risk (RPN), maintenance resources can be allocated based on the anticipated effects that maintenance will have on reducing operational risks of those selected failure modes with highest RPN.

4.4 Developed Risk Linked RCM Method

4.4.1 Risk Linked RCM Analysis Process

The risk linked RCM process, which is developed on the basis of expanding the traditional RPN calculation, is broadly described here. Figure 22 shows the overall risk linked RCM process, divided into 8 main steps. It can be seen from this figure that the risk linked RCM process provides a comprehensive method that addresses not only the analysis process but also the preliminary input requirements (left side of the flowchart) and follow-on output activities, which are necessary to ensure that the risk linked RCM effort achieves the desired results. This flowchart and its principles can be applied to virtually all types of systems. In general, steps 1 and 2 form the basis of the analysis procedure, where the system is chosen and defined for the risk linked RCM analysis. The scope (system boundaries) is decided and an in-depth functional failure analysis (FMEA) is performed. From this FMEA, the failure modes, their effects and the occurrence of the failure mode are known. In step 3, the actual link with risk management models and RCM is made. In this step, the expanded version of the RPN calculation is applied in e.g. two scenarios and the impact on each business value and the likelihood of that impact on each business value is assessed in accordance. Crucial inputs in this step, as shown in figure 22, are the rankings for the severity, occurrence and detection, which should be extracted and based on the same definitions as used by risk management models. Based on the *initial* RPN prioritization (step 5), detailed maintenance tasks are identified in step 6. These identified maintenance tasks are assessed on their potential risk reduction by means of a *revised* RPN calculation (step 7). In the end, a risk based maintenance concept for each failure mode is available.

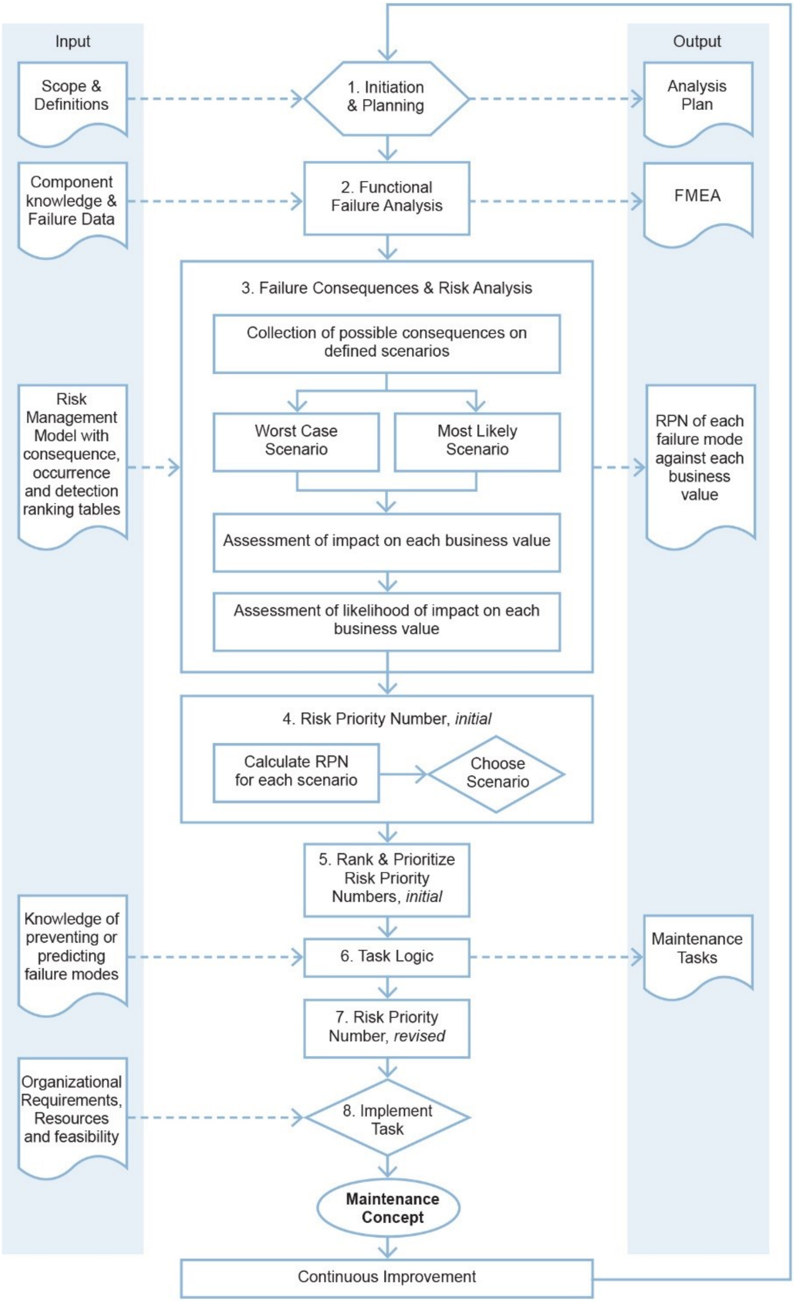


Figure 22: Overview of the Risk Linked RCM process.

4.4.2 Implications of Risk Linked RCM for a Maintenance Organisation

The above mentioned modification incorporates risk-based decision tools into the RCM process. On one hand, such a risk linked RCM modification and assessment requires significant resources in terms of time, data and people from different levels of the organisation. On the other hand, however, this endeavour towards using the RCM method will improve the organisations maintenance management activities. The developed method provides a powerful and pragmatic tool to utilize for maintenance management activities. Maintenance should contribute to the overall business goal, which is to sustain and control assets performance within boundaries during their lifecycles. In figure 23, we illustrate how the developed approach, finally, blends into the operational, tactical and strategic level of the maintenance organisation.

In principle, figure 23 indicates for each level of the organisation what input data is required to perform a risk linked RCM analysis. More importantly, it has shown how the results, in turn, benefit each level of maintenance decision-making. At the strategic level, the complete asset risk profile for each failure mode of the analysed system can be ranked from high to low risk. Accordingly, an *initial RPN* and *revised RPN* (after maintenance task has been considered) are available. At the tactical level, the FMEA analysis can be used as input for important performance indicators to track the asset performance of a group of assets. Subsequently, it forms the basis for increasing the opportunity to use condition monitoring and diagnosis methods for a specific dominating high risk failure mode. Perhaps, the most important implication of the feedback takes place on an operational level, where the current maintenance tasks can be revised with the new or updated maintenance tasks resulting from the task logic analysis. In the end, we believe that such a wide approach towards maintenance management will provide network utilities to assess existing maintenance strategies and develop advanced mixes of new maintenance strategies. The success of such a comprehensive approach towards maintenance professionalization can only stand when there is employee and management understanding and therefore we strongly encourage having a solid link of our developed method (or similar methods) with the overall maintenance decision-making process.

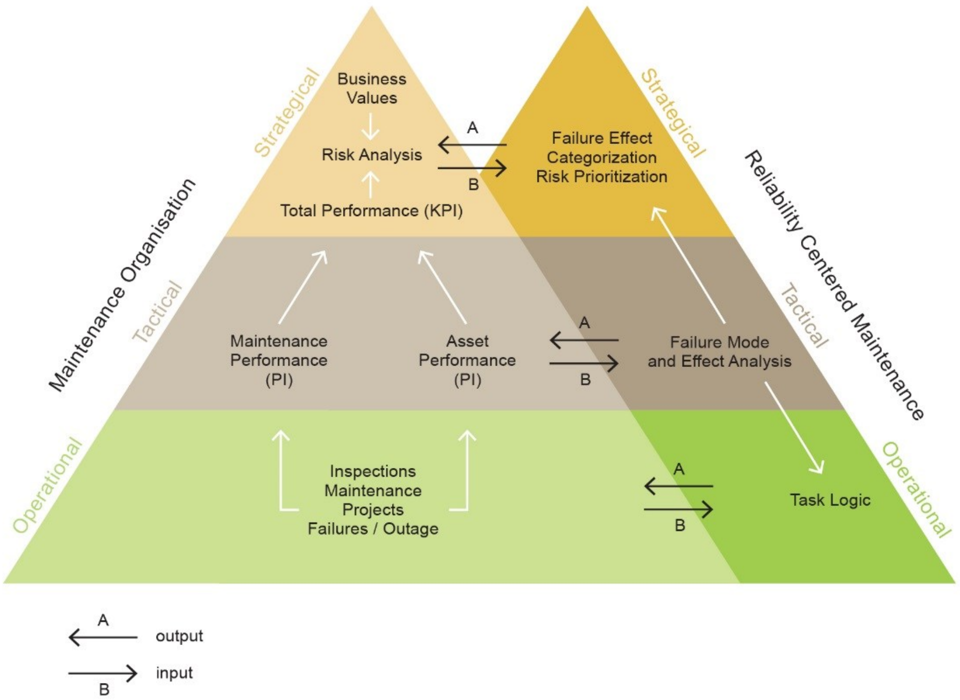


Figure 23: From each level (operational, tactical and strategic) information is required to perform a solid RCM assessment. Nonetheless, the outputs from such analysis form an important source of information for predictable maintenance planning.

4.5 Case Study: Risk Linked RCM Method

4.5.1 Dutch Case Study: Power Transformers

In this section, a case study performed at a Dutch DNO is described. In this case study, the objective was to apply the risk linked RCM in order to renew and improve on an existing maintenance concept for high voltage power transformers. This DNO expects that such a risk linked RCM will improve maintenance effectiveness and provide a mechanism for managing maintenance with a high degree of control and awareness. We focus on the following potential benefits:

- The reliability of the system (power transformer) will be increased by using more appropriate maintenance activities
- Risk reduction vs. costs for a particular business value is assessed for each maintenance activity

- A full documented process is produced in which different organisational knowledge is conglomerated in a process that can be reviewed and revised in the future
- Maintenance managers have a management tool which enhances control and strategy
- The maintenance organisation obtains an improved understanding of its objective, purpose and the reasons for which it is performing the scheduled maintenance tasks.

The remainder of this section will discuss the case study by following the steps from the flowchart shown in figure 22 of section 4.4.

Step 1: Initiation & Planning

In the first step, it is determined what the extent is of the study. The purpose is to establish an optimal maintenance concept. In general, the assessment of the need for a risk-based maintenance analysis should be a regular management activity within the organisation for continuous maintenance improvement. This case study had the nature of a pilot project, thus the learning experience was the central theme here. The risk linked RCM method had to be assessed in order to demonstrate its practical applicability. In the initiation and planning phase, the system which was chosen for investigation during this pilot phase was a 150/50/23 kV power transformer. A simplified one-line diagram representation of the transformer in the network part is given in figure 24.

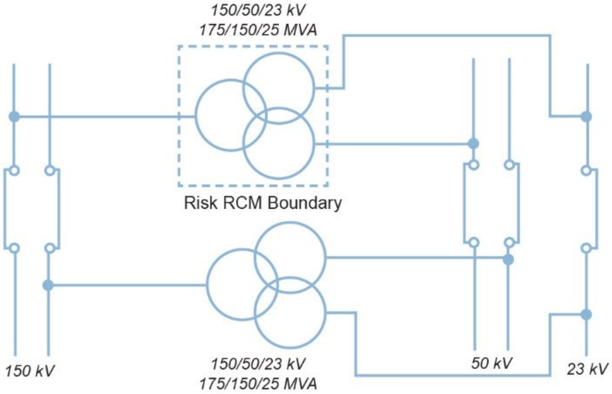


Figure 24: Redundantly, n-1, configured network in which the 150/50/23 kV transformer chosen for the risk linked RCM study is shown. The risk linked RCM is only applied for one of the power transformers within the chosen boundaries.

Power transformers are one of the most critical assets in power systems due to their economic value and important function in the overall electricity network. Power transformers are used to transform the voltage down (or up) to distribution voltage levels. A power transformer consists of many sub-systems and equipment such as a cooling system, active part (windings and core of the transformer), tap changer, oil contention & preservation and bushings. Throughout the lifetime of an in-service power transformer, it undergoes various forms of ageing and degradation phenomena. The current maintenance management concepts for power transformers are based on either solely historic manufacturer's guidelines or traditional DNO specific actions (for instance oil analysis). These maintenance concepts might need reconsideration in terms of determining whether they are still acceptable or adequate. At the same time, the current maintenance concepts have not been carefully assessed against risk management principles and their added value or impact on the business values. Once a system for analysis is chosen, the following aspects to consider are the availability of data, knowledge and people for carrying out the risk linked RCM analysis. This might seem straightforward, however, it probably is the most crucial step for the complete remainder of such a project. The risk linked RCM team for this case study consisted of representation of all levels (strategically, tactical and operational) of the maintenance and asset management organisation. This approach ensures that the effort of the case study is concentrated on the most important failure modes for the whole organisation. Besides internal representation, the team was also enriched by external experienced RCM facilitators, university collaboration and manufacturer's involvement. This is shown conceptually in figure 25.

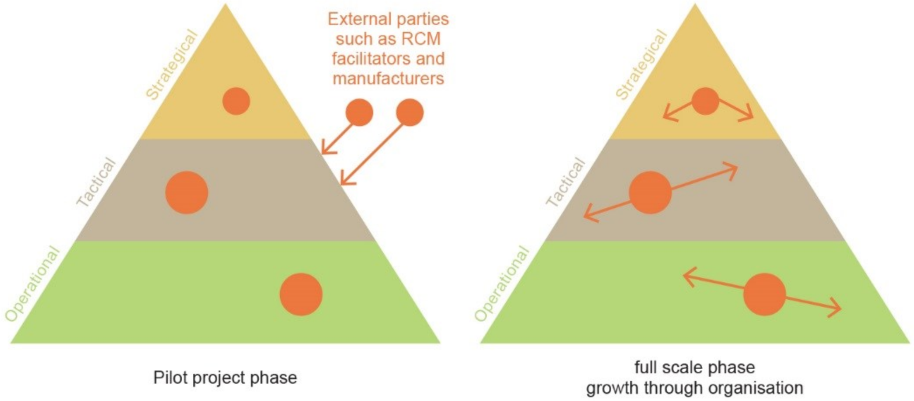


Figure 25: Risk linked RCM is first introduced in a pilot phase with a small group from all levels of the organisation and implemented in a careful and controlled environment. In a full scale implementation, the knowledge from the pilot phase is gradually disseminate and grown through the whole of the organisation for all levels. Additionally, external parties are also consulted in this process.

Step 2: Functional Failure Analysis

In this step, a clear understanding of the power transformers components functions, failure modes, failure effects and consequences are expressed in terms of the organisations objectives. To be able to develop a new maintenance concept using RCM this analysis is crucial. In general, FMEA is suitable for this purpose. Field data combined with expert knowledge should be analysed and used to determine causes (failure modes) and occurrences to help better perform the calculation of the RPN and support the FMEA. To acquire this field data and experience knowledge, different data sources are consulted. Amongst others, failure data records, in-depth failure investigation results, manufactures knowledge and component expert knowledge are used.

Functional partitioning is used to break down the total functionality into more manageable and analysable blocks. Initially, high level functions are partitioned followed by lower level functions that, in the end, combine to form a functional model of the total system under analysis. It is important to note that there are many ways of undertaking this and the extent to which the functional partitioning takes place depends strongly on the maintainability of the items which are to be defined in the RCM analysis. Moreover, organisations usually have an asset hierarchy which is sometimes already functionally based and thus forms an ideal basis for the breakdown. In figure 26, the functional partitioning of the power transformer is schematically shown.

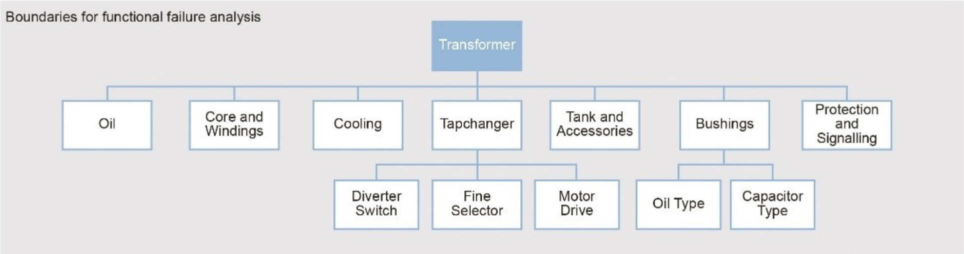


Figure 26: Functional partitioning of the transformer for the FMEA analysis.

From this point onward, the following steps, as described in section 4.2.2, are used:

1. Identify function
2. Identify functional failure(s)
3. Identify functional failure cause (s)
4. Identify effect of the failure (s)

This forms the core of the FMEA analysis part of the risk linked RCM analysis. In total, following the above mentioned steps, 65 failure modes for this power transformer have been identified. These can be further subdivided, according to the functional partitioning, as follows:

- Tap changer:
    - 14 failure modes
- Core and windings:
    - 7 failure modes
- Transformer bushings
    - 16 failure modes
- Tank and accessories
    - 3 failure modes
- Oil
    - 8 failure modes
- Cooling
    - 8 failure modes
- Protection & Signalling
    - 8 failure modes

A brief summarized overview of a part of the FMEA results is shown in table 8. For each sub-system, one failure mode is assessed and the results are shown. The complete overview of all the identified and analysed failure modes can be found in appendix C.

Table 8: Failure Mode and Effect Analysis (FMEA) for a number of power transformer functional failures

Function	Functional Failure	Worst Case	Most Likely	Effect	Cause	Cause 1	Cause 2	Cause 3
1 - Tap changer - 1.1. Diverter Switch								
Switching over the load current without interruption, independently and fast	Load current is interrupted	Internal short circuit > loss of tap changer > transformer can be repaired	Internal short circuit > loss of tap changer > transformer can be repaired	Arcing > gas formation > short circuit > loss of tap changer	Vacuum bottle leakage	Vacuum bottle leakage	Material/ production error	
2 - Core and Windings								
Windings provide the conduction of current and induction of the magnetic fields	Insulation breakdown	Partial discharge > short circuit in windings > differential protection triggered > transformer irreparable		Short circuit in windings - hotspot - partial discharge	Ageing of paper insulation	Degradation of paper insulation	Ageing	
3 - Tank and Accessories								
Enclosing the oil and encasing of the active parts	Leakage and / or intrusion	Leaking gasket, pipes or valves leading to significant leaking > oil level indicator triggered > maintenance crew sent	Leaking gasket, pipes or valves leading to minor leaking > oil level indicator not triggered	Oil leakage and moisture intrusion	Leaking - gasket	Gasket failed		

4 - Oil								
Insulation of all parts which are under voltage and transfer of heat	Oil does not satisfy the electrical characteristics: Breakdown voltage	Moisture > moisture absorption by paper > partial discharge > short circuit in windings > differential protection triggered	Moisture > moisture absorption by paper > partial discharge > short circuit in windings > differential protection triggered	Moisture > impaired breakdown voltage > partial discharge	Moisture - silica gel	Moisture and / or pollution	Failing air dryer	Saturated silica gel
5 - Cooling								
Conduction of heat out of the core / windings	Insufficient circulation of oil	Temperature in core & windings increases> alarm signal in control room > maintenance crew sent	Temperature in core and windings increases but remains under the alarm level	Temperature in core & windings increases> alarm signal in control room	Defective valves	Insufficiently open valves / valves		
6 - Bushing - 6.1. Capacitor type (high voltage side)								
Provide an isolated connection between the transformer windings and the cable termination	Short circuit between the transformer tank and the conductor	Short circuit > disconnection of transformer - loss of bushing - fire on the transformer -	Short circuit > disconnection of transformer - loss of	Short circuit > disconnection of transformer - loss of	Oil level impaired - gasket	Low oil level	Leaking gaskets	

		irreparable transformer	bushing - fire on the transformer - reparable transformer	bushing - fire on the transformer - corona effect		
7 - Protection and Signalling						
Disconnecting the transformer in case of too high oil flow from the tap changer to the conservator	Excessive flow is not or wrongly detected and / or transformer is not disconnected	Failure of the system at the time it is addressed > transformer is not switched off > transformer burns	Failure of the system at the time it is not addressed	Failure of the system at the time it is addressed	Protection relays	Failure protection relay tap changer or interruption in the trip circuit

Step 3: Failure Consequence and Risk Analysis

In general, this is the step where risk is linked to the traditional RCM analysis. In this step, the consequences of each identified failure mode is defined in two scenarios and the impact of each scenario is scored against the business values, see section 4.3.2. During this process, the failures are also classified into *hidden* or *evident* categories. The classification of whether the failure is hidden or evident is determined by answering the following question:

- Will the functional failure become apparent to the operator under normal circumstances if the failure mode occurs on its own?

If the answer on this question results in a *yes* the failure is evident, otherwise the failure mode will be categorised as hidden.

It was already said, earlier in this chapter (section 4.3), that the ranking tables for *occurrence, severity* and *detection* can be developed, particularly, for this risk linked RCM study. Existing risk management ranking tables can, alternatively, be used. The purpose of a risk linked RCM is to actually adopt as much as possible the definitions, ranking tables and criteria from risk management. Even though there is a risk model that is robust, nevertheless additional changes had to be made during the pilot. These additions were needed, because there were variables missing in the current model. A ranking table for the *occurrence* was required and a ranking table for the assessment of the likelihood of the consequences (impact). The ranking tables for *occurrence*, *severity* and *detection* are shown in the following tables.

Table 9 Ranking table with RPN calculation values for occurrence of the failure mode.

Occurrence Failure Mode		
RPN value	Calculation Value	Description
10	100	Certain (>=100x per year)
8	10	Highly Probable (10x per year)
7	1	Very Probable (1x per year)
6	0,1	Probable (1x per 10 year)
5	0,01	Possible (1x per 100 year)
3	0,001	Improbable (1x per 1000 year)
1	0,0001	Almost Improbable (<1x per 1000 year)

Table 10: Ranking table with RPN calculation values for severity of the failure mode.

Severity	RPN value
Very Serious	10
Serious	7
Minor	5
Minimal	3
None	1

Table 11 Ranking table with RPN calculation values for occurrence of the business values (likelihood on impact).

Occurrence Business Value	Calculation Value
Certain (1x per x)	1
Probable (1x per 10x)	0,1
Possible (1x per 100x)	0,01
Improbable (1x per 1000x)	0,001
Almost Improbable (<1x per 1000x)	0,0001

Table 12 Ranking table with RPN calculation values for detection.

Detection	RPN Value
Direct (e.g. signal to control centre)	1
Within half year	3
Within a year	4
Within 5 years	6
Within 10 years	8
> 10 years or not detectable	10

Step 4: Calculate Risk Priority Number for each Scenario and choose Scenario

This step uses the risk analysis calculation from step 3 to calculate an initial RPN value for each identified failure mode for both scenarios. Based on the outcomes, the scenario with the highest value of the RPN on a certain business value is chosen for further analysis firstly.

In order to demonstrate how the updated RPN formula is adopted together with the ranking tables to calculate an initial RPN, one of the failure modes is chosen to explain this. The chosen failure mode is the bushing. The functional failure of the bushing is caused by a lowered oil level due to an oil leakage. The reason for elaborating on the case is because the DNO experienced such a similar failure. This provided a realistic description of the consequences in case of a bushing failure.

Formula (2) and (3) must now be used to calculate the initial RPN for the failure of the bushing on this failure mode (described in table xx FMEA). The most likely scenario will be used to explain this procedure.

$$\boldsymbol{RPN_{most\ likely} = S_{ML\ (business\ value)} \times \left(O_{ML\ (business\ value)} \times O_{failure\ mode}\right)_{most\ likely} \times D} \quad \mathbf{(3)}$$

Together with the whole risk linked RCM team, the frequency of occurrence of this failure model is assessed, namely $O_{failure\ mode}$ from formula (3). For this purpose, the question is asked: “How many times in a certain lifetime interval they have experienced this failure mode”?

For the capacitor type bushing, it was found and agreed that such a failure mode is *possible* (meaning 1 time in 100 years). The actual failure had occurred after 30 years of operation and according to the ranking tables this corresponds to the category *possible*. Thus, from the ranking table of the occurrence of failure mode, the calculation value is extracted:

$$\boldsymbol{O_{failure\ mode} = 0.01} \quad \mathbf{(4)}$$

The description of the most likely scenario is extracted from the FMEA table and can be summarized as follows:

Transformer is switched off by protection, bushing is exploded, burn damage on the transformer, transformer repairable, no injuries (nobody present).

Subsequently, the impact on the different business values is assessed together with the likelihood of this impact. Due to redundancy and because no person was present, the financial business value turned out to be the highest. From the assessment, it was found that on the business value *finance* the impact was *very serious* (complete loss of bushing and fire on the transformer) and the RPN calculation value was extracted from the ranking table of the severity:

$$\boldsymbol{S_{business\ value} = very\ serious = 7} \quad \mathbf{(5)}$$

Along this line, the likelihood of this impact is assessed. According to the ranking table for the occurrence on business value, the $O_{business\ value}$ is extracted. This was assessed and found to be certain:

$$\boldsymbol{O_{business\ value} = certain = 1} \quad \mathbf{(6)}$$

Formulas (5) and (6) are combined to calculate the conditional occurrence and to extract the RPN value for RPN calculation.

$$\boldsymbol{O_{conditional} = 0.01 \times 1 = 0.01} \tag{7}$$

From the occurrence table used by risk management, 0.01 corresponds to a ranking RPN value of 5.

$$\boldsymbol{O_{conditional} = 0.01\ corresponds\ to\ RPN\ value = 5} \tag{8}$$

The final parameter is the detection value. For this, the question is asked: "How is this failure mode detected by the operator"?

For this failure mode, from the experienced failure, was found to be undetectable. There was no oil level indicator built on this type of the bushing and no signalling of oil levels to the control centre. Therefore, the detection RPN calculation value was extracted from the detection ranking table and was:

$$\boldsymbol{D = 10} \tag{9}$$

Using (6), (9) and (10), the initial RPN value for the most likely scenario is chosen:

$$\boldsymbol{RPN_{initial,most\ likely} = 7 \times 5 \times 10 = 350} \tag{10}$$

Likewise, the RPN value for the worst case scenario is calculated. The scenario with the highest RPN value is chosen. These previous steps have consecutively been applied to all the 65 identified failure modes for the power transformer.

Step 5: Rank and Prioritise Risk Priority Number, initial

For each identified failure mode, an initial RPN value is calculated. These values are ranked and prioritised against each other in order to have an overview of each failure mode against each business value expressed in terms of initial RPN values. In figure 27, the initial RPN results are given for this particular failure mode on each business value for both scenarios.

Figure 27: Initial RPN results for the most likely and worst case scenario for each business value.

Step 6: Task Logic

The next step within the risk linked RCM process is to assess the most appropriate failure management concept consisting of maintenance tasks in order to avoid or mitigate the failure mode or its consequences. This has been discussed in section 4.2.2.

Table 13 Simplified task logic results.

Failure mode(s)	Short circuit between the transformer tank and the conductor due to lowered oil level caused by leaking gaskets
Current maintenance/ inspection	none
New maintenance/ inspection	1 yearly visual inspection of oil level

Step 7: Risk Priority Number, revised

The appropriate maintenance tasks that have been identified in the previous step have the potential to either prevent, predict or neither of the previous two. Added to that, they can avoid or mitigate the consequences of a specific failure mode. An assessment of these maintenance tasks by calculating the RPN value in case these tasks had been implemented, results in a revised RPN value. Based on the identified maintenance task, the failure mode can be detected within a year, thus the *detection* value in the RPN calculation will change from 10 (not detectable) to 4. The results are shown in figure 28.

$$\boldsymbol{RPN_{revised,most\ likely} = 7 \times\ 5 \times 4 = 140} \qquad \mathbf{(11)}$$

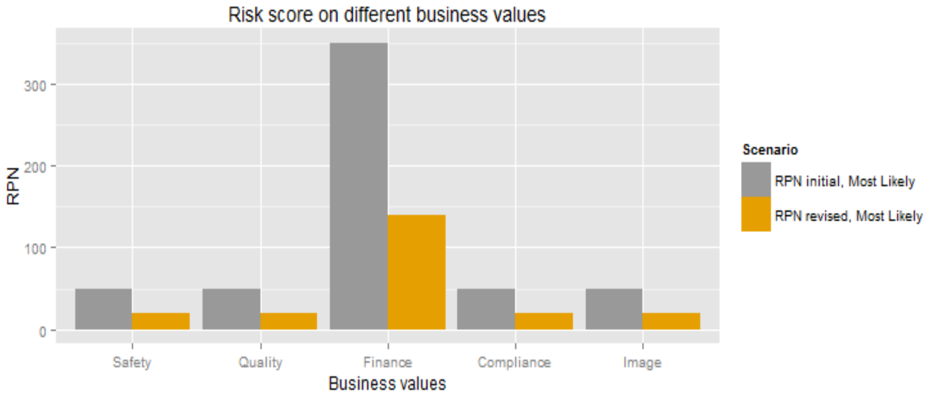


Figure 28: Initial and revised RPN results for the most likely and worst case scenario for each business value.

Step 8: Implement Task

On the basis of the differences between the initial and revised RPN, the effectiveness of a certain maintenance task can be assessed. An extensive review of different maintenance tasks has been performed. The reviewed documents are from CIGRE [61], [62], EPRI [63] and the manufactures specifications together with the utilities maintenance tasks. Based on this review three categories are made, namely: corrective maintenance, time based maintenance and condition based maintenance. For all the failure modes each categories revised RPN has been assessed and based on these results a risk based maintenance concept is advised. The detailed results are given in appendix C.

However, the implementation of a maintenance task that results from the risk linked RCM analysis requires additional considerations. The cost of the maintenance task plays an important part in the determination of which one is, ultimately, selected (e.g. yearly inspection vs. online condition monitoring). Moreover, other organisational aspects play a significant role, such as logistics, man-hours required for the tasks, personnel skills for executing the task, task interval selection (criteria for this).

In the long term, such comprehensive maintenance concept approaches will only achieve their objective with continuous improvement developments. In this context, it is of significant importance to monitor maintenance effectiveness and to adjust the risk linked RCM if/when needed. Existing failure modes and potential new ones should be reviewed and identified regularly as assets or operating conditions change. The ability to measure and report maintenance performance KPIs (chapter 3) forms the fundamental basis for continuous improvement.

In section 4.5.1 we mentioned a number of anticipated benefits that we would achieve with the case study experience. Here we evaluate them briefly:

- The reliability of the system (power transformer) will be increased by using more appropriate maintenance activities
    - With this case study applied on power transformers we have demonstrated that a mix of appropriate maintenance activities can be developed which can be assessed against each corporate business value.
    - Due to the long lifetimes of assets, such as transformers, it has not yet been quantitatively demonstrable how much the reliability is increased by adopting appropriate maintenance activities.

- Risk reduction vs. costs for a particular business value is assessed for each maintenance activity
    - With the developed Risk linked RCM method and case study we have demonstrated that RPN calculation for various maintenance activities can be studied for each particular business value. Based on the insight from the RPN analysis it will become possible to assess the costs vs. risk reduction.

- A full documented process is produced in which different organisational knowledge is conglomerated in a process that can be reviewed and revised in the future.
    - The case study has allowed the development of a fully documented process and its practical application. In doing this strategic, tactical and operational organisation information and knowledge has been conglomerated.
    - Most of this information is now well-documented in dedicated software tools and in-house tailor made spreadsheet models. These are all available and at the disposal of the responsible department and follow-up applications of this model.

- Maintenance managers have a management tool which enhances control and strategy

    - With the developed Risk linked RCM the maintenance department has an efficient tool that can be used to develop maintenance concepts with manageable risks. These risks are assessed against overarching business values and thus provide means to enhance control of maintenance from safety, environmental, legislative, financial and technical point of view. Not only the maintenance managers will benefit from this, but also the asset manager.

- The maintenance organisation obtains an improved understanding of its objective, purpose and the reasons for which it is performing the scheduled maintenance tasks.
    - Most of current maintenance activities are either manufacturer based or some form of preventive maintenance. From this case study we have experienced and found that reasoning from failure mode perspective and translating this effect to single business values in terms of risks has allowed for an improved understanding of the purpose of certain maintenance tasks in terms of added or non-added value to the overall performance of the asset. Moreover, we have found from this case study that there are significant differences between standard manufacturer maintenance activities (which are most of time based on extreme operation conditions) and operating environment specific developed maintenance activities.

4.6 Conclusions and outlook

4.6.1 Conclusions

In this chapter, a new risk-based maintenance methodology has been developed and presented. One of the recent emerging trends in electricity network companies is to incorporate the concept of risk into more operational activities such as maintenance management. This methodology is named the *Risk Linked Reliability Centered Maintenance* (Risk linked RCM). The method adopts risk management, as a calculated dimension, to make the link with the traditional RCM approach. In general, it builds on the fundamentals of the RCM method. In conclusion, the risk linked RCM have the following characteristics:

- The method is generalized and can be applied to different types of assets
- The methodology is linked to the corporate risk management model and principles
- The methodology can deal with differences in consequences of failure modes on multiple business values
- The developed method, followed from the case study is found to be a practical yet sufficiently accurate for risk-based maintenance management

The traditional calculation of the RPN has been expanded in order to ensure that the analysis of the consequences of failure modes are treated and assessed in a realistic way. We found that the traditional RPN calculation was not able to deal with the likelihood of a certain consequence due to a failure mode occurring.

Due to the multiple business values of different inherent nature, the analysis of consequences, in practice, should be dealt with and incorporated in the calculation. This has been introduced by expanding the traditional RPN calculation and making use of two scenarios for each failure mode. The expanded RPN calculation formula is:

$$\boldsymbol{RPN_{scenario} = S_{business\ value} \times \left(O_{business\ value} \times O_{failure\ mode}\right)_{scenario} \times D}$$

Moreover, it can be concluded that in the developed risk linked RCM methodology, the frequency of occurrence of a failure mode and the consequences of this failure mode on business values are currently analysed independently. This provides a way to calculate all risks associated to their failure modes and rank them against each other.

It is important to note, and to conclude, that the absolute values of the RPN themselves do not contain useful information. It is when the RPNs are compared to each other, that they become valuable. More importantly, they should be measured using the same scale and ranking tables.

The case study that has been described and worked out in this chapter has shown the applicability of the risk linked RCM method for practical purposes. A striking and beneficial aspect of the risk linked RCM is actually what has been found during the application in the case study:

- The proper initiation of the project and selection of participants is essential for a successful adoption of full scale risk linked RCM in the future

- A common notion of risk and the ability to objectively deal with occurrences of failure modes and consequences requires commitment, understanding and acceptance of the benefits of risk incorporation into maintenance management
- In order to deploy full-scale application of such comprehensive maintenance management concepts, management commitment, leadership and ownership is required to support the change that such paradigm shifts require, most importantly over a longer period of time.

On the whole, it can be concluded that with the adoption and application of the developed risk linked maintenance concept, maintenance can be based on risk analysis and can be expected to provide cost and risk effective maintenance. Such an approach will, inevitably, assist in preventing and predicting failure modes where possible and worth doing. In cases beyond this ability, the risk linked RCM approach also facilitates the minimization of the consequences of failures. Risk-based maintenance concepts can be applied to re-examine existing maintenance concepts by means of risk management decision-making processes in different stages of the lifecycle of the system or asset under analysis.

4.6.2 Outlook

In this chapter, the focus has been on the development of a maintenance management concept that, on a strategic level, would be able to incorporate the corporate risk management principles into maintenance management. The risk linked RCM process that has been developed, however, will require more probabilistic techniques in order to deal with probability of failures. In chapter 5, the usefulness of statistical Life Data Analysis (LDA) will be discussed. With the use of LDA, the proposed risk linked RCM methodology can be matured in the sense that the methodology will be more comprehensive through more quantitative risk analysis characteristics. This is necessary in order to have a more realistic quantification of risk factors, which is affected by the quality of the consequences study (this chapter) and the accuracy of the estimates of the probability of failures (the next chapter).

5 Statistical-Based Computational Tools for Maintenance Management

5.1 Introduction

5.1.1 Background

In chapter 4, a thorough analysis of risk-linked RCM model is described, which can basically be seen as a *Risk Based Maintenance (RBM)* model. Although the risk-linked RCM model encompasses a comprehensive integrated approach, it did not yet touch upon the computational tools that are required for objectively dealing with the failure behaviour of assets in the electrical power industry and the predictions of future failures in order to develop directed maintenance policies. Failure behaviour of assets can be approached in two ways: 1) through statistical-based analysis and 2) sensor-based condition monitoring. The former is discussed in this chapter and the latter is chapter 6.

In many situations, decisions in maintenance management are made under high levels of uncertainty. To deal with the uncertainties surrounding maintenance management, there is growing need for quantitative techniques and tools to seek for greater precision [64]. Depending on the knowledge that it is already known where and when precision is required, statistical methods are powerful tools. However greater precision is not necessarily required as a general trend. Nevertheless, in the power distribution sector the application of predictive methods is in its early years, mainly driven by the forward looking regulation method in this sector. In this chapter, we will specifically elaborate on the statistical methods for analysing failure behaviour of assets and their uncertainties. The failure behaviour of an asset in the power grid is modelled based on available lifetime data of populations of assets. Predictions of future failures are made using these developed models. In this chapter, we will introduce the basics of statistical *Life Data Analysis (LDA)* and its relationship with decision-making in maintenance management.

5.1.2 Outline of the chapter

In section 5.2, the procedure for LDA will be described explaining the important steps to consider when preparing its application for practical purposes. Data collections, databases and requirements are described with the focus on practical implications. In section 5.3, a practical case study where LDA has been used is presented. In section 5.4, conclusions are made and an outlook for the way forward is given.

5.2 Statistical Life Data Analysis

5.2.1 Statistical failure distribution

In general, each asset has a specific function within an overall system. According to the definition for reliability, an asset (or item) has the ability to perform a required function under given conditions for a given time interval. Usually, this ability is denoted in terms of probability to fulfil the required function within a determined level of performance.

A failure is the situation where the probability of functioning is outside this level of performance. In this context, the central theme in LDA is to mathematically determine the failure distribution as a function over time. From the derived mathematical functions of the statistical distribution, conclusions about the current and future failure behaviour of a population of assets can be drawn. After these conclusions have been drawn, maintenance and asset management decisions, such as when to replace, inspect or maintain given a certain criteria can be made. The method that is described here, namely *Statistical Life Data Analysis*, includes several subsequent steps beyond LDA. Broadly outlined, these steps are:

1. Specific selection of assets or asset groups (populations)
2. Collection of detailed information about the number and age of installed and failed assets or components
3. Use of the statistical goodness of fit test for finding the best fitting statistical distribution
4. Use of the derived statistical failure distribution to extract information about the reliability and failure rate behaviour of the assets in order to support asset and maintenance management.

Asset failure parameters vary from component to component or from situation to situation. Such parameters are denoted as *random parameters*. Random parameters are represented by *probability distribution functions*, also known as *failure distributions* [65]. Failure distribution functions are mathematical equations allowing a large amount of information, characteristics and behaviours to be described by a small number of parameters.

Often, failure distributions are defined by statistical functions such as *probability density function (pdf)*, the *cumulative distribution (cdf)*, the *reliability function (R)*, and the *failure rate function (λ)*. The *failure rate* is a concept that is very important in maintenance and reliability context. The failure rate represents the number of failures in a given interval of time, with respect to the number of units being still in operation at the beginning of the interval [66], [67]. The relation of these often used statistical functions is graphically shown in figure 29. In

Appendix D the mathematical equations for the above mentioned statistical functions are given.

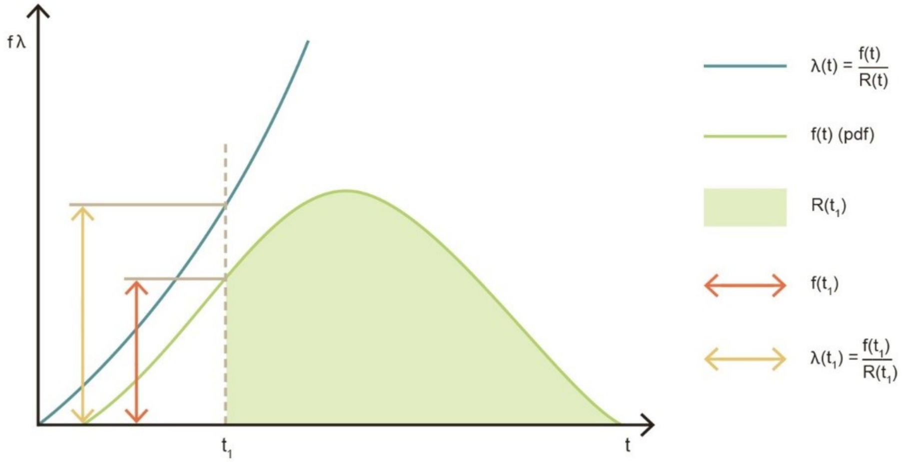


Figure 29: Shows a graphical representation of the probability density function (pdf), the cumulative distribution (cdf), the reliability function (R), and the failure rate function (λ) [67].

Throughout the literature, many different statistical probability distributions can be found [65]. Some of these distributions do better represent life data and each one of them has a predefined form of *pdf*. Some commonly used failure distributions are [65] Normal distribution, Log-normal distribution, Exponential distribution, Weibull distribution.

5.2.2 Parametric Distribution Fitting Procedure

The previously mentioned failure distribution assumes statistical distribution and this method is widely known as *parametric distribution fitting method*. An alternative method is the *non-parametric method*. More detail can be found in [65].

Typically, by using the parametric method, the information associated with many data point (failure data, failure mode analysis date, etc.) can be reasonably modelled with one of two parameters. This parametric method will be used for the LDA. Parametric distribution fitting comprises a number of steps and a straightforward procedure is shown in figure 30.

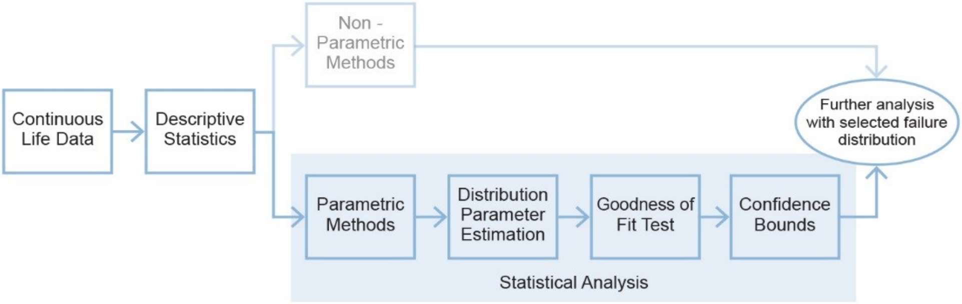


Figure 30: Parametric distribution fitting procedure for statistical life data analysis.

In summary, the procedure steps for parametric distribution fitting are:

1. Data collection and preparation
    - Complete data (all units have failed)
    - Censored data (not all units have failed)
2. Distribution parameter estimation
    - Probability plotting
    - Rank Regression
    - Maximum Likelihood Estimation (MLE)
3. Goodness-of-fit Test
    - Visual inspection
    - Correlation coefficient
    - Likelihood Value
    - Other methods, Kolmogorov-Smirnov test, Anderson-Darling test etc.
4. Confidence bounds

Detailed description of these individual steps can be found in [66], [68] [69], [70] [71].

5.2.3 Data Collection

Statistical failure distribution models rely on the data i.e. *life data* and *time-to-failure* of a component, to make predictions. The accuracy of any prediction is directly dependent on the quality and completeness of the supplied data. The combination of complete data and appropriate model choice will usually result in acceptable predictions depending on the goal and application for which the predictions are intended.

Typical for life data is that failure data is classified as a failure while the un-failed components (in-service data) are classified as suspended data. Suspended data means that the units are still operating at the time the reliability of these units is to be determined. Life data is gathered during the whole life of a technical component, starting with the installation and ending with its disposal. Furthermore, collected life data for statistical analysis should have the following properties [67], [70], [66], [71]:

- Randomness
- Independency
- Homogeneity
- Sufficient amount of data

In the analysis of life data it is deemed advisable to use all available data. In practice, however, it is hard, expensive and sometimes impossible to collect all required life data. Therefore usually, the available data is incomplete or includes uncertainties as to when a component failed or was installed exactly. To adequately interpret this, life data can be separated into two categories [71]:

- Complete Data (all units have failed)
- Censored Data (not all units have failed)

Complete Data – Complete data is used when the value of an observation is known completely. For example, if the time-to-failure for a cable joint population with 200 units is observed and all 200 units have failed (and the time-to-failures has been recorded), then the complete information as to the time of each failure is known. It goes without saying that processing complete data is much more efficient and easier than censored data.

Censored Data – Censoring occurs when the value of an observation is only known to some extent. Censored data is often encountered when analysing practical life data, especially in case of electrical power systems where the majority of installed equipment is still in-service, and usually the exact age of equipment at the moment of failure is unknown. Three censoring schemes are possible:

1. Right-censored data (suspended data): When a data set is composed of components that did not fail, it can be referred to as right-censored data or suspended data. The term "right-censored" indicates that the event is located to the right of the data set, which implies that certain components are still operating.

2. Interval-censored data: This reflects uncertainty in the exact times the equipment failed or exact age of an equipment upon failure. Interval data is often encountered in asset related databases when components are not constantly monitored.

3. Left-censored data: This censoring scheme is a special case of interval-censored data. With left-censored data the time-to-failure for a particular component is known to occur between time zero and some inspection time.

5.3 Case study: Application of statistical life data analysis for medium voltage power cables joints

In this case study, the parametric distribution fitting method as described in section 5.2 is applied to large populations of 10 kV cable joints with the aim of obtaining an indicator of the future failure expectancy. This case study is based on [68], [69], [70] and [71].

5.3.1 Medium Voltage (MV) Distribution Network

The medium voltage (MV) infrastructure in the Netherlands is almost 100% realized by means of underground cable systems (approximately 100.000 km). Historical data indicates that the most dominating component related failures (85%) are observed for MV cable systems. A cable system consists of a cable part, cable joint and cable termination. A vast majority of the distribution grid outage times is due to failures in MV cable joints (45%). A case study for the application of statistical life data analysis was carried out for a particular region of 10 kV distribution network of Stedin. Three types of 10 kV cable joint populations were investigated. The three categories are according to the used joint insulation:

- Mass insulated joints (liquid mixture of oil and resin)
- Oil insulated joints
- Synthetic insulated joints

Different insulating materials have different ageing mechanisms, which should be taken into account when performing statistical studies (homogeneity). The number of 10 kV cable joint failures resulting in power delivery outages in this region is high compared to other regions. The available population and failure data for this region was significantly more complete, which makes it appropriate for statistical analysis.

5.3.2 Available 10 kV Cable Joint Data

Failure Data Collection: Paper-based outage (failure) data recording started, partly, around 1976 in the Netherlands, followed by a database collection tool in 1991 named *"Kema Nestor"*. At the time that this case study was performed, the available MV failure data for the period 2004 until 2009 had been consistent and could be used in a viable way. The development of failure data recording is shown in figure 31.

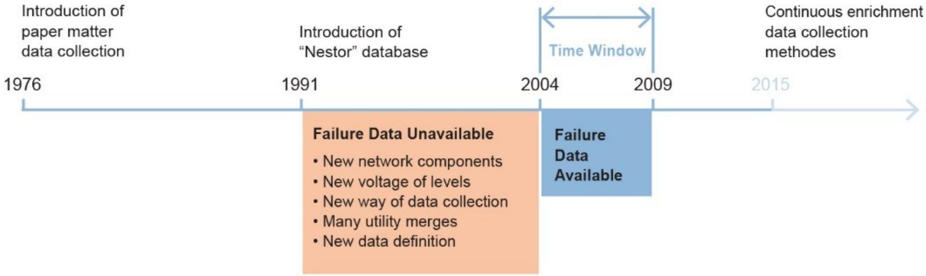


Figure 31: Timeline showing the availability of failure data in distribution network for this study. This time window reflects the period where failure data is available. In between, failure data is often missing or incomplete.

The available failure data takes into account roughly 556 reported cable joint failures, within the last 6 years. It often happens that the exact age of the cable joint at the moment of failure is unknown to the utility. To be able to take these incomplete data into account, estimated age intervals for the reported failures are used to tackle this issue. This is shown in figure 32 for the three categories of cable joint populations.

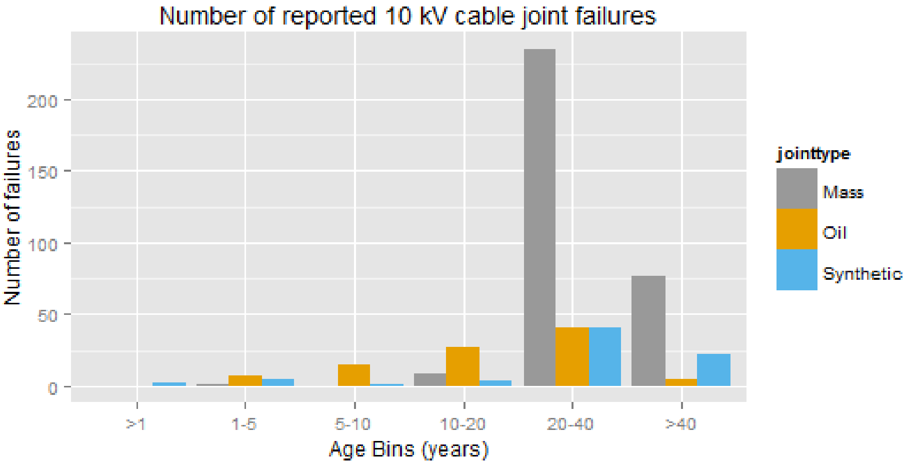


Figure 32: 10 kV joint failure records for the period 2004-2009 for three categories of cable joints. As result of unknown exact age at the moment of failure of a component, age intervals are used to estimate the age of the failed components.

In-service Data Collection: Besides failure data, information regarding the un-failed cable joints is used. The total recorded population of all three types of cable joints is roughly 32000 pieces. During this case study, two issues with missing and incomplete data had to be addressed. Firstly, for large portions of the joint population, the exact *age* (year of installation) is not specified or unknown. Such records are often missing for assets that were installed more than 20 to 30 years ago. Secondly, for some parts of the cable joint population, the corresponding *joint type* is unknown. The first shortcoming is addressed by dividing the number of joints without age, proportionally, and adding these joints to the joints installed in particular years (conceptually shown in figure 33). The formula developed for this procedure is:

$$New\ \#\ of\ joints_{age,i} = \left(\frac{recorded\ \#\ of\ joints_{age,i}}{total\ \#\ of\ joints\ with\ age} \times Total\ \#\ of\ joints\ without\ age\right) + recorded\ \#\ of\ joints_{age,i} \qquad (12)$$

The second shortcoming is addressed by using information, based on expert knowledge, regarding the historic application of certain joint types. These experts still have knowledge of the history of when a certain type of joint was taken into operation (conceptually illustrated in figure 33). As a result, it was possible to make rough estimations of the missing records and incorporate these in the statistical analysis.

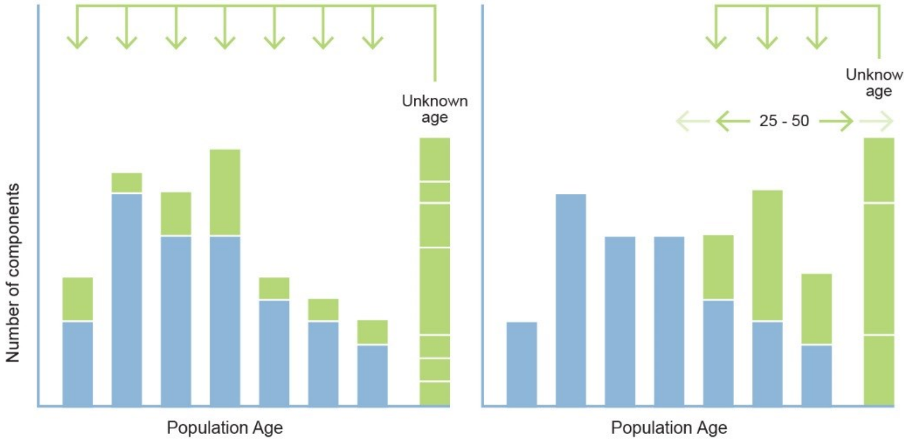


Figure 33: Simplified impression for the estimation methods which are applied to incorporate the missing data (missing asset installation year). The blue histograms illustrate the population of which the year of installation was known, while the green histograms illustrate the portion of the population of which the exact year of installation was not known and how it was incorporated into the known part.

5.3.3 Application of Parametric Distribution Fitting

The available failure data and in-service data of the three types of cable joint populations were used as input. For the statistical calculations, the software tool *Reliasoft Weibull++* was selected. Based on a) this statistical analysis of the available life time data and b), not to be neglected, engineering knowledge, the corresponding failure distributions (probability model) are selected. Basically, the next straightforward steps cover the procedure for life data analysis:

1. Failure and in-service data collection and preparation for statistical analysis
2. Failure distribution parameter selection
3. Goodness-of-fit tests (used to diagnose if the fitted statistical distribution matches the data)
4. Confidence bounds (is used to indicate the estimated range of values which are likely to include an unknown population parameter)
5. Selection of the best fit (selected failure probability model)

It should be mentioned that for step 2, the Maximum Likelihood Estimation (MLE) method for parameter selection is used. MLE has the ability to take into account large numbers of suspensions (explained in chapter 5) and large data sets. It is reported [60] that MLE is asymptotically consistent, which means that as the data sets increase in size, the estimates converge to the true value.

Results for 10 kV Cable Joints: The failure rate (*λ (t)*) and probability density function (*pdf*) allow different assets to be compared with other. In figure 34 and 35, the *pdf* curve and the failure rate curve are shown, respectively. From figure 34, the density of failure probability can be examined for the three different cable joint groups. The peak value of the *pdf* curve for the synthetic insulated cable joint (green) is higher than the remaining ones. Typically, this implies that synthetic insulated cable joints have a higher probability of failure when the components age is near the peak value (mean life).

From figure 35, it can be seen that the failure behaviour is different for each population of cable joints. For all three populations, their failure rates rise over years according to the increasing right wing of the bathtub curve. Additionally, it can be seen that the populations' age quite similarly, however, the rate of rise of the failure rate as a function of equipment age differs from each other (figure 35). Subsequently, the failure behaviour of oil insulated joints (red line) and of mass insulated joints (blue line) differs from each other.

The most likely reason why the failure rates for the oil insulated cable joints are higher is due to lowered liquid levels in the oil type joints. As mentioned in [72], a lowered liquid level in joints filled with viscous material is often due to thermal heat cycles as result of daily load cycles. Basically, lowered liquid levels result in reduced electrical breakdown strength of the component, which sooner or later will lead to electrical discharges and may finally lead to breakdown of the component.

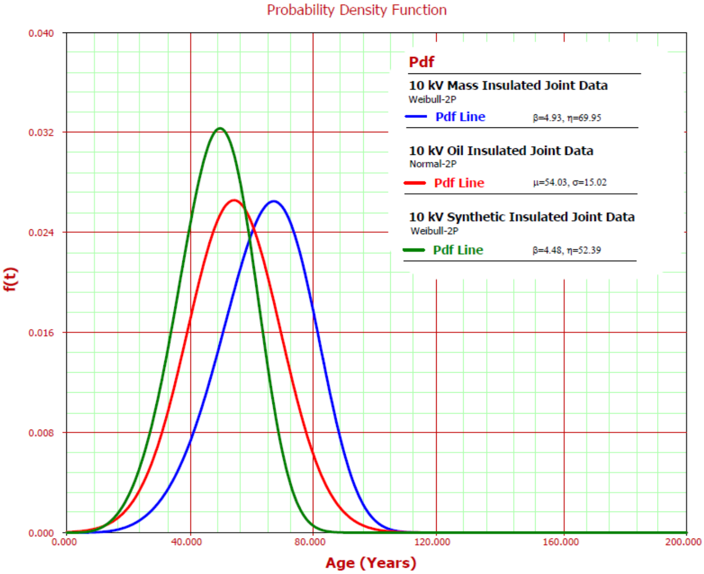


Figure 34: Probability density functions (pdf) for three different types of 10 kV cable joints

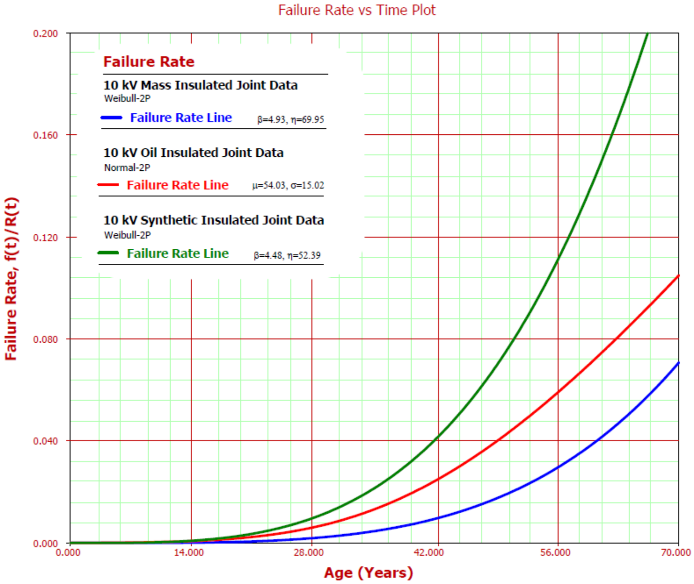


Figure 35: Failure rate curves for the three different types of cable joint populations.

Sensitivity Analysis: For the case of synthetic insulated cable joints, experts at the DNO indicated that the cable joint failures, which are reported in the age intervals [20-40] and [>40] years (see figure 36) are probably failures of 10 kV resin joints that were installed in the 1970's. These resin joints, often referred as *"Nekaldiet"* joints, have resulted significantly to outages in the past years, however, are not applied anymore and replaced as much as possible. Consequently, a sensitivity analysis was performed, using the calculated failure rates, to assess the failure behaviour of synthetic cable joints without the suspect *"Nekaldiet"* failures.

After consulting experts at the utility, it was agreed to exclude all failures which were recorded in the age bin [>40] years and a number of failures from the age bin [20-40] years. Likewise, the in-service data was adjusted. These considerations were based on the viewpoint that *"Nekaldiet"* joints were installed a few decades ago and, therefore it was very likely that this group of synthetic joints had operated sufficiently to have reached ages higher than 20 years. Two scenarios were analysed, in which failure data points were removed as follows:

- All failures from age bin [>40] year and 10 failures from age bin [20-40] year
- All failures from age bin [>40] year and 20 failures from age bin [20-40] year.

The calculated failure rates, according to the best fit failure distribution (Weibull), are shown in figure 36.

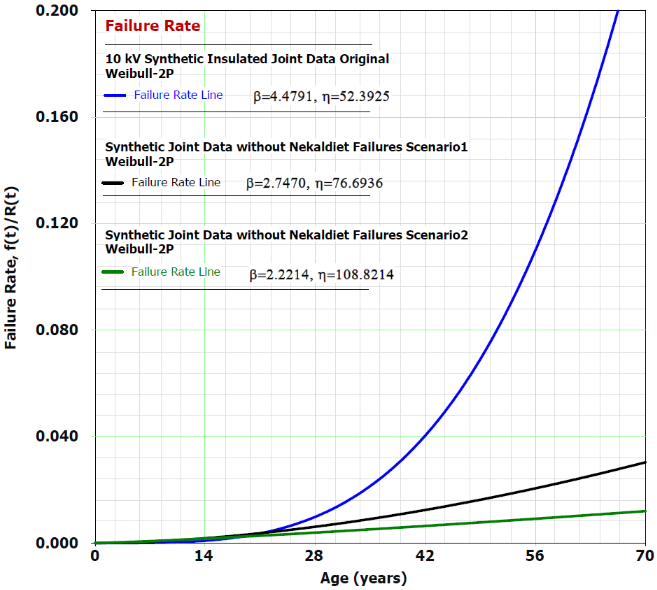


Figure 36: This figure shows the failure rate plots for three subsets of life data for synthetic insulated cable joints. The blue failure rate plot represents the original data record, while the black and green failure plot represent scenario 1 and 2, respectively.

From figure 36, it can be found that the failure rates are considerably lower for the synthetic joints when the suspect *"Nekaldiet"* failure records are excluded from the statistical analysis. Therefore, we may reasonably conclude that the suspect *"Nekaldiet"* failure records negatively impact the overall failure behaviour of the synthetic insulated joint population. More specifically, the asset manager can justify, based on these results, that replacing aged *"Nekaldiet"* cable joints, or applying condition monitoring or inspections to cable feeders with these types of joints, can be a feasible strategy to mitigate future failures as part of the maintenance concept.

5.3.4 Asset Management and Maintenance Decision-Support

Aspects, such as failure probability and future failure expectancy form the basis for asset management activities such as maintenance and replacement strategies. Knowledge and information of these aspects can contribute to the decision process. With the results of the statistical analysis from the previous section, information regarding the failure probability and the failure frequency at a certain age of asset groups in the near future can be extracted. Three possible supporting tools for asset managers which can be used for maintenance management are discussed here. These are:

1. Predicting future cable joint failures
2. Failure count diagram
3. Percentile Life

Predicting future failures: Predicting future performance is a very important objective from an AM viewpoint. For this case study, future failure predictions for all three types of investigated 10 kV cable joints are calculated. The failure predictions are shown in figure 37 for the synthetic cable joint population.

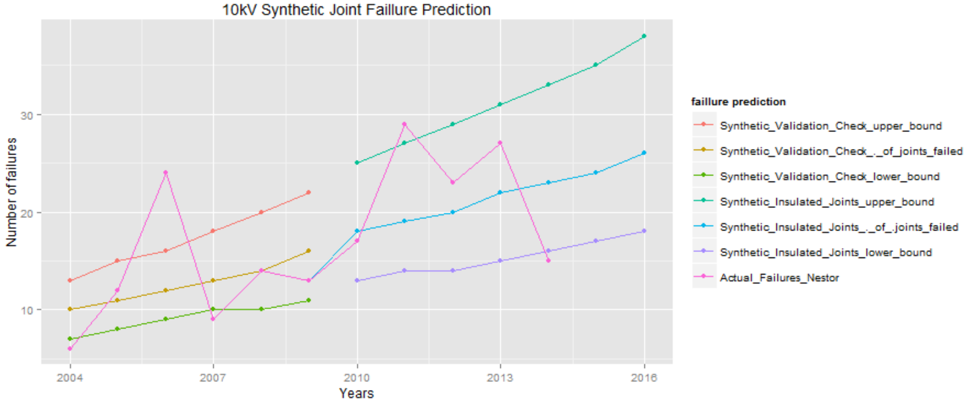


Figure 37: Estimation of the number of total expected failures for the coming six years for 10 kV synthetic insulated joints. The red line gives the number of predicted failure starting at 2010 until 2016. In the period 2004-2015 the actual number of failure (purple line) is compared to the estimated number of failures for that period. The results of a fictive 5% replacement of oldest joints in the years 2010 and 2011 are indicated with the brown trend.

From figure 37, it can be seen that the estimated number of failures (green line) based on the analysis are comparable with the actual number of failures in the period 2004-2009. Therefore, we can conclude that the computed failure rate model reasonably describes the failure behaviour of the considered population. The computed failure rate model for the synthetic joints is used together with the population of 2010 to predict the number of failures in that particular year.

For 2010, a number of 18 failures are predicted with a variation between 13 and 25 when taking into account the respective 90% lower and upper confidence bounds. From this point on, for every next year, the ages of the remaining population of joints are made one year older. Simultaneously, the estimated failures from the previous year are subtracted from the population. It is also taken in account that every joint failure introduces two new joints. With this information, the asset manager can determine whether the expected numbers of future failures are acceptable, or, whether structural replacement is necessary in the coming years.

To illustrate the powerful use of statistical computed models, we have assumed a fictitious replacement of the 5% of the oldest cable joints with the highest risk failure in the years 2010 and 2011. In figure 38, the yellow trend line shows the effectiveness of such a replacement strategy on the future failure expectancy. In the same vein, a condition based maintenance policy can be assessed on its overall effectiveness on the future failure behaviour.

The previously shown predictions were performed in the year 2010 with the aim to forecast the failure expectancy within the coming 5 to 6 years. We have used actual recorded failure data from 2010 until 2014 to verify the accuracy and whether the predictions make sense. This analysis has been performed in 2014 and the results for the synthetic insulated cable joint population are shown in figure 38. We have found from this updated analysis that the actual recorded failures for 10 kV synthetic cable joints from 2010 to 2014 fall reasonably well within the confidence bounds of the predicted number of failures. This shows the usefulness and potential for applying statistical based predictions for mid and long term asset failure behaviour in asset and maintenance management.

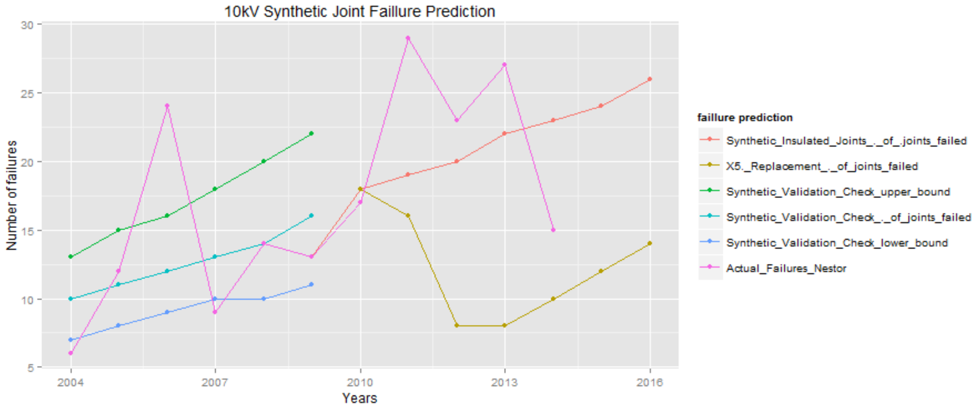


Figure 38: Estimation of the predicted number of total failures from 2010 until 2016 for 10 kV synthetic insulated joints. The red line gives the number of predicted failure starting at 2010 until 2016. The bar diagrams show the actual recorded number of failures from 2004 until 2014.

Similar studies have been done for the oil and mass insulated cable joints and the results can be found in [70] [71] [68] [69].

An interesting finding was the ability to use the computed statistical distributions as a means to extract uncertain or unknown data. This was the case, for example, with the 10 kV mass insulated cable joints. For the mass insulation cable joint population, the future predictions and historic validation were not, in the first place, agreeable. It is worth noting, that for almost 60% of the mass joint population, no exact installation year was specified in the databases. These incomplete datasets were taken into account as described earlier (figure 33).

In order to assess whether this first estimation, regarding the 60%, might be an improper estimation, a number of new estimations were examined. In a second attempt, the 60% of data was not divided proportionally, but according to a certain age interval, as shown in figure 33. The main reasoning behind this second attempt was based on experts' opinions, who indicated that mass-insulated joints were mostly used a few decades ago. Thus, it was likely that the missing 60% data should be of a population which is older than roughly 20 years. Therefore, this 60% was proportionally divided in various age intervals, satisfying this assumption. Different scenarios were used namely; age intervals of [20-30], [20-40], [25-50], etc. The expected future failure outcomes for the interval [25-50] years were most in accordance with the actual occurred failures in the period 2004-2009. In figure 39, two scenarios (black and blue plot) are illustrated together with the actual recorded number of failures (red plot).

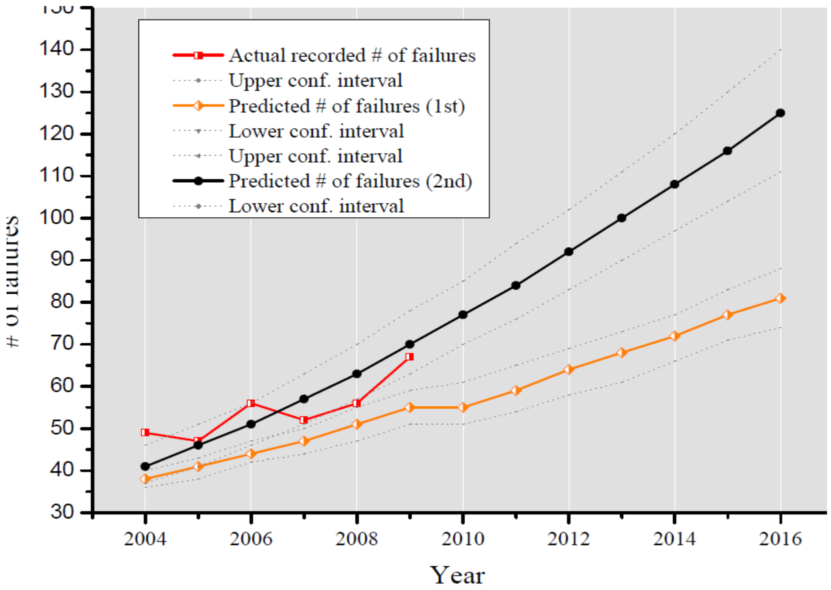


Figure 39: This figure shows the failure prediction for the mass insulated joints together with the corresponding 90% confidence intervals. The blue plot represents the first case (60% of missing data is estimated proportionally), while the black plot indicates the second case (60% of missing data is estimated using specific intervals, based on expert judgement).

Under these circumstances, it can be concluded that based on the analysis, it seems that the population of mass-insulated joints without recorded installation year (60% of the population) are older than 25 year. However, it should be noted, that these assumptions are based on the available data at the moment of the study. Another way of reasoning might reveal that there might have been more failures of mass-insulated joints in the past, of which the records are missing, and therefore the failure rates obtained here could be conservative values. Whether the mass-insulated joint population is of an older age category or the numbers of failures in the past are higher, in either case, the asset manager now has more knowledge on the failure behaviour of the mass-insulation joint population. With this information, the asset manager can determine if the expected numbers of future failures are acceptable or whether structured replacement or pin-pointed condition monitoring is necessary in the coming years, as part of the AM strategic and operational policies.

Failure Count Diagram: With a failure count diagram, it will be possible to assess the impact that typical increasing failure rates have on the installed equipment base. In practice, it is usually encountered that utilities do not know the exact age of a component at the moment of failure, and thus make estimations of the age in the failure records. With the failure count diagram, it can be calculated, in relative terms, how many components of an installed population of a particular age contribute to failures [73]. The failure count diagram for the synthetic insulated cable joints is shown in figure 40.

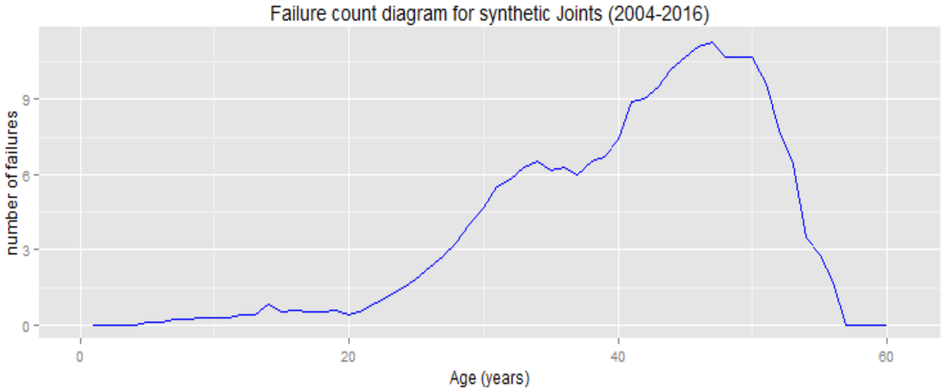


Figure 40: Shows the total number of failures occurring each year for the synthetic insulated cable joints. The maximum is reached at age 47, when the combination of high failure rate and high number of remaining units peak.

When considering the failure rate curves shown in figure 34 and 35, it can be seen from the failure count diagram (figure 40) that failures in intermediate years (between 30 and 60 years) are the real cause of the system reliability problem. More than half of the failures occur in the range of 21 and 51 years. The very old cable joints (older than 50 years) indeed have a higher failure rate, however, most of the time, their number is too low to generate a high total failure count. The failure count diagram is a representation of the relative contribution to failures of synthetic joints as function of their age. This diagram can be seen as an important tool in managing reliability, maintenance and replacement policies. Similar analyses have been performed for the oil and mass insulated joints, showing that each population have unique failure count behaviours.

Percentile Life: The *B-life* or *percentile life* gives the estimated time when the probability of failure will reach a specific point. For instance, if 10% of the cable joints are expected to fail by 15 years of operation, then, it can be stated that the B (10) life is 15 years. The value of the B(x)-lives can assist the asset manager in establishing which level of reliability is acceptable and at which age this level of reliability is reached, implying that maintenance or replacement is necessary. In table x, the B(x)-lives are shown for synthetic insulated cable joints.

Table 14: B(x)-lives of synthetic insulated 10 kV cable joints. The corresponding upper and lower 90 % confidence bounds are also listed.

	Synthetic Insulated Cable Joint Population		
	Component Age (year)		
	90 % Bound	*B-life*	*90 % Bound*
B(1)-life	17	**19**	21
B(10)-life	30	**31**	33
B(25)-life	38	**40**	42
B(50)-life (mean life)	45	**48**	52

With the statistical information from table 14, the asset manager can assess and compare the reliability. Additionally, the B(x)-lives can be used to assess how many cable joints are actually older than a certain chosen B(x) level. The level of B(x)-life which the asset manager can choose for a certain population of component, depends on the network type, component, impact of failure, failure mode etc. If, for example, the asset manager is interested in getting to know how many cable joints of each population are older than the B (10)-life, then the calculated B (10)-life together with the in-service cable joints can be used for this.

5.4 Case study: Application of Monte Carlo Simulation (MCS) to Support Risk-based Decision-Making

In the previous case study, the failure distribution models for three types of cable joints were computed using statistical methods. The results from that case study are especially useful for decision-making regarding those particular asset groups. In this case study, the results from the previous case, are used together with additional failure rate data of cables to analyse a real medium voltage network part. The analysis in this case study encompasses an application of *Monte Carlo Simulation (MSC)* for risk-based decision-making in asset management. Detailed descriptions and results of this study can be found in [74], [75], [76]. In general, the MCS is a probabilistic method for risk assessment which can provide results in the form of probability density functions. Using simulations, MCS performs a series of experiments on the studied system. The MCS generates complete probability distributions of random variables and can reproduce the systems random behaviour. This is possible because of its ability to involve the variability of input parameters. More information can be found in [77].

5.4.1 10 kV sub-network of Stedin with 12 radial feeders

The MCS is applied to investigate failures in these radial feeder systems could have been predicted. In order to do this, the MCS simulation is first started in an earlier year 2005 and simulated up to 2013 (mission time of 9 years). By doing this, the predicted number of failures for the 12 radial feeders is compared to the actual number of failures. In this case study *cables* and *cable joints* are modelled, using MATLAB, for the 12 feeders. The failure behaviour of these components (time-to-failure) are used as input for the MCS. For the cable joints, the probability functions from the previous case study are used and for the cables historic data of Stedin is used to extract the failure rate. In the table 15 a summary of the input data is given.

Table 15: The parameters of the probability distributions for 10 kV cables and cable joints at starting year.

	Assumed probability distribution	**Parameters**
PILC cable	Exponential	$\lambda = 0.0702$
XLPE cable	Exponential	$\lambda = 0.0021$
Oil-filled joint	Normal	$\mu = 54.03$ $\sigma = 15.02$
Resin-filled joint	Weibull	$\beta = 4.93$ $\eta = 69.95$
Synthetic joint	Weibull	$\beta = 4.48$ $\eta = 52.39$

In order to customize the probability distributions for the cable joints (to normalize them to the starting year) the general probability distributions are left-truncated at the starting year of the simulation. The algorithm of the MCS can be found in appendix E.

Results of the MCS: The results of the 12 investigated feeder systems, are shown in a Box-and-Whisker plot in figure 41. From figure 41, it can be seen that all the actual number of failures were, correctly, included in the predictions of the MCS. Therefore, we can conclude that the MCS is able to predict future failures for network systems in a reasonable way using probabilistic input data. However, from figure 41, it is also clear that the actual occurred outages have very different probabilities of occurrence as predicted through the MCS. The 90th percentile of the predictions indicates an event with the probability of occurrence of less than 0.1 and these events are labelled as extreme events. From the results of the MCS of the feeder systems in a sub-network of Stedin, 33% of actual failures occurred with a probability of less than 0.1. It could be that other aspects are influencing the occurrence of failures (for example other failure causes). This still needs further investigation. These extreme events are further analysed by investigating the influence of the cable length, the number of joints in the feeder systems, the soil type and the average component age.

From this analysis, it is found that these factors indeed have an influence on the occurrence of extreme events. The result of the analysis was that systems with cable length larger than 10 km, systems with more than 50 joints and systems installed in peat soil are more likely to encounter extreme events. Furthermore, the higher the average components age in the feeder system is, the higher the probability of extreme events will be. From these results, it is clear that other factors influencing the behaviour of the system should be included in the way the MCS results are interpreted.

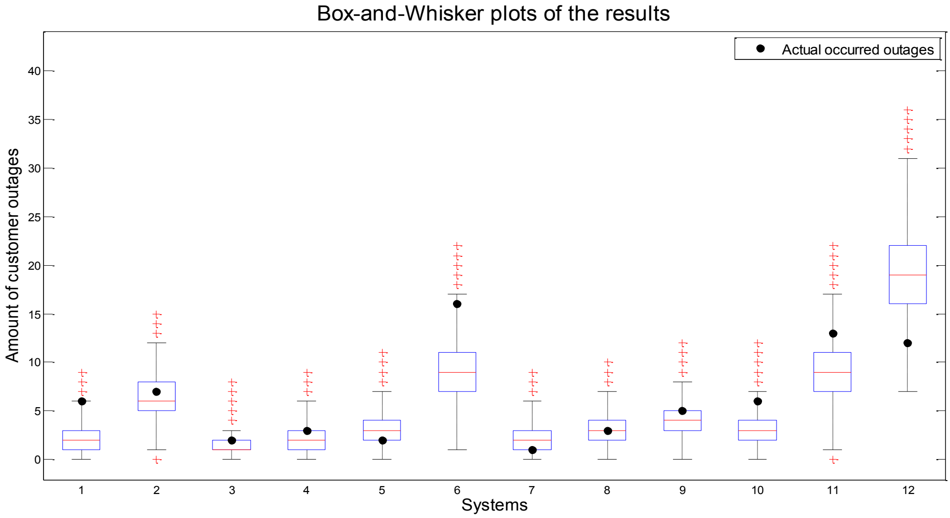


Figure 41: Box-and-Whisker plots of the results for the MCS of the 12 systems in comparison with the actual occurred amount of customer's outages. For 7 systems, the actual occurred outages fall within the interquartile range (IQR), defined by the box. The actual occurred outages of the remaining 6 systems fall within the whiskers, representing rare events. All the actual occurred outages are captured by the probability distributions of the predicted customer outages through the MCS.

In summary, the goal of this case study was to prove the applicability of MCS for risk-based decision-making aspects within asset management. With the ability to predict sub-system failure behaviour and find expert judgements for rare or extreme outcomes, the maintenance organisation can act accordingly by developing dedicated mitigating strategies. As mentioned earlier, the MCS case study presented here is part of a larger study and more details and results can be found in [74].

5.5 Conclusion and Outlook

5.5.1 Conclusions

The content of chapter 5, namely the ability to statistically describe the failure behaviour of assets and systems, forms the prerequisite for maintenance management, reliability predictions and total lifecycle analysis. Due to the growing need for computational tools for risk management, statistical methods are required to be made more applicable for real-life purposes. In this chapter, however, the statistical life data analysis has been application oriented. Furthermore, we have showed that failure data and in-service data of assets, when captured and stored, can reasonably be used to compute statistical failure distributions. In chapter 4, an extensive framework was developed to link the asset failure causes through risk management business values to RCM. This, together with the ability to statistically predict failures forms a powerful computational tool in maintenance decision-making. The statistical computational tools that are discussed in this chapter are, thus, complementary for the risk-linked RCM model that was previously developed in chapter 4.

Statistical Life Data Analysis: From the case study with the application of statistical life data analysis, we have found with the currently available lifetime data and appropriate applied statistical procedures that the failure probability and failure rate functions can be reasonably obtained. We found that the advantage of statistical life data analysis is the ability to describe for a large population of assets with different ages and other characteristics a small number of statistical parameters. These parameters, in turn, can be used to extract valuable asset and maintenance management information regarding failure behaviour, future failure expectancy, failure count diagrams and B-lives.

Monte Carlo Simulation: On a system level, we have found that the exploitation of the previously calculated failure distributions supports implementation in the MCS and provide information about the probabilities of outages in the feeder systems. From the case study, it was found that with the application of MCS, it was possible to probabilistically predict the actual occurred failures within the 12 feeders over the mission time (9 years of simulation time). Moreover, when risk mitigating measures, as part of investment or maintenance policies, are chosen, the effectiveness of these can be analysed through rerunning simulation of the systems.

Generally speaking, electric network assets normally age when in service, therefore, in due course, these assets will be characterized by increasing failure rates and result in higher costs more maintenance, repair, replacement or consumer costs for degraded performance. Current approaches or either reactive or preventive (without adequate predictive or risk management policies) and therefore not completely able to address the fact that the failure rates will rise in the future. With the application of more and more probabilistic (statistical) computational tools DNOs will have the ability to predict failures and direct the decision-making regarding replacements, maintenance and cost-effective budgets plans more accurately with a predictive nature.

Through our experience with the application of statistical computational tools, we also have to mention some shortcomings of such models. We have listed them here:

- Firstly, statistical results are, in general, based on the use of the mean values as the measure of central tendency. If the deviations of these mean values are large, then the probability of ascertaining the failure rates and resulting maintenance management needs with accuracy is decreased. This is usually the case with normal distributions. In the case of Weibull distributions, the failure distribution considered the first failure (fails according to the weakest link) and basically the issue with the mean values is not applicable.
- Secondly, with statistical application the homogeneity of the data is assured, such as constant operating conditions, hours of operation and other relevant environmental aspects. Nevertheless, in practice, these aspects are not always homogenous and may change, which might influence the accuracy of statistical results. Even though this is possible, recent research [67] found that the variability due to inhomogeneity (variable loads) does not influence the (average) statistical results significantly, given their application for large population analysis. In fact, this previous research and also our experience learns us that DNOs most of the time still tend to use past experiences and gut feelings for arguing failure rate changes. With statistics they, to a small extent, have more facts and figures available for describing the failure behaviour of these populations.
- Lastly, the lack of credibility of collected data may negatively affect the perceived usefulness of statistical results. Data that is incorrectly recorded, unrecorded failure data, lack of adequate description of what was wrong and what repairs were performed introduce calculation errors as well as require time consuming data ordering and careful analysis. With the upcoming role of statistical computation tools for asset and maintenance management, DNOs are starting to invest and take care of data quality issues through comprehensive data enhancement programs. Also, we have found that statistical analysis can supportive the validation of incomplete data to a certain extent. We expect to have positive advancement in data analytics in the times ahead.

5.5.2 Outlook

In this chapter, we have discussed the application of statistical based computational tools for maintenance management. These are powerful tools for the analysis of populations of assets regarding the prediction of asset and system failure behaviour using available historic failure and in-service data. This analysis of whole populations is known as top-down analysis. In the next chapter, the upcoming role of sensor-based condition monitoring for maintenance management, namely the bottom-up methodology, is described. This use of condition monitoring techniques within the electricity network industry is gaining more and more interest, which also introduces new maintenance management possibilities. However, as will be shown in chapter 6, large scale implementation is still reluctantly seen, due to various reasons. In chapter 6 a condition monitoring framework to support understanding and consistent implementation of such techniques is developed and introduced.

6 Condition Monitoring Framework for Maintenance Management

6.1 Introduction

6.1.1 Background

It was stated in the introduction of chapter 5 that failure behaviour of assets can be approached in two ways which are 1) through statistical-based analysis and 2) field inspection and condition monitoring. In this chapter, we will elaborate on the latter. It must be noted that the focus in this chapter will not be on the technological side of the condition monitoring, but on the management side of its application. We have found, as will be discussed in this chapter, that the shift in the electricity network industries towards condition-based maintenance as a strategic goal is still undertaken reluctantly. Although condition monitoring technologies have rapidly developed and became more affordable, the implementation and wide-spread adoption in electricity networks is still not seen. In this chapter, we discuss the possible reasons for this and introduce the need for a holistic management approach towards condition monitoring. In fact, we suggest that it is necessary to first develop a structure for a maintenance management organisation (chapter 3), develop a risk linked maintenance framework (chapter 4), understand the asset population's failure behaviour through computational tools (chapter 5) and, eventually, consider the role of condition monitoring and the necessity for a condition monitoring framework for maintenance management (this chapter).

6.1.2 Chapter outline

In section 6.2, the upcoming role of condition monitoring in a risk based asset management environment is described. Also, a case study is presented about the perceptions towards condition monitoring technologies. In section 6.3 a condition monitoring framework for maintenance and asset management is developed and described. In section 6.4, the chapter comes to a close with conclusions.

6.2 Upcoming role of Condition Monitoring in Maintenance Management

6.2.1 Condition Monitoring and Risk Management

As was already described in chapter 2, asset management is frequently implemented in a triple-level regime. The levels are *strategic*, *tactic* and *operational* level from the management side to the technical side. With regard to risk management, each layer can be described on the basis of a *technical* and *non-technical* triggered risk category. In the following, we will elaborate on these two types of risks and relate them to condition monitoring.

Technical Risk - These risks are, in general, triggered by failures and, traditionally, the primary target of investigation in maintenance management. The systematic treatment of these risks was discussed during the development of the *risk linked RCM* framework in chapter 4. In the following, we discuss each level of AM from a technically stimulated risk viewpoint.

- At the *operational level*, the causes of failures are investigated, diagnosed and prevented.
    - Condition diagnoses are performed to detect failure causes.
    - The timetable to coordinate preventive maintenance with operation, inventory, human resource, safety measures and other civil works is called maintenance schedule.
- At the *tactical level*, the "risks of asset system failures" are investigated.
    - The failures of asset systems, rather than assets, are investigated as stimuli of "risks". The term "failure mode" refers to the sequence of aging factor, asset deterioration, asset failure and asset system failure.
    - The consequences of failures are evaluated in several "business values".
    - Control of these "technically stimulated risks" is realized through dedicated replacements and maintenance concepts.
    - A preventive maintenance plan specifies
        - which maintenance strategy should be applied on which specific asset, and
        - the diagnosis procedure to be applied on an asset, if it falls in a condition-based maintenance plan.
        - how diagnostic outputs should decide the maintenance schedule.
    - Replacements of long-living assets (typically primary-side high-voltage components) are decided based on a fixed schedule rather than decided risk-based.

- At the *strategic level*, the full spectrum of risks should be managed and controlled.
    - Update the KPI system and review the financially summed risks of asset portfolio.

It is important to stress that from our experience, the main challenge of managing risks with technical stimuli is trying to understand their technical cause (trigger) of failure and the proper diagnosis (predictive) method to understand the condition of assets. The left triangle in figure 43 represents the management of risks with technical stimuli. It has a larger area at the operational level (shown as O1), showing that a large part of the effort is directed towards understanding the technical causes of failures. The future trend will more and more require contribution of diagnostic methods and condition monitoring technologies in this area (O1).

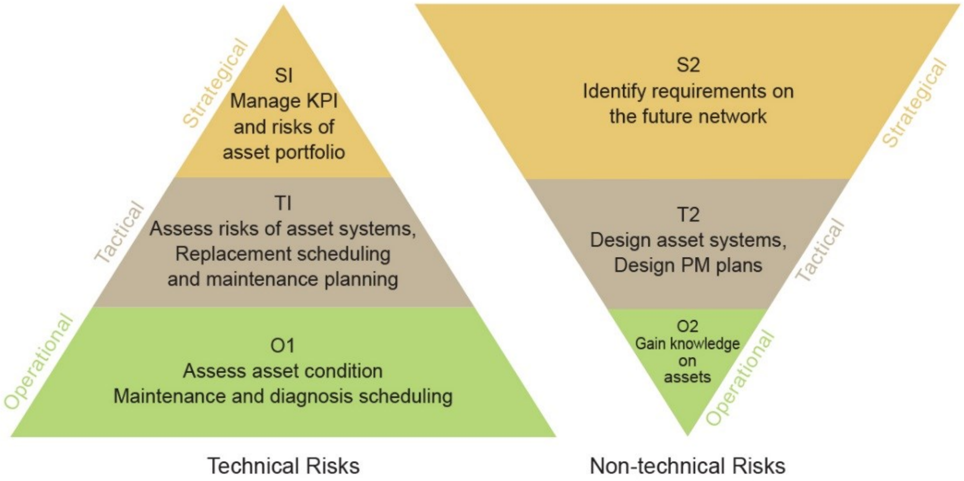


Figure 43: Represents two categories of risks. The left triangle summarizes the technically triggered risks. The right inverted triangle summarizes the non-technically triggered risks for the same three levels of AM. Condition monitoring is related to area O1, operational layer of technical triggered risks.

Non-Technical Risks: These risks are not considered in maintenance management which is often a largely technical area, but considered by strategy specialists and policy analysts. Additionally, these types of risks are normally long-term, so their probabilities and consequences are difficult to predict (e.g. the case that Germany abandoned nuclear power). Consequently, asset managers can only contribute to control these risks through providing innovative technical design of assets/asset systems. In appendix F, more detail about the non-technical risks for each AM layer can be found.

International trends in future maintenance regimes show two main developments. Firstly, there is consensus among asset managers that a risk-based approach for maintenance will form the main guiding principle in the future (as discussed in chapter 4). Secondly, the developments in the area of sensor technology and data analysis are rapidly evolving.

Therefore, it is expected in the future, that decisions are made based on facts and figures coming from more asset specific condition assessments rather than on average (degradation) ageing curves. Since the condition of assets vary with time and due to applying condition monitoring technologies, asset specific risks can be assessed as "moving" risks which can be controlled.

Yet, in practice, the implementations of wide scale condition monitoring systems are carefully rolled out and these activities are usually still considered innovation (pilot) projects. Typically, the reason behind this is because it is often unclear on strategic level what the added value of condition monitoring technologies might be. In the following we will describe the role of condition monitoring in a risk-based management era, and elaborate on the technically triggered risk area O1 (as shown in figure 43).

6.2.2 Role of Condition Monitoring within Risk-based Maintenance

The definition of condition monitoring, according to [78] is:

"Condition monitoring, on or off-line, is a type of maintenance inspection where an operational asset is monitored and the data obtained analysed to detect signs of degradation, diagnose cause of faults, and predict for how long it can be safely or economically run"

Condition diagnostics and monitoring techniques have been applied in the past and gained the interest, especially, at management level [10], [34], [79]. In general, condition monitoring in the power industry has been applied as a method to gather information for the following reasons:

- To manage life expenditures and to ensure that equipment ratings are not exceeded, by monitoring loads and stresses on equipment
- To prevent and locate defects or failures. Also, to monitor symptoms of deterioration. This information can be used for the purpose of just-in-time warnings and as data for condition assessment for guiding maintenance and replacement activities, hence supporting AM decisions, especially, on operation level.

The interpretation of data coming from condition monitoring systems, the initial investment costs of these systems, and the reliability miss-match of diagnostic systems with the equipment being monitored and the volume of data (big data challenge) daunted the application of condition monitoring systems. Another important issue is the timeliness with which the acquired condition data can be provided and the relationship with the time to failure of this specific asset [34], [79].

Nowadays, most of these challenges still remain and form an obstacle for large scale applications of condition monitoring, especially the costs for setting up a condition monitoring programme are considered. Due to this, it is often unclear to asset managers what the added value of condition monitoring systems is, especially in terms of potential benefit to risk-based management.

In figure 43, we explained that the assessment of asset condition forms an important part in the O1 (operational) area. In order to fulfil the tasks for the assessment of asset condition, it is required to have insight (information) of the following aspects [79]:

- Technical knowledge of the component
- Functional description of the component
- Stresses which are imposed by loads and/or environments
- How these stresses deteriorate the components

In quantitative risk studies, measurable data is required to determine the equipment condition, probability of failure and associated risk(s) for the calculation of the probability of failure requires statistical failure analysis. However, to meet the requirements stated above in order to fulfil the tasks for the assessment of asset condition requires the application of at least some form of diagnostics or condition monitoring. In table 16, we listed the aspects in which condition monitoring contributes to the assessment of risks with technical stimuli, hence contributing to the operational level of the left triangle shown in figure 43.

Table 16: Detailed listing of the role of condition monitoring to assess technically triggered risks

Contribution of condition monitoring to the assessment of risks with technical stimuli

- Asset specific:
    - Contribute to a specific asset service condition and remaining life assessment
    - Contribute to sub-systems (families of population) of assets with a long time condition behaviour assessment
    - Contribute to gain knowledge of measured condition in the whole lifecycle of assets (e.g. assessing the changing risk of failure of critical components based on whole lifecycle condition data)

- Just-in- time reaction:
    - Contribute as warning as an input for alarms for timely made decisions for preventing failures
    - Contribute to environmental hazards prevention such as warnings for harmful substance release (this can additionally be used in the non-technical risk stimuli)

- Predictive performance contribution:
    - Contribute to obtain predictive information about the degradation of assets operating in the network. This can be useful for identifying critical service condition for equipment.
    - Contribute to study the impact of environmental influences on the condition of assets

In general, this list can be regarded as input for the probability of an event and as influencing input for the consequence of failure (as denoted in table 6 in section 4.2.3). These consequences can be reduced because component deterioration can be dealt with before, for example, safety is affected, service is interrupted or significant damage occurs. This is explained as follows:

- Regarding the probability of a stimulus (failure mode)
    - Reducing equipment major failure probability
    - Preventing extensive life cycle loading and/or temporary overloading of an equipment
    - Removing already deteriorated equipment conditions before they create a major failure and cause unplanned outage

- Regarding the consequences of failures
    - Preventing high cost of major and fatal failures equipment repair (incl. replacement)
    - Preventing consequential damage of neighbouring equipment
    - Controlling outages (planned outages)

- Lowering insurance fee at insurance companies
- Avoid penalties

6.2.3 Survey Results: Perception towards Condition Monitoring at a Dutch DNO

A survey was conducted as part of this research [80] in order to investigate the internal perception for condition monitoring technologies at two departments at a Dutch DNO, Stedin. This survey was based on the approach of CIGRE Working Group B3.12 as reported in [79]. The number of respondents is 21 of which 17 are from the DNO and 4 from a service provider involved in condition monitoring services. The respondents are selected based on expertise, years of experience, role, and decision-making mandate. This forms the focus group for the survey. The respondents had the possibility to give more than one answer on a question. In the following figures a number of results out of our survey are presented and discussed.

Survey question: ***"What drives/ will drive Stedin's decision to apply condition monitoring systems/ techniques?"*** The responses are given in figure 44.

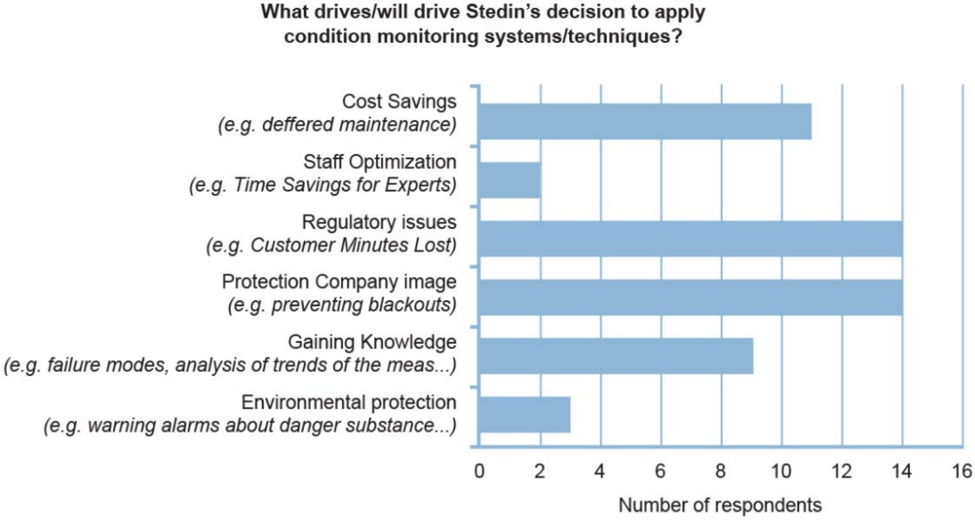


Figure 44: Survey results related to the drivers for applying condition monitoring techniques/ systems.

The results from the respondents indicate that they expect that Stedin's decision to apply condition monitoring is predominantly driven by regulatory issues and protection of company image. Cost savings and gaining knowledge of assets failures are also indicated as drivers to apply condition monitoring. Comments were made stating that safety issues and the ability to make effective replacement decisions were also perceived as drivers for condition monitoring.

Survey question: ***"Where does the value come from using condition monitoring systems/ techniques?"*** The responses are given in figure 45.

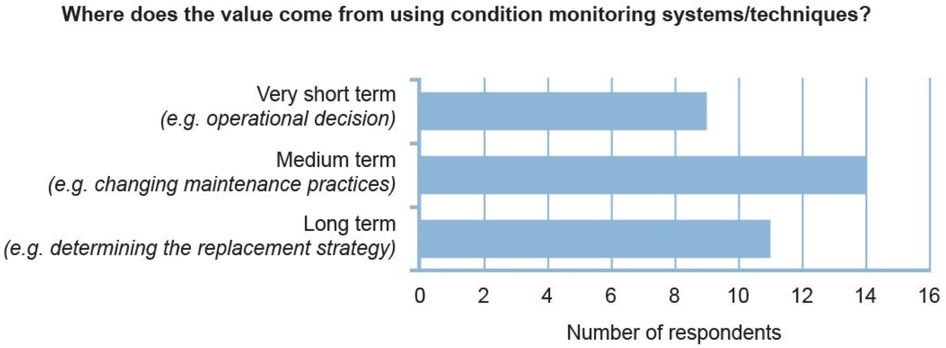


Figure 45: Survey result indicating the time frame in which added value from condition monitoring application is expected.

This question and its results had the aim to show to what extent condition monitoring practices could have an impact on the very short (operational), medium (tactical) and long term (strategic). In particular, all the respondents of the asset management department believe that condition monitoring has an impact on all three decision-making areas.

Survey question: ***"How is condition monitoring perceived at Stedin?"*** The responses are given in figure 46.

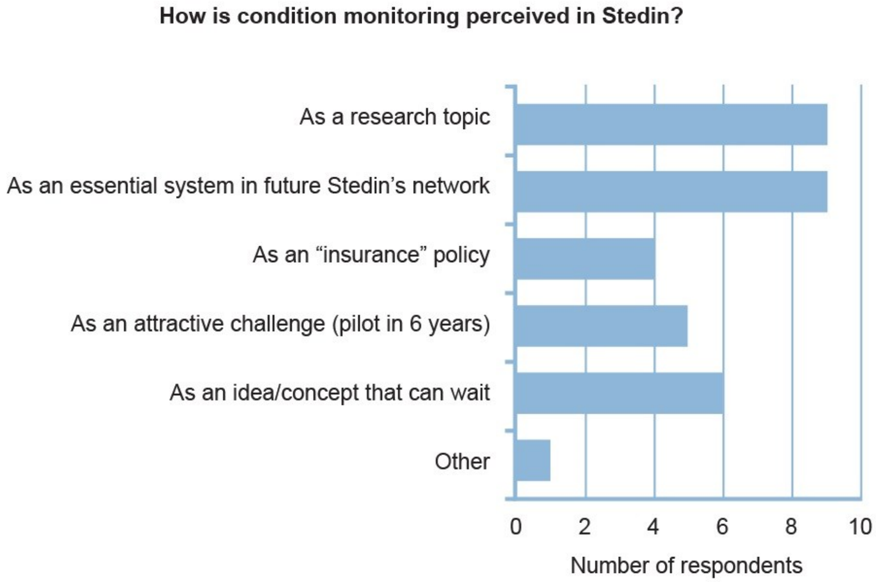


Figure 46: Survey results showing how condition monitoring is perceived at the DNO.

The responses underpin the previously made statements that utilities are reluctantly deploying condition monitoring on large scale. We see that the perception towards condition monitoring varies from a research topic, an idea/concept to an essential system in the future.

Moreover, comments were made describing that result management, novelty of the techniques, reliability of the systems, integration in the organisations processes and systems, are all issues that go beyond just simply solving technological challenges. Stedin needs to develop a policy for condition monitoring practices. Even though Stedin is investigating new techniques, several comments remarked that the research on condition monitoring has a low profile and it is not supported enough by the management.
A closer look at the responses also show that within the DNO the operational department and asset management (strategic) departments have different perceptions towards condition monitoring, as is shown in figure 47.

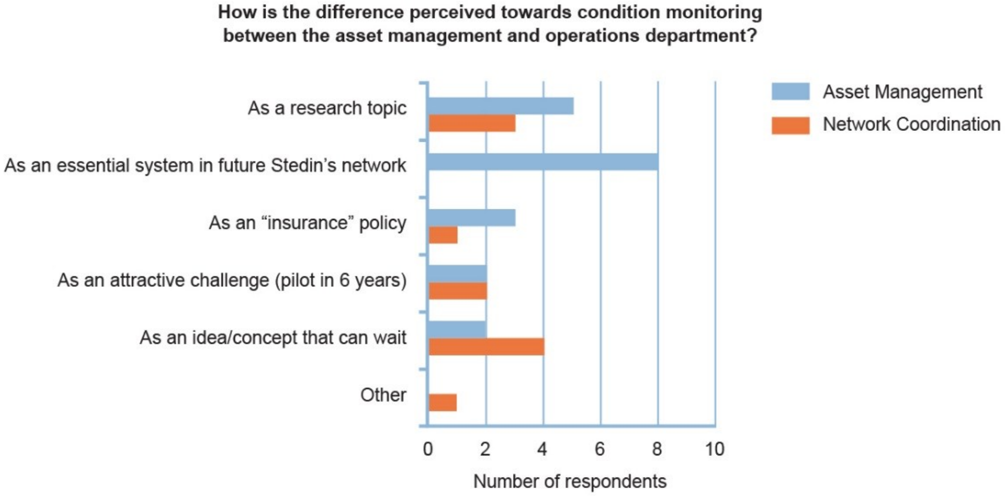


Figure 47: Survey results indicating the difference in perception towards condition monitoring between the asset management and operations department within one company.

The value from condition monitoring for Stedin is driven by different aspects as seen in the survey results of figure 44. From the survey results from figure 47 it is shown that the perception within different departments of Stedin are different. Looking at the results of figure 45, where most of respondents expect that the value of condition monitoring comes from medium and long term practices, it might also be explained that the network coordination department has another perception towards condition monitoring as this department is focused more on short term operational decisions. Nonetheless, no respondents from the operations department ticked the option "as an essential system of the future Stedin's network" whereas almost all the respondents of asset management did so. Contradictory answers are reported for the option "as an idea/concept that can wait" as well. However, the result should not be seen as a lack of interest of the operations department towards condition monitoring, but rather that benefits on short term are not sufficiently proven on operational performance of assets. The respondents of the network coordination department, which is an operational department, might need more practical convincing in that regard.

In summary, this survey within a single DNO shows that there is need for alignment regarding the contribution and added value of condition monitoring in different layers of the organisation. For this reason, the relation of condition monitoring and risk management was previously discussed from a wider viewpoint (triple layer asset management model).

Moreover, the survey results indicate that most likely a framework or policy for condition monitoring is required. Such a framework or policy would clarify how, when and why to apply condition monitoring and most desirably should be supported with a clear overall maintenance management vision (e.g. such as described in chapter 3 and 4). In the next section, a direction towards such a condition monitoring framework will be introduced.

6.3 Towards a Framework for Condition Monitoring

6.3.1 Condition Monitoring Strategies

Generally speaking condition monitoring strategies can be divided into three classes. These are:

- Inspections
- Condition diagnoses
- Trend monitoring

Inspections are mainly qualitative checks using, in most of the cases, human senses such as touch, sight, smell and hearing. However, simple measurement tools can also be used for performing inspections. Inspection methods are traditional methods and are still a viable condition monitoring method. *Condition diagnoses* are quantitative measurements that are performed and compared with predetermined control (warning) limits. *Trend monitoring* are measurements of which the results are plotted in order to detect deviations and to assess rate of deterioration for predictive purposes.

These three classes of condition monitoring strategies can be further categorized into *offline* and *online* measurements. In the case of *offline* measurements, it is required to shut down the component. One version of offline measurement is to perform them in a laboratory or on samples in a laboratory. Another version is to perform the measurement onsite. *Online* measurements are applied during operation with the possibility to have near-real time trend analysis of deterioration of the condition of assets. *Online* measurements, most of the time, require more expensive instrumentation and data handling skills for autonomous analysis. In many cases, it happens that during *online* measurements the accuracy and sensitivity of the measurements are lower than during *offline* measurement. In these cases, when prompted by the *online* measurement, in-depth accurate *offline* measurements are used as well. Hence, we believe that in a condition monitoring policy *offline* and *online* systems will be complementary to each other, because they are applicable in different stages of a components degradation process. Moreover, depending on the goal of the condition assessment (i.e. in-depth condition analysis, defect detection or trending degradation development, etc.) each type of system will add value.

6.3.2 Introducing a Condition Monitoring Framework

Condition monitoring technologies has matured significantly in recent years. *"Prices are declining, signal processing and analysis techniques are being built right into data collection units, measurement units are shrinking in size and reliability and durability of the monitoring equipment are improving"* [81]. Much development has been on the technological side. Through our previously discussed survey, but also through other international surveys, such as CIGRE WG B3.12 [79], we observe that there is still a need for a framework from a maintenance management perspective to place condition monitoring contribution into the maintenance context. There are several reasons for this reluctance [23], [82], [83], [84]:

- The asset population is usually large and thus a wide scale implementation of condition monitoring is difficult to justify economically.
- Lack of in-depth knowledge of failure modes of the wide range of assets which are present in the networks and the complexity to assess these.
- Lack of existence of clear processes and concepts for the integration of operational technology (OT) and information technology (IT).
- Uncertainty with aspects such as cybersecurity implications when deploying condition monitoring. Also, uncertainty and lack of experience regarding the reliability of condition monitoring systems compared to the primary network assets.
- The challenge with the big amount of data that will come once deployed largely.

In order to, objectively, select out of a number of condition monitoring technologies, maintenance decisions need to be informed by a number of information sources. The most crucial of these is knowledge of how assets function and could fail. On a system level and for risk based purposes, it is also required to have knowledge of the consequences of failures (whether an unacceptable risk is present). The latter is important because due to the high number and wide variety of assets in electricity networks, the application of condition monitoring will be most effective on high risk and critical systems or components. Such a risk linked approach for maintenance management was explained in chapter 4 and forms a fundamental requisite for other maintenance developments such as a condition monitoring framework. The in-depth knowledge of *failure modes*, *stress factors*, *ageing mechanisms*, *historical failure statistics*, *predicted failure rates*, *material knowledge*, *expert knowledge* and *risk levels* will form key information streams within the framework for selecting amongst condition monitoring technologies. We found that for network maintenance management, a mix of strategies comprising corrective, time based and condition based approached will prevail. However, the selection amongst these will be more risk-based (i.e. assessed by means of calculated risk methods). The focus here is on the part where such a risk-based approach is in favour of the application of condition based maintenance related to condition monitoring. We developed a framework (figure 48), in which the asset manager has to make a decision between corrective or preventive maintenance tasks for a certain failure mode resulting from a FMEA [84]. In the case of a preventive maintenance action, the choice for a condition-based approach can be decided by having knowledge of the ageing models behind the failure modes.

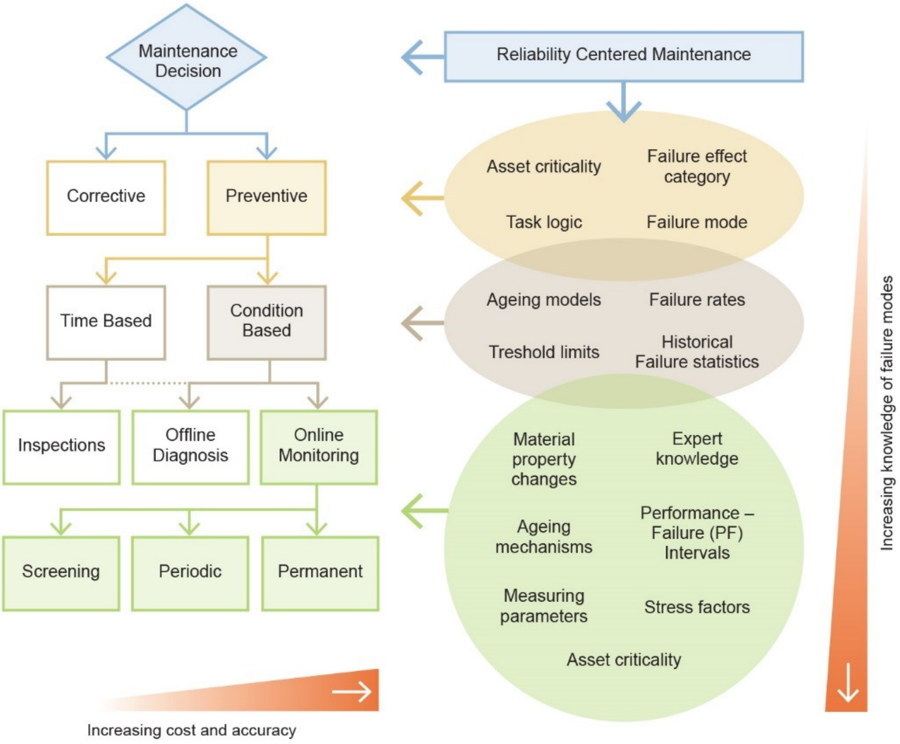


Figure 48: Framework for selection of condition monitoring [84].

If there is an increasing ageing or deteriorating parameter that is related to the dominating failure mode and can be predicted based on condition measurement, then condition monitoring can be a viable and effective option. After the selection of a condition based task, a method for measuring the parameters that indicate the condition and state of the asset must be selected.

In order to select amongst inspections, offline or online, in-depth knowledge is required such as the stress factors that play a role, the ageing mechanisms, material properties, measurement parameters, performance-failure intervals and usually specific expert knowledge. Part of this knowledge cannot be derived from direct measurements in the field, but require measurements on model samples in laboratories. In laboratory experiments, destructive tests can be performed and stress models can be investigated in more detail. Together with the other sources of knowledge, it can be used to derive more qualitative measures for the condition of an insulation system. The other way around can also contribute in understanding failure mechanisms in more in-depth. That is, using the experience from online condition monitoring results to verify and investigate the defected location of the asset in a laboratory environment.

Given that the above mentioned knowledge has been studied and online condition monitoring has been chosen as an approach to identify changes in the dominant ageing processes for effective maintenance allocation, then the asset manager still needs to consider which type of online condition monitoring should be used. At this point, information regarding the value and age of the asset, the operational environment, criticality and other business values (e.g. image, finance, quality of supply, etc.) should be used as input. As mentioned earlier, there are also different methods possible to apply online condition monitoring, ranging from low cost, quick, less accurate screening systems to advanced, high cost, accurate permanent monitoring systems. For this purpose, a three stage condition monitoring approach can be followed [84]:

- Stage 1 “Screening”: A preliminary condition assessment by means of simple tools such as handheld partial discharge tools, thermography tools, and acoustic measurements is performed. The results from stage 1 can be used as input for selecting amongst stages 2 or 3 or for direct maintenance actions based on the condition.
- Stage 2 “Periodic Monitoring”: In this stage, based on, for instance, the information from stage 1 or other detailed information (age of component, historic inspections, lab results, failure data, location in the grid, etc.), it can be decided to trend a certain condition indicating parameter for a specific period of time either by inspections or diagnostics measurements.
- Stage 3 “Permanent Monitoring”: In stage 3, an advanced stage, the most critical locations are known because of previous stages 1 and 2. Therefore, the asset manager can decide to deploy permanent online condition monitoring systems to

trend and locate defects in advance in order to allocate preventive maintenance actions based on the condition of the asset under monitoring.

On the whole, this framework can be used as a guide to assist asset managers in identifying the relationship between failure modes and ageing processes to select amongst condition monitoring regimes. It can give more clarity in the direction of linking scientific knowledge of insulation failure modes and maintenance management actions. Added to this, it provides and helps in setting rules for selecting amongst condition monitoring systems and helps in raising questions and new focus when doing this. In appendix G two case studies [23], [82], [83] of the application of condition monitoring are described in detail, which are based on the reasoning as provided in this framework.

6.4 Conclusions

This chapter has introduced an approach on condition monitoring from a risk management point of view. The following conclusion can be drawn:

Management level:

- The establishment of a common understanding for condition monitoring within a typical triple layer asset management organisation is needed in order to clarify the added value and contribution of condition monitoring.
- There is still no clear line of sight on operational, tactical and strategic layers of an asset management organisation towards the role of condition monitoring in risk-based maintenance.
- For this reason, we have also introduced and developed a condition monitoring framework that can assist in establishing a complete understanding of the holistic approach.

Tactical level (condition monitoring framework):

- In order to establish a policy for condition monitoring, organisation will be required to develop a condition monitoring framework which is based on information coming from each asset management layer.
- The in-depth knowledge of failure modes, stress factors, ageing mechanisms, historical failure statistics, predicted failure rates, material knowledge, expert knowledge and risk levels will form key information streams within the framework for selecting amongst condition monitoring technologies.

Operational level (Case studies provided in appendix G):

The results of the case studies are just a glimpse to indicate the usefulness of these technologies in proactively preventing or gaining more knowledge of known and unknown failure modes in network assets. In the coming years, more of such experiences are expected to come. More importantly, the *technical side* and *management side* of maintenance management will need to align their activities more and more and expectedly this will happen through risk-based regimes.

7 Conclusions & Recommendations

7.1 Thesis Recap

A trend towards well-founded forms of maintenance management of electricity distribution networks is observed worldwide. This new approach is generally associated with risk-based maintenance management. Risk-based maintenance regimes are intended to ensure higher efficiency and ultimately establish a broader view on maintenance as a business function, i.e. a potential profit contributor. At the same time, it is intended to find efficient and practical mixes of maintenance activities for distribution network assets beyond the sole technical aspects of maintenance. Maintenance departments will be expected to function in a broader sense and move away from "silos" thinking. These days, maintenance departments are required to consider more financial aspects and manage maintenance budgets. Furthermore, risk-based maintenance processes are required, maintenance and asset key performance indicators (KPI's) are needed, resources and new skills need to be managed. Maintenance department decisions are accountable for strategic, tactical and operational aspects of an organisation. The promise of risk-based management can hence only be fulfilled once explicit and straightforward frameworks, analytical tools and technological methods for developing and supporting maintenance management decision are set in place. Thus, an integral, multi-disciplinary, approach towards maintenance management needs to be established, which is a challenge that has been taken up in this thesis.

In section 7.2, the conclusions belonging to the research questions of this thesis are given and discussed. In section 7.3, a number of recommendations for future research directions are explained.

7.2 Conclusions

The overall objective of the research was formulated as follows:

"To assess and investigate an organisation-wide maintenance management framework for electricity network companies, which includes the establishment of decision-making methods and tools to practically predict failure behaviour of assets; for determining the right maintenance concept within a risk management regime including condition monitoring and statistics"

The following research questions, which have been addressed throughout this research, are the proof of the existing gap between maintenance management and operational parts in electricity distribution utilities. Each research question is addressed by means of empirical research approaches which include survey studies, practical case study implementation, data analysis methods, field measurements and development of methods based on field observation and analysis. Based on the addressed research question and the applied research methods we can conclude that the overall objective of this research has been met.

7.2.1 Research Question 1: Organisation-Wide Maintenance Management

The first research question asks: *"What are the organisation's supporting pillars that need to be considered when designing an organisation-wide maintenance regime?"*

This research question has been addressed in the first part of chapter 3. Here we have found from both theoretical and empirical evidence that an integrated and organisation-wide approach for maintenance management will play an essential role when evolving to risk-based maintenance. An overall finding is the necessity to have a clear maintenance management process and organisation in order to identify the key enabling organisational pillars that will play an important role in steering maintenance management improvements. In doing so, we have found that the following 6 pillars for effective and efficient management of maintenance need to be taken into account:

- Organisation & process management (takes into account that organisational structures, processes and roles are uniformed and documented)
- Policy management (takes into account the policy, standards and specifications)
- ICT management (takes into account data requirements, information systems and maintenance management systems)
- Quality management (takes into account data quality aspects)
- Financial management (takes into account portfolio, performance and administrative aspects)
- Knowledge management (takes into account asset as well as personal knowledge aspects such as training, pilot projects and future trends)

We have found that the effectiveness is increased even more when in such an organisation-wide maintenance approach, each technical asset group is linked to each of the above mentioned organisational pillars. This results in a matrix approach with an expanded view of asset groups and organisational pillars which enables the establishment of an integrated maintenance management model and organisation. That is, the ability to understand the level of integration of each pillar for the asset groups and establishing the priorities of such pillars for improving that which have not come up to the mark yet.

7.2.2 Research Question 2: Maintenance Management Maturity Model

The second research question asks: *"How can the development (maturity level) of a maintenance organisation be modelled and measured?"*

In the second part of chapter 3, this research question is addressed. In this research, we have developed a maintenance management maturity model for measuring and monitoring the integral corporate vision of the multidimensional processes necessary for the organisation-wide maintenance management professionalisation. Such a model is used to translate the vision of each supporting pillar for maintenance professionalisation (research question 1) into measurable and monitor-able set of levels. Furthermore, with the maturity model levels measured, the maintenance organisation will have a fixed framework of how they can evolve towards improved maintenance management capabilities. This is demonstrated for two sets of measurements in the years 2012 and 2014. In the developed maintenance maturity model, three levels of maturity are adopted:

- "Practically Managed" (Reactive/ corrective focus. Occurring risks are vigorously acted on)
- "House in Order" (Preventive focus. Risks are known and managed)
- "Best in Class" (Predictive focus. Risks are related to lifecycle and reliability)

Overall, from the development and application of the maintenance management maturity model, we conclude that the model provides:

- a fundament for a starting point for the further development of maintenance management
- a framework for actions and priorities in contributing to the further development and professionalisation of maintenance management
- a way to clarify what constitutes improvement for the maintenance organisation
- a directive for a united awareness of a desired path towards growth and professionalisation in maintenance management

7.2.3 Research Question 3: Utility Risk-Linked Reliability Centered Maintenance Model

The third research question asks: *"What is required to link existing (well-developed) maintenance concepts to the overall corporate business values in order to establish a method for tactical maintenance management purposes to select amongst most effective maintenance activities taking into account the overarching risk management philosophy of asset management?"*

In general, we extracted from literature research that the trend for risk-based management is driven by the fact that risk adds an analytical dimension with the characteristics of being comparable, measurable and manageable. In this thesis, a uniform, systematic and methodological approach has been established. This methodology is named the *Utility Risk Linked Reliability Centered Maintenance* (Utility Risk Linked RCM). The traditional calculation of the Risk Priority Number (RPN), which is already known in conventional RCM approaches, has been expanded in this research in order to ensure that the analysis of the consequences of failure modes are treated and assessed in a pragmatic way. That is, that the expanded RPN calculation can include the likelihood of failure modes and its consequences separately and independently for multiple business values. Due to the multiple business values of different inherent nature it is important to incorporate the analysis of consequences in the calculation. In conclusion, the developed *risk linked RCM* has the following characteristics:

- The method is generalised and can be applied to different types of assets
- The method is linked to the corporate risk management model and principles
- The method can deal with differences in consequences of failure modes on multiple business values
- The developed method is practical yet sufficiently accurate for risk-based maintenance management

The practical application of the developed model brings us to the next essential conclusions:

- The proper initiation of the project and selection of an RCM team is essential for a successful adoption of full scale risk linked RCM in the future
- A common notion of risk and the ability to objectively deal with occurrences of failure modes and consequences requires commitment, understanding and acceptance of the benefits of risk incorporation into maintenance management
- In order to deploy full-scale application of such comprehensive maintenance management concepts, management commitment, leadership and ownership is required to support the change that such paradigm shifts require, most importantly over a longer period of time

7.2.4 Research Question 4: Statistical-Based Computational Tools for Maintenance Management

The fourth research question asks: *"Which quantitative techniques, based on statistics, are applicable to adequately predict failure behaviour of assets for maintenance management purposes?"*

Life Data Analysis (LDA) has been adopted as a means to statistically describe the failure behaviour of assets and systems. We applied a straightforward LDA procedure for obtaining failure probabilities and failure rates of assets. The application of this procedure provides the following:

- An understanding of failure behaviour of populations of assets
- An understanding of life expectancy of populations of assets
- A method for predicting future failure expectancy
- An input for developing maintenance policies, selecting amongst condition monitoring policies and defining optimum maintenance task intervals
- An understanding of component related failure probability models which can be used as input for system related risk management analysis (such as Monte Carlo analyses of networks)
- An input for providing guidelines for asset and maintenance management decision support

Electric network assets age when in service, therefore, in due course, these assets will be characterised by increasing failure rates and this will result in higher costs and more maintenance, repair, replacement or consumer costs due to degraded performance. This is an unavoidable point that is often overlooked and up to the present time approaches have either been reactive or preventive (without adequate predictive or risk management policies) and therefore not completely able to address the fact that the failure rates will rise in the future. With the application of more and more probabilistic (statistical) computational tools, DNO's will have the ability to predict failures and steer the decision-making regarding replacements, maintenance and cost-effective budgets plans more accurately.

7.2.5 Research Question 5: Upcoming Role of Condition Monitoring in Maintenance Management

The fifth and final research question asks: *'Which role will the upcoming development in condition monitoring systems play in maintenance management?"*

Condition monitoring technologies are developing rapidly and are slowly becoming more financially attractive for deployment. Nevertheless, it is being applied carefully and reluctantly at DNO's. This is mainly due to a lack of a common perception on the contribution and due to the lack of a condition monitoring framework which is related to overall asset management philosophies. From empirical evidence, we have concluded that the following factors contribute to this:

- The asset population of DNO's is usually large and thus a wide scale implementation of condition monitoring is difficult to justify economically
- Lack of in-depth knowledge of failure modes of the wide range of assets which are present in the networks and the complexity to assess these
- Lack of an integrated, organisation-wide approach towards maintenance management make the added value of condition monitoring unclear and un-assessable
- Lack of existence of clear processes and concepts for the integration of operational technology (OT) and information technology (IT)
- Uncertainty with aspects such as cybersecurity implications when deploying condition monitoring. Also, uncertainty and lack of experience regarding the reliability of condition monitoring systems compared to the primary network assets
- The challenge with the big amount of data that will be generated once deployed largely

For this purpose, the establishment of a common understanding within a triple layer asset management organisation for condition monitoring is introduced. This will aid in clarifying the added value and contribution of condition monitoring. This is necessary owing to the fact that, in practice, there is still no clear line of sight on operational, tactical and strategic layers of an asset management organisation towards the role of condition monitoring in risk-based maintenance. In line with this, this thesis introduced and developed a condition monitoring framework that establishes a complete understanding of this holistic approach. The framework provides a platform for asset managers in identifying the relationship between failure modes and ageing processes to select amongst condition monitoring regimes. Such a framework is intended to give more clarity in the direction of linking scientific knowledge of failure modes and maintenance management actions.

7.3 Recommendations

7.3.1 Data Types and Information Strategy

The *Utility Risk Linked RCM* approach can be improved by also modelling risks caused by external sources, for example actual soil condition, weather influences, public acceptance, obsolete assets, etc. The risk-based decision-making process thus will require a holistic approach where different sources of data will be required. Nowadays, the majority of asset management departments still lack the solution for the integration of such data sources in information systems to support the decision-making. The level of detail of data is mostly recorded on asset level and often collected by hand or outside enterprise-wide databases. An interesting point of improvement is to focus on the integration of existing databases such that decision makers can easily use the right information. A possible direction for this improvement is the suggested work of CIGRE Technical Brochure 576 [30] in which general principles for information technology strategies for asset management are given. The inclusion of information technology strategies into frameworks such as the developed risk linked RCM in this thesis will benefit the overall value and needs to be considered.

7.3.2 Predictive Management Related to OPEX

This thesis has described the overall upcoming role that condition monitoring regimes will have in risk-based maintenance management. The inherent predictive nature can pose challenges for the maintenance budget planning. In general, financial controllers expect a proactive approach to budgeting from maintenance managers regarding the OPEX. In fact, it is usually expected that maintenance managers will know better which components should be replaced, inspected, maintained or refurbished and at what cost within the planning and budgeting period. When larger numbers of assets will be monitored by means of condition monitoring technologies and predictive decision-making methods, the possibility to proactively determine OPEX budgets will perhaps become a challenge. This can either result in the discouragement in applying more predictive tools or may have implications on the budgeting preparation methods. In which case, the latter is mostly managed by financial planning and regulatory expectations. In this light, future research on the topic of budget planning of predictive maintenance schemes is recommended. In order to approach this, the impact of predictive methods on the budget planning period (corporate planning period, practical control periods and life capability of assets) needs to be investigated in order to determine the most suitable or practical forecast period.

7.3.3 Regulation in relation to Asset Management Time Scales

Another area of concern, and therefore recommended for future research, is the effectiveness of the current price-quality regulation scheme applied in the Netherlands with regard to asset management of assets with a long life capability. In a nutshell, price-quality regulation was introduced in order to prevent that adverse cost savings would impair the reliability and performance of networks. The general idea behind this was to provide annual financial incentives in order to ensure that network companies would be inclined to work towards an optimal mix of decisions to balance quality (performance) and costs in such a way that it is socio-economically optimal. Such financial incentives have a lag of two years i.e. the incentive for year *t* is based on the performance observed in year *t-2*. The primary purpose of price-quality regulation is to assure that the incentives for higher cost efficiency do not translate into simply cost reductions and eventually a degradation in quality, which can only be observed after some years. The basic idea is to internalise the incentives for optimal quality into the decision-making process [5]. However, a basic limitation of this approach is that the financial incentives are provided in the short term, while the lifetime of network assets is longer and the impact of cost decisions on quality outcome typically materialize sometime after these incentives have been paid out. In fact, there is limited knowledge and research available on the impact that the short term regulations schemes have on the long term nature of asset management decisions. It is arguable whether companies adopt new technologies less quickly to budget prioritizations because of regulation implications. A research recommendation is therefore to answer the question how decisions that are made in the present time (investments, maintenance, replacements, standards, etc.) ensure over a certain period of time the output that is expected from network companies by regulators and whether the introduction of new technologies is supported, restrained or rather discouraged by a certain regulation scheme.

7.3.4 Integrated Network Capacity and Maintenance Planning Framework & Tools

This thesis has only considered the development of a risk-based maintenance framework and described tools and technologies for this purpose. An open area still remains in the field of integrated frameworks for network capacity (power flow and short circuit studies) and maintenance planning (failure, condition and performance of assets and dynamic loading). With the increasing complexity of electricity networks due to more and more distributed energy resources (DER) resulting into bi-directional rather than uni-directional flows of power, the demands on maintenance become higher. Yet, at the same time, there are continuous pressures on maintenance budgets. Therefore, we foresee the need for research supporting the integration of capacity and maintenance decisions [85]. A field of improvement can be the integration of risk management into capacity planning combined with maintenance aspects. Moreover, as data becomes more and more electronically available, it is recommended to develop software and analytical tools for integrated network capacity and maintenance decision-making, which is nowadays assessed in separate computational tools and most of the time in separate departments.

7.4 Overall Reflection on this Research

The content of this research is intended for a double audience. On one hand for those active in the application, i.e. business oriented field of the management of maintenance and on the other hand for those interested in scientific underpinning of their maintenance methodologies. However, our experience teaches us that conducting scientific research in the managerial area entails some obstacles. From the scientific viewpoint it is not always possible to conduct investigations that are quantitative measurements, however, unlike in the physical sciences, the results obtained are more qualitative observables. This is chiefly because challenges likely to be encountered in the measurement and collection of data are in subjective areas such as feelings, emotions, opinions, attitudes and perceptions. We have experienced that these problems occur whenever we attempt to measure abstract and subjective conducts such as risk perceptions, impact on business values, value from technologies, etc. Despite this, it remains of utmost importance for management areas to conduct research in order to solve dysfunctional organisational problems. Such challenges have to be measured, analysed and explained. Therefore we developed a set of research methods which enables managers to understand, predict and control their environment in an objective manner.

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Appendix A

Overview of Different Business Values Applicable to Risk Management

Here a benchmark of different business values applicable within risk management is provided (provided by Stedin).

Company	**Safety**	**Quality**	**Financial Performance**	**Law and Regulation**	**Image**	**Innovation**	**Customer Satisfaction**	**Sustainability**	**Stakeholder relationship**
Stedin (DNO)	x	x	x	x	x	-	-	-	-
Stedin (2015)	x	x	x	x	-	-	x	x	-
Eneco	x	-	x	x Integrity	x Reputation	-	-	-	-
Tennet (TSO)	x	x	x	x Compliance	x Reputation	-	x	x Environment	-
Enexis (DNO)	x	x	x Affordability	x Legality	-	-	x	x	-
Liander (DNO)	x	x	x	-	x	-	x Service	x	-
Shell	x People	x (Technical, Economic, Cultural, Organisational, Politics)			x Reputation			x Environment	
Prorail (Railway)	x	x	x	x Compliance	x Reputation	-	x	x	x
TU Delft (Research, TBM faculty)	x	x	x Efficiency/ Productivity	-	x Effectivity	x Ergonomic	x Effectivity	x Ecology	x Effectivity

Appendix B

Development Process of Maintenance Management Maturity Model

Here the process underlying the development of the maintenance management maturity model is given in figure 49. The M^4 model is mainly inspired by the Institute of Asset Management (IAM) Capability Maturity Model which is suggested to be used for measuring the capability of organisations when adopting asset management according to PAS 55. When attempting to translate this model to a practical arena and specifically to maintenance management there were practical gaps identified. The available models did not satisfy the needs and specific relevant requirements of maintenance management as such. On the basis of a selected focused group approach of experts of multidisciplinary competencies, a brainstorming (inductive method) was adopted to develop the M^4 method. The 6 organisation pillars are reached by means of multi-voting decision making approaches. The identical focused group has also been interviewed and involved in the development of the assessment logic of the maturity levels.

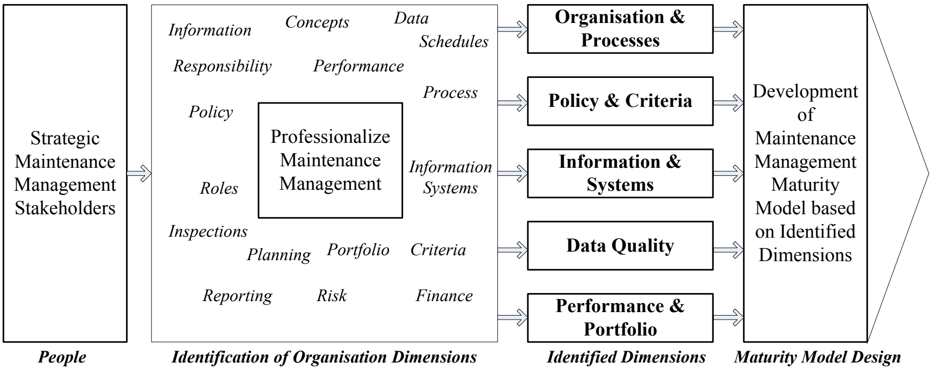

Figure 49: Simplified representation of the development process of the Maintenance Management Maturity Model design

A simplified overview of the levels of assets that are assessed in the maintenance maturity model (M^4) is shown in figure 50.

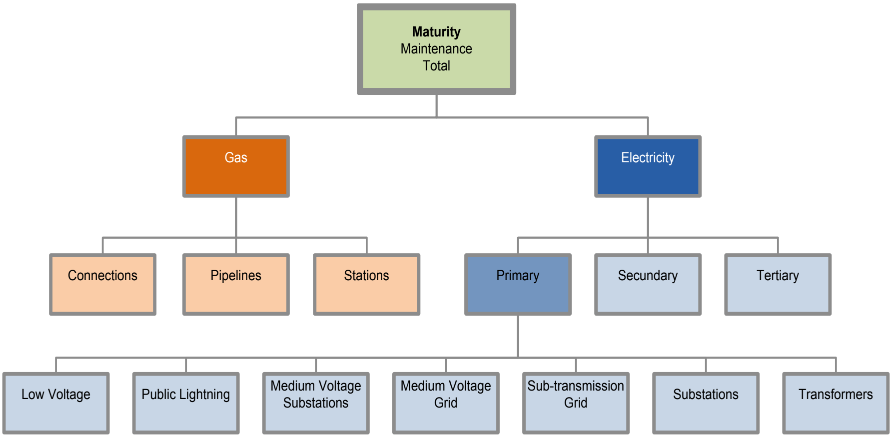

Figure 50: Different asset groups which are assessed by means of the developed maintenance management maturity model

A summary of the number of questions per domain and the overall characteristics of these questions are provided here:

Domain	# of questions	Characteristics
Organisation & Processes	8	Guaranteeing continuous improvement processes with roles of designated (inter-) departments that are documented. - Are processes described, documented and uniform. - Are roles uniform, organized, followed - Knowledge and training
Policy & Criteria	10	This domain is concerned with the fact that policies and criteria are documented, recorded and implemented. Appropriate strategic policies are translated to criteria on that basis of which maintenance planning can be performed. - Are policies documented and followed - Are criteria's adapted and updated on time - Are manufacturer, product and maintenance specifications available and used
Information & Systems	12	This domain is related to the information requirements and information systems used for maintenance management for each asset group and whether required information is available and recorded in the systems. - Are assets registered, available in systems, and structured - How is information gathered. - Inspection and failure reports available and used - Is the information supporting lifecycle management capabilities

		- Is analysis and reporting possible, automated and uniform - Are systems asset centric, uniform, coupled and available
Data quality	6	This domain is related to the degree to which data is suitable for the purpose for which it is used on strategic, tactical and operational level of the maintenance processes. - Insights in the quality of data such as, timely, completeness, correctness - Are data quality measurements performed and how are they done - Are criteria for data quality assessment available - How are data quality issues dealt with
Performance & Portfolio	13	This domain is responsible for transparent financial and portfolio planning business rules, suitable for the operational environment, leading to a uniform way to categorize maintenance activities. - How are maintenance and inspection actions scheduled and reported - Are KPI's followed and available - Maintenance planning and actions and effect of maintenance - Financial planning and administration

The procedure that is followed during the maturity level assessment is given in the flowchart shown in figure 51.

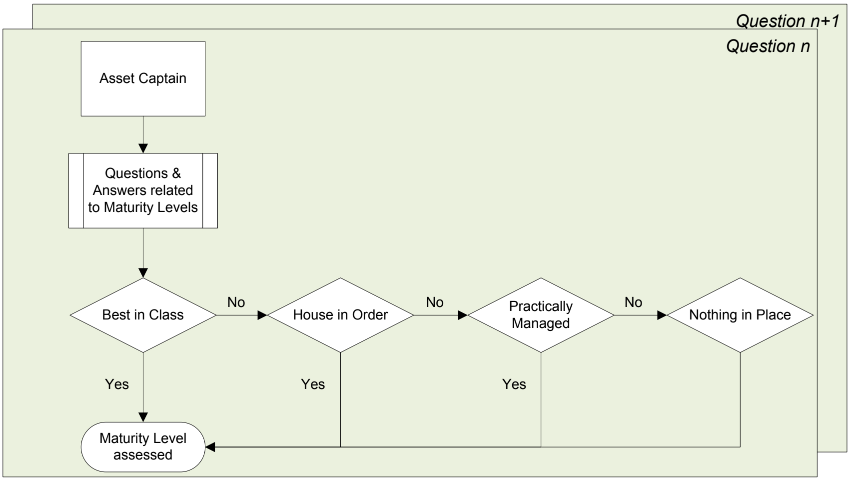

Figure 51: Flowchart of the procedure that is followed during the assessment of the questions when establishing the maturity levels.

Here a summary results from the internal questionnaire related to "What is at least needed to grow towards the maturity level "House in Order given:

What is required to grow towards "House in Order"	
Domain	**Summary**
Organisation & Processes	Formalisation, approval and stability of all maintenance roles and processes (in- and outside the asset management department).
Policy & Criteria	Produce and formalize all the policy, criteria and product specifications. Improvement of the failure data recording process for assets. Drafting and carrying out health assessments for gas network assets, such as is the case for electricity networks assets.
Information & Systems	Finalizing the project entailing the complete *Computerized Maintenance Management System (CMMS).*Implement a number of specific *Geographical Information System (GIS)* changes and updates. Moreover, the link between static asset data systems and dynamic failure and inspection data systems is required.
Data quality	Monitoring data quality in a formal and structured way in order to prevent data pollution and discrepancies.
Performance & Portfolio	Implement measures to be able to demonstrate the effectiveness of maintenance on the following years planning and budgets. Establishing means to ensure that maintenance management plans are guiding decisions and not solely based on budgets.

Here a summary of the results from the internal questionnaire related to "What is at least needed to grow towards the maturity level "Best in Class" is given.

What is required to grow towards "Best in Class"	
Domain	**Summary**
Organisation & Processes	Long term strategy for maintenance management and using risk management as guiding principle. Internal and external auditing. Creating and securing a line-of-sight throughout the whole company regarding maintenance management.
Policy & Criteria	Formalize all the policy, criteria and product specifications. Securing the continuous improvement cycle. Improving and developing lifecycle asset maintenance

	management models *(RAMS)* and risk-based maintenance management models.
Information & Systems	Establishing component level in-depth analytical methods supported by information and systems. Integrating *CMMS, ERP, GIS* and other specific information systems with each in a common data architecture.
Data quality	Securing the current data quality levels. Enriching operational data quality levels. Creating an awareness on the operational levels (in the field) for recording field data with precision and useful quality.
Performance & Portfolio	Linking financial planning with asset planning in order to provide lifecycle modelling by means of analysing the risk reduction for every spend budget. Development and implementation of maintenance *Key Performance Indicators (KPIs)* most favourable based on *RAMS* philosophy.

In [86] and [87] an extensive overview of different benchmarked maturity models is provided. The authors in these references distinguish the maturity models based on the application domain they are developed and applied for. These range from generic to specialized domains such as IT support management. From this overview it is found that a number of maturity models are developed which are directed to maintenance management. In the following these reported maintenance maturity models together with the developed with M^4 are given.

Literature Review of Maintenance Maturity Models together with M^4

Reference name	**Levels**	**Dimensions**	**Assessment Items**
[88], Maintenance management based on organizational maturity level	Survey based	5	Propose 15 assessment areas
[81], Maintenance Maturity Grid	6	10	Generalized assessments criteria
[89], Integrated maintenance scorecard	4	4	Based on 4 perspectives defined from the balanced scorecard
[54]*, maintenance management maturity model (M^4)*	***4***	***5***	***Based on 49 proposed question assessments***

Appendix C

Revised Risk Priority Numbers for different Maintenance Policies

A complete list of the identified failure modes with the related failure code is given here:

List of the failure mode codes	
Failure mode code	**Brief description of failure mode**
Tap changer related failure modes	
R1	no solid connection between main and selector windings due to improper contacts (long term effect LTE)
R3	no solid connection between main and selector windings due to improper contacts (burn-ins and slack due to short circuits)
R4	no solid connection between main and selector windings due to improper contacts (wear and tear)
R6	mechanical slack due to wear and tear of components
R7	mechanical block due to weariness of material
R8	vacuum bottle leakage
R9	Bridging resistor defect due to mechanical weariness or overloading due to short circuits
R10	contacts defect
R11	Improper (too slow) switching due to weariness of springs
R12	block in intermediate tap position due to weariness of springs due to mechanical defect
R13	defect of air dryer due to silica gel saturated due to mechanical defect
R14	lowered quality due to normal utilisation
R15	leakage in the conservator
M1	no voltage or command signal
M2	internal electrical defect
M3	internal mechanical defect
Core & Windings related failure modes	
KE3	windings do not/ unsatisfactorily conduct current or do not/ unsatisfactorily induce the magnetic field due to ageing paper insulation
KE6	windings do not/ unsatisfactorily conduct current or do not/ unsatisfactorily induce the magnetic field due to defective paper insulation (harmonics)
Oil Type Bushing related failure modes	
OD1	short circuit in insulated oil bushing between the tank and conductor due to contaminated bushings
OD6	bad/ improper connection between windings and cable termination due mounting or material defects

OD7	ring type current transformers not connected or short-circuited due to mounting or material defect
OD8	ring type current transformers not connected or short-circuited due to vibrations
Capacitor Type Bushing related failure modes	
CD1	short circuit in insulated oil bushing between the tank and conductor due to contaminated bushings
CD5	short circuit in insulated capacitor bushing between the tank and conductor due to incorrect oil level packing)
CD6	short circuit in insulated capacitor bushing between the tank and conductor due to ageing of paper insulation
CD7	bad/ improper connection between windings and cable termination due mounting or material defects
CD9	ring type current transformers not connected or short-circuited due to vibrations
Tank and Accessories related failure modes	
T1	oil leakage due to improper sealing of gaskets
T2	oil leakage due to corrosion of appendages
Oil related failure modes	
OL1	contaminated oil due to moisture (saturated silica gel)
OL2	contaminated oil due to moisture (improper working oil lock)
OL3	contaminated oil due to moisture (leakage)
OL4	contaminated oil due to moisture (resistance changes)
OL5	contaminated oil due to moisture (aged paper insulation)
OL6	chemical and physical ageing of oil due to overloading
OL7	aged oil due to normal operating conditions
Cooling system related failure modes	
KO1	impaired cooling due to unsatisfactory oil circulation (unsatisfactory opened seal/ valve)
KO2	impaired cooling due to unsatisfactory oil circulation (unsatisfactory venting of radiator)
KO3	impaired cooling due to unsatisfactory air circulation (failed ventilator)
KO4	impaired cooling due to unsatisfactory air circulation (clogged grate)
KO5	impaired cooling due to unsatisfactory air circulation (clogged radiator)
KO6	impaired cooling due to unsatisfactory air circulation (ventilator system failure)
KO7	unable to keep oil inside due leakage sealing/gaskets
KO8	unable to keep oil inside due leakage of radiator (corrosion)
Protection & Signalling related failure modes	
BE1	No or unjust detection of too high flow and/or transformer is not switched off due to failure of the protection relays MR or interruption of the disconnection circuit
BE2	No or unjust detection of too high flow and/or transformer is not switched off due to failure of the Buchholz-relays or interruption of the disconnection circuit

BE3	No or unjust detection of gas development and/or transformer is not switched off due to failure of the Buchholz-relays or interruption of the disconnection circuit
BE4	No or unjust signalling of lowered oil level (tank) due to failure of the oil level meter (relays) or interruption of the signalling circuit
BE5	No or unjust signalling of lowered oil level (tap changer) due to failure of the oil level meter (relays) or interruption of the signalling circuit
BE6	Does not provide temperature measurement due to failure of the resistive thermometer or interruption of the signalling circuit
BE7	No or unjust signalling of too high temperature due to failure of the distance thermometer or interruption of the signalling circuit
BE8	Difference in current is not or unjust detected and/or transformer is not switched off due to failure of the differential relays or interruption of the signalling or switching circuit

The detailed results of revised Risk Priority Numbers (RPN) for three categories of maintenance policies (corrective, time based and condition based) for each failure mode of a power transformer is given in the following figures.

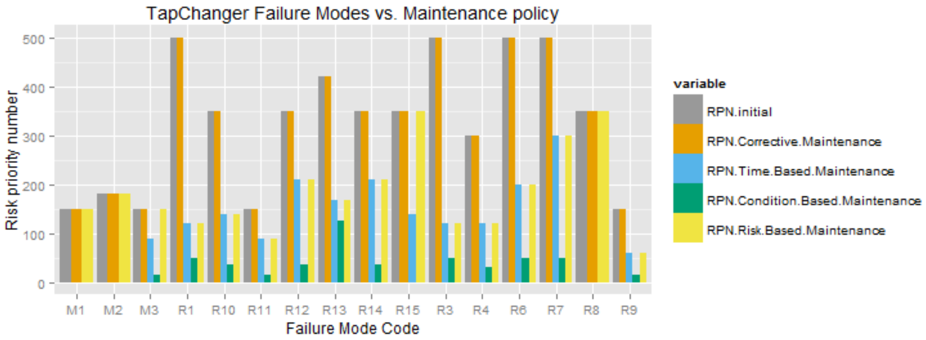

Figure 52: Revised RPN for different maintenance policies for the transformer tap changer failure modes

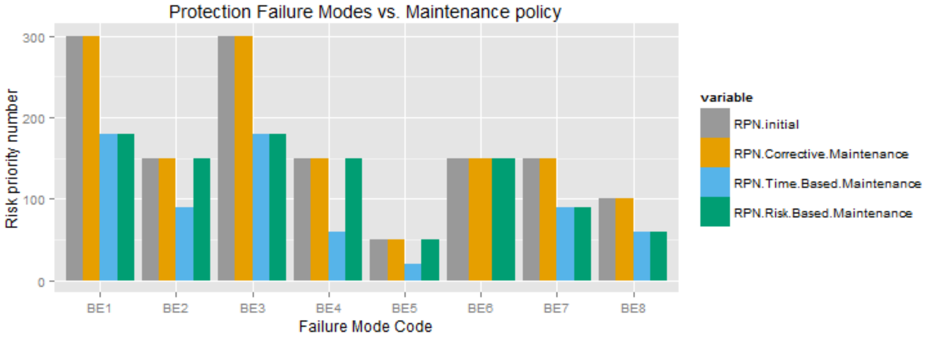

Figure 53: Revised RPN for different maintenance policies for the transformer protection & signalling failure modes

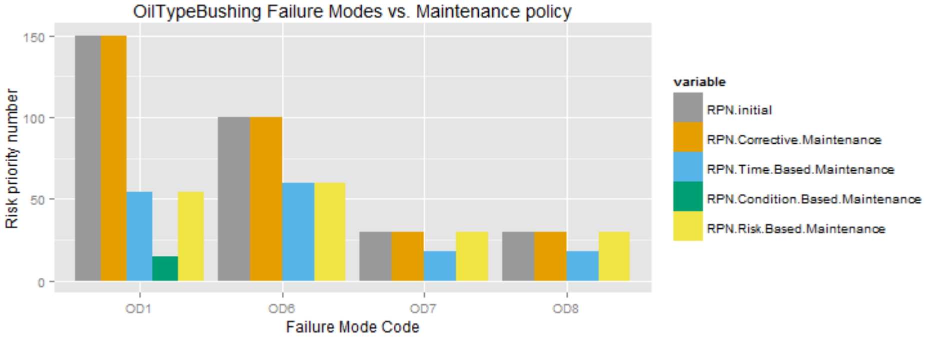

Figure 54: Revised RPN for different maintenance policies for the transformer oil type bushing failure modes

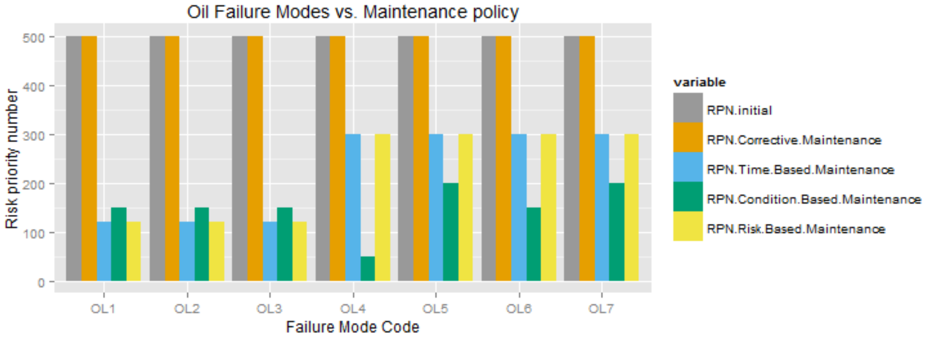

Figure 55: Revised RPN for different maintenance policies for the transformer oil failure modes

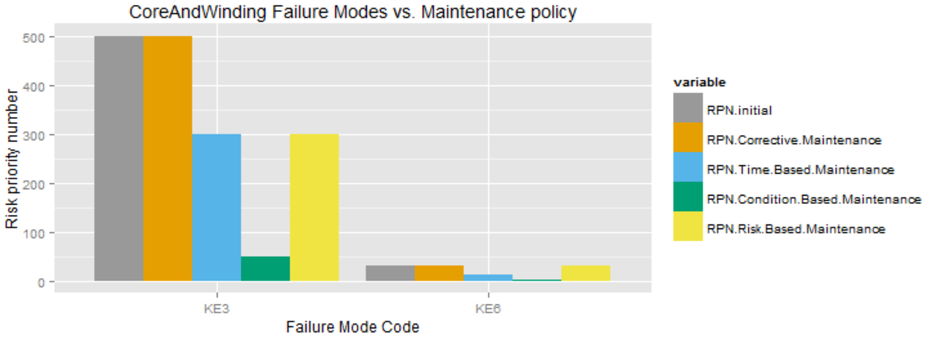

Figure 56: Revised RPN for different maintenance policies for the transformer core and winding failure modes

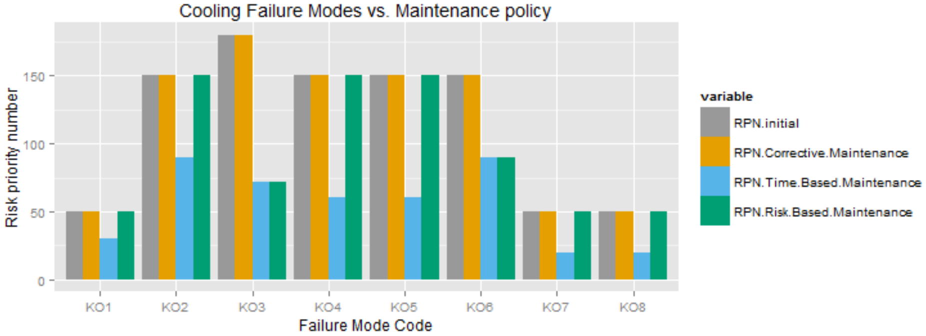

Figure 57: Revised RPN for different maintenance policies for the transformer cooling system failure modes

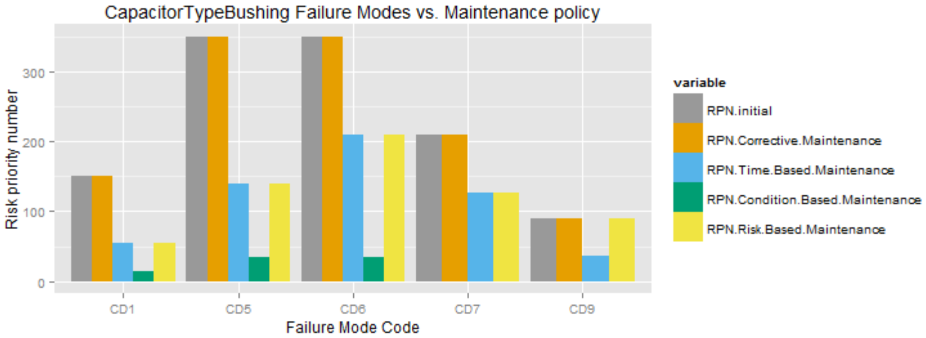

Figure 58: Revised RPN for different maintenance policies for the transformer capacitor type bushing failure modes

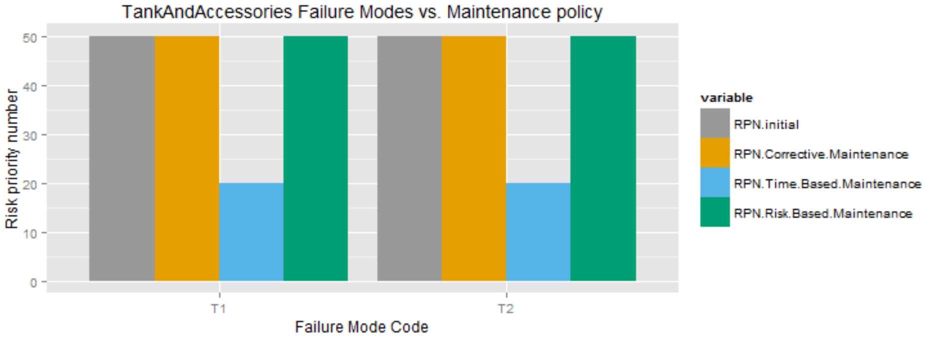

Figure 59: Revised RPN for different maintenance policies for the transformer tank and accessories failure modes

Appendix D

Statistical Lifetime Distributions

From statistical reliability engineering, given a continuous random variable *X*, the following statistical failure functions can be denoted [71]:

Probability Density Function – The probability density function *(pdf)* of a continuous random variable, *X*, is a function that describes the probability that *X* assumes a value in the interval *[a, b]*. If *X* is a continuous random variable, then the *pdf*, of *X*, is a function *f(x)* such that for two numbers, *a* and *b* with *a<b*:

$$P(a \leq X \leq b) = \int_a^b f(x)dx \text{ and } f(x) \geq 0 \, for \; all \; x \qquad (D.1)$$

That is, the probability that *X* assumes a value in the interval *[a, b]* is the area under the density function.

Cumulative Density Function – A cumulative distribution function*, cdf*, refers to the probability that the value of a random variable falls within a specific range. The *cdf* is a function *F(x)* of a random variable, *X*, and is defined for a number *x* by:

$$F(x) = P(X \leq x) = \int_{0,-\infty}^{x} f(s)ds \qquad (D.2)$$

The *cdf* is the integral of the *pdf*, and reflects the probability that *f(x)* will be equal to or less than *x*.

Reliability Function – The reliability function, R *(t)*, can be derived using the previous definition of the *cdf* function. This *cdf* (3.2) is also called the unreliability function, *Q (t),* which is the probability of failure in the region of 0 and *t*. From equation (D.2) the association between *F(t)* and *Q(t)* becomes:

$$F(t) = Q(t) = \int_0^t f(s)ds \qquad (D.3)$$

In general, there are only two states that can occur: success or failure. These two states are also mutually exclusive (they cannot occur at the same time). Since reliability and unreliability are the probabilities of two mutually exclusive states, the sum of both is always equal to unity. Therefore:

$$Q(t) + R(t) = 1$$
$$R(t) = 1 - Q(t)$$
$$R(t) = 1 - \int_0^t f(s)ds$$
$$R(t) = \int_t^\infty f(s)ds \qquad (D.4)$$

The Failure Rate Function – The failure rate function, *λ(t)*, is a function of time and has a probabilistic interpretation, namely *λ(t).dt* represents the probability that a device of age t will fail in the interval *(t, t+dt)*. The failure rate function is equal to the probability of a component failing if it has not yet failed. Since the *pdf* is the probability of a component failing and the *cdf* is the probability that it has already failed, the failure rate can be mathematically characterized as follows:

$$\lambda(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{1 - \int_0^t f(s)ds} = \frac{f(t)}{R(t)} \qquad (D.5)$$

The failure rate function can be expressed as failures per unit time, e.g. 2 failures per year. The above mentioned quantities *f(t)*, *F(t)*, R*(t)* and *λ(t)* can be converted into each other. Therefore, they contain all information about the failure process of the system under consideration.

Appendix E

Monte Carlo Simulation algorithm

The algorithm for the MCS is programmed in Matlab. The flowchart shown in figure 60 presents the principle of operation of the Matlab code.

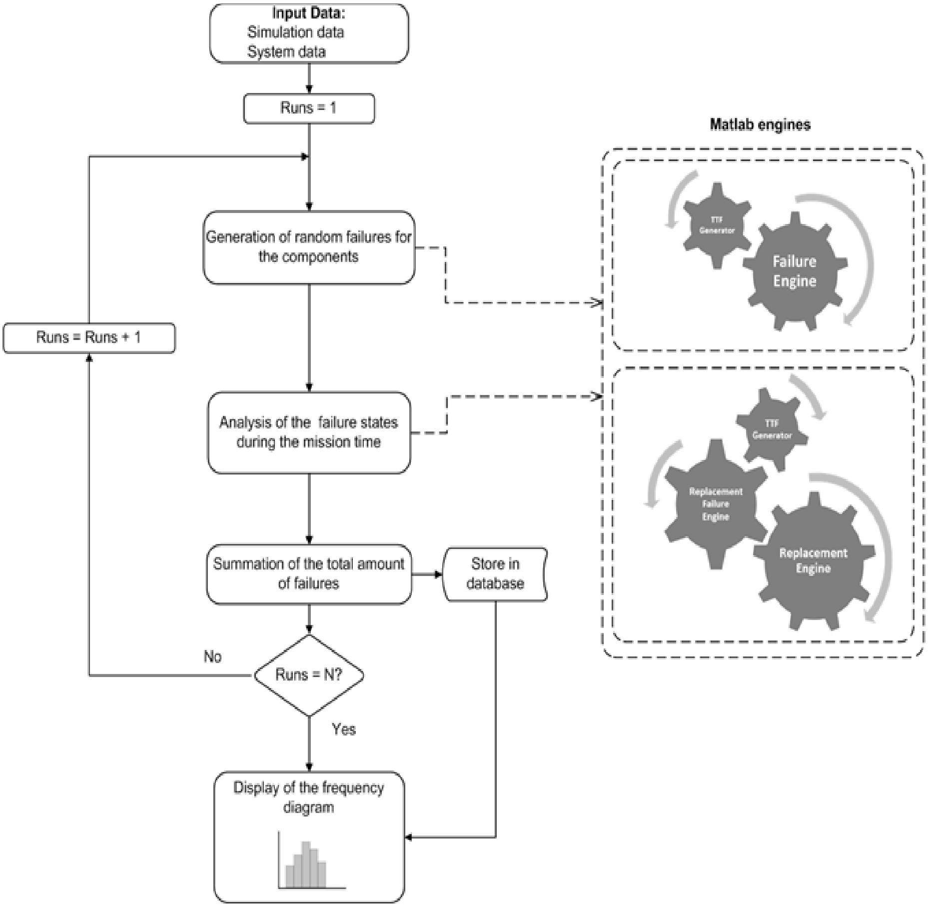

Figure 60: Flowchart representing the principle of operation of the MCS algorithm **[74]**.

The simulation starts with the generation of random failures of every component in the radial feeder system. This is done in the Matlab engine 'TTF generator' where a random number for the random variable TTF is generated from the associated probability distribution of the component. After this, the failure states are determined using the 'Failure Engine' to define if the failures occurred within the mission time. All failures outside the mission time are neglected. For failures within the mission time a replacement is performed. A failure of either a cable or a joint leads to the replacement with two new synthetic joints and a small length of XLPE cable. In order to check if these newly installed components fail within the remaining mission time, a TTF is generated and analysed for these component. All simulated failures within the mission time are summated and stored in a database. The whole process is repeated 5000 times and finally the results are shown in a frequency plot of the amount of customer outages is.

Appendix F

Non-technical triggers for risk management

Non-Technical Risks: These risks are not considered in the relatively technical maintenance management, but considered by strategy specialists and policy analysers. Additionally, these risks are normally for long-term, so their probabilities and consequences are difficult to predict (e.g. the case that Germany abandoned nuclear power). Consequently, asset managers can only contribute to control these risks through providing innovative technical design of assets/asset systems. In the following, we discuss each level of AM from a non-technically triggered risk viewpoint.

- At the *strategic level*,
    - Analyse future networks, determine risks with commercial or societal stimuli.
    - The solutions to these risks are frequently not optimised in standard risk management system such as risk register. Since they are long-term and difficult to quantify (i.e. unlikely to be included in a KPI system), the asset portfolio should simply be redundant, robust or flexible enough to survive in each scenario.
    - Such robustness or flexibility can be interpreted technically as hard requirement on asset systems. These requirements are called strategic requirements.

- At the *tactical level*, an equally important task is to design new/replaced/refurbished asset systems, as well as their preventive maintenance plans, so that they can cope with strategic requirements.

- The *operational level* should investigate ways to operate and maintain new components and environments introduced by strategic requirements.

The right triangle in figure 43 represents the management of risks with non-technical stimuli. It has a larger area at the strategic level (S2), because the diversity (different specialities) and long term characteristic of these types of risks require a wider human resource (knowledge of overall system) to study.

Appendix G

Case Studies of the Application of Condition Monitoring

Case study 1: Experience of Online Partial Discharge Monitoring on a Wide-Area Medium Voltage Network

In this case study, the application of a handheld online monitoring device to detect partial discharges (PD) is described. The measurements were performed in the medium voltage (MV) network of Stedin in the Netherlands [83].

Parts of the MV network have been designed with the principles of un-earthed star-point grounding (floating system). An advantage of such a design is that the voltage between the phases themselves, in case of a phase to ground fault, is hardly influenced. Consequently, the loads are not changed and the system remains in operation. However, the downside to this is that the absolute voltages of the healthy phases are increased by a factor $\sqrt{3}$ in the case of a phase-to-earth. As result of a dormant fault in an un-earthed 10 kV network of Stedin, a long lasting earth fault (> 6 hours) occurred. After this dormant fault was finally isolated by the protection system, it was also found from the failure investigation later on that the earth fault was the cause and had been present for approximately 6 hours. There were especially concerns about possible higher levels of PD activities in surrounding cable joints, terminations and cables. The asset managers then argued that this long lasting earth fault, which resulted in elevated voltage levels on the healthy phases, might have stressed surrounding assets and caused them to come into a critical state. As a "first line in defence", without time consuming or costly investigations, the asset managers decided to carry out measurements to get a rough initial result whether this long lasting earth fault might had stressed the nearby assets. A quick, low cost PD screening was selected.

A two stages approach was set up:

- Stage 1: A quick PD scan was performed at the primary HV/MV substation assessing the outgoing cables and local switchgear assets.

The quick scan was performed by the PD handheld device, which comprises of a combination of inductive *High Frequency Current Transformer* (HFCT) and capacitive *Transient Earth Voltage* (TEV) sensors. On the basis of the results of stage 1, Stedin would decide on one or combinations of the following stages:

- Stage 1: Perform offline PD detection and localization measurement of suspected feeders (from stage 1).
- Stage 2: Perform permanent PD monitoring measurements on suspected feeders (from stage 1).
- Stage 3: Perform a wide-area PD handheld screening on both sides of the cable and all Ring Main Units (RMU's) in the between the circuit.

Stage 1: Primary substation level PD handheld screening: At the primary (25 kV/ 10 kV) MV substation, that energizes the feeder that had the previously described earth fault, a quick PD screening measurement was carried out. In total, 27 single cable sections have been diagnosed with the PD handheld system. At the first stage an HFCT sensor was installed to measure any PD activity on the cable screen wire which is connected to the main earth point of the substation. These measurements take about 1 to 2 minutes per single feeder. Secondly, the TEV sensor was used to measure the overall condition of the 10 kV switchgear. Colour coded criticality was indicated (LEDs) and digital dB signal (acoustic) on the display. To reduce background noise level, a 100 kHz filter was used with HFCT sensor.

In table 17, the combined results from the HFCT and TEV sensors for 4 out of the 27 measured cable sections are given. Cable section A, for instance, had high PD magnitudes in both cases, namely with and without high-pass filter. However, this cable is a feeder to a local metro station and the level of high frequency noise at this location substantially influenced the measurement results, making it very difficult to draw conclusions from these. Cable section C showed, with filter, no significant PD activity and was therefore classified as "no action required". It was found that cable sections B and D have moderate PD magnitudes and also relatively high levels for local (switchgear) dB value (TEV sensor).

Table: 17 Results from stage 1 measurements for 4 out of 27 measured single cable sections and switchgears (combination of HFCT and TEV sensors).

HFCT (LED) *b - blink (not constant)*																		**TEV (average dB)**		**Overall PD index**
Section	**Measured phases**	**PD signal (no filters)**								**PD signal (100kHz filter)**										
A	**L1**	🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	🟧	🟥	🟥		**HI**	🟩	**High**
	L2	🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	🟧	🟥	🟥			⬜	
	L3	🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	🟧	🟥	🟥			⬜	
B	**All**	🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	⬜	⬜	⬜		**19**	🟩	**Moderate/High**
		🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	⬜	⬜	⬜			🟨	
		🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	⬜	⬜	⬜			⬜	
C	**All**	🟩	🟨	🟨	🟧	🟧 **b**	⬜	⬜		🟩	⬜	⬜	⬜	⬜	⬜	⬜		**17**	⬜	**No action**
		🟩	🟨	🟨	🟧	🟧 **b**	⬜	⬜		🟩	⬜	⬜	⬜	⬜	⬜	⬜			⬜	
		🟩	🟨	🟨	🟧	🟧 **b**	⬜	⬜		🟩	⬜	⬜	⬜	⬜	⬜	⬜			⬜	
D	**L1**	🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	🟧	⬜	⬜		**21**	🟩	**High**
	L2	🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	🟧	⬜	⬜			🟨	
	L3	🟩	🟨	🟨	🟧	🟧	🟥	🟥		🟩	🟨	🟨	🟧	🟧	⬜	⬜			⬜	

🟥	High PD activity: Need to be checked from both sides or another method as soon as possible
🟧	Moderate to High: Need to be re-checked with PD handheld or another method within 1 year
🟨	Moderate: No action necessary within 2 years
🟩	No PD (no action necessary): No action necessary within 5 years

Therefore, Stedin decided to carry out a wide-area (far end and multiple RMU) network PD handheld measurement for sections B and D, in particular, from the far end side of the cable and at all RMU's in the circuit between both ends of the cable.

Stage 2: Monitoring on a Wide-Area Medium Voltage Network: In stage 2, the cable sections B and D were measured from the far end. Section B is an outgoing feeder with multiple MV/LV secondary stations in between. In total, 12 secondary MV/LV substations and all intermediate cable sections connecting these MV/LV substations (behind cable section B) were measured with the PD handheld device at the terminal. From these online measurements, it was found that two MV/LV locations had high local PD activity. Finally, in collaboration with the maintenance department and the service provider, it was decided to investigate these two switchgears (RMU) at these MV/ LV locations by means of in-depth visual inspections. Under controlled conditions, in order to continue the electricity supply, they were taken out of service and inspected.

In figure 61, a one-line diagram schematic representation is given of the 12 locations. Location 1 (L1) corresponds to cable section B (in table 17) and location 2 (L2) to cable sections D (table 17). Locations 3 through 12 (L3-L12) are the MV/LV secondary substations behind cable section B.

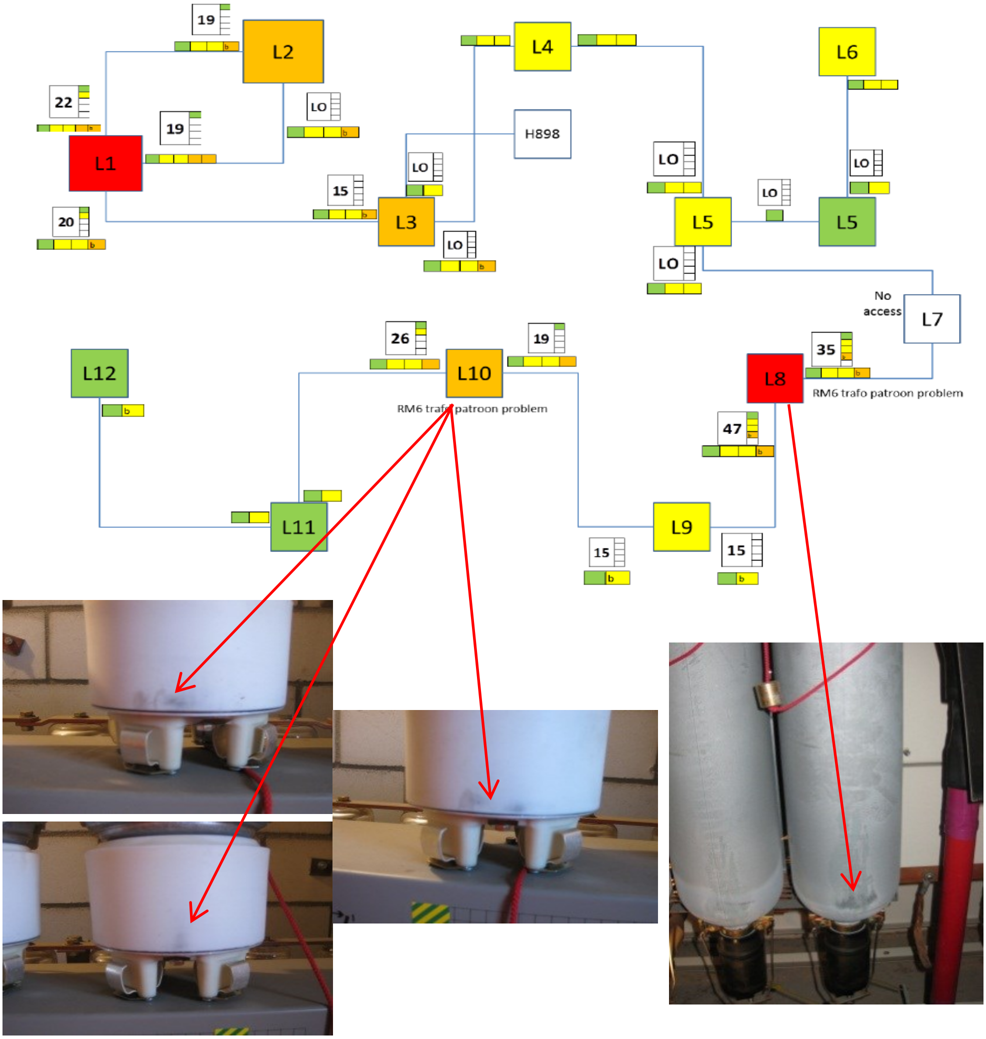

Figure 61: Results of PD measurements for 12 locations. Locations L8 and L10 were taken out of service for in-depth inspections. L8 and L10 had a higher TEV (capacitive) and HFCT (inductive) results of PD activity locally. During the inspection of these MV switchgears (RMU's) suspect traces were found, which may be a possible source of the higher HFCT and TEV results. However, this was not confirmed.

In summary, the wide-area approach of handheld PD screening technology has provided Stedin with a fast and low cost method to measure the PD activity and assess potential high risk assets. It was found that the assets, with high PD activity, had traces of possible degradation on different locations in the asset of which, as far as known, the utility had no experience. On the basis of these findings, it was decided to reach out to the manufacturer of this switching equipment to further investigate the suspected traces and its possible causes and mitigating actions.

Overall, the application of online PD handheld screening led to the detection of possible indications of defective or weak insulation systems in a fast and low cost way. Nonetheless, the correlation between measurements from stage 1 and stage 2 is not yet clear enough. If the measurement results of stage 1 would not have been threatening, it would not automatically have meant that location L8 and L10 were free of suspect defects. This might imply that measurements with the PD screening tool, solely, at the far ends are not sufficient enough and justifies measurements at all adjacent MV/LV locations. This may be attributed to the attenuation of PD signals and disturbance of noise signals in wide-area distribution networks.

Case study 2: Continuous Diagnostic Measuring for MV Power Cable Networks

In this case study, an experience with a continuous monitoring system for medium voltage power cable networks is given. At present, 83 systems are being used, many of these guarding the main feeders in the city of Rotterdam in the network of Stedin. This monitoring system works as described in [23], [82]. Briefly described, two inductive PD sensors are placed in the cable network, one sensor at position A and the other at position B. These positions can be several kilometres (km) apart from each other. From a defect spot X between these positions A and B, electromagnetic waves from PD pulses travel along the cable in two directions, away from the defect spot X. Each of the two sensors cab detects the PD pulse passing. The PD amplitude, together with the time of arrival, is stored.

Here we will share an example where a defect was detected and preventively removed. In figure 62, the PD activity for one the MV power cables is shown. This cable is 3.1 km in length (with a mix of PILC and XLPE cables). The joint at 1647 meters showed considerable increase of the PD intensity over a period of two months. This first led to a warning level 2 (yellow: meaning that there is striking partial discharge activity, somewhat increased failure probability, the advice is to monitor the development over time), followed by a warning level 1 (red: meaning that there is a high failure probability, the advice is to replace immediately in critical circuits), shown in figure 62.

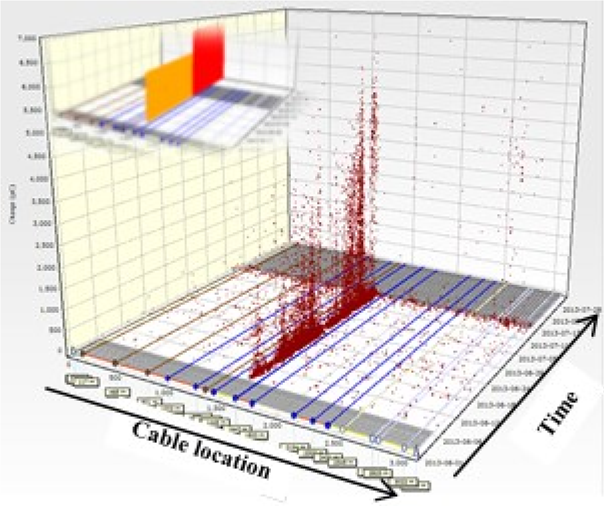

Figure 62: PD map as a function of time (z-axis) for the whole cable (x-axis). The PD intensity is plotted on the vertical axis [23].

Based on this warning level 1, Stedin did a further check with an *offline* PD test (OWTS) in order to pinpoint the defective location with more accuracy. Through this, a defect location was identified and the joint was replaced and dissected. By doing so, a failure in the city centre of Rotterdam was prevented. In the transition joint at the XLPE cable side, it was found that there were clear sparking traces from the semiconducting screen towards a metal tube. The defective spot inside the joint as found during dissection is shown in figure 63. The weakness found is subject of further investigations.

Figure 63: Part of the defective joint showing clearly the degradation of the insulation screen.

List of Publications

Book Chapters

R. P. Y. Mehairjan, Q. Zhuang, D. Djairam, J. J. Smit, "Upcoming Role of Condition Monitoring in Risk-Based Asset Management for the Power Sector", Engineering Asset Management - Systems, Professional Practices and Certification, ISBN 978-3-319-09506-6, pp 863-875, Springer International Publishing, November 2014

R. P. Y. Mehairjan, M. van Hattem, D. Djairam, J. J. Smit, "Risk-Based Approach to Maintenance Management Applied on Power Transformers", Volume 1 Proceedings of 2014 World Congress on Engineering Asset Management, ISBN 978-3-319-15535-7, pp 415-434, Springer International Publishing, March 2015

R. P. Y. Mehairjan, M. van Hattem, D. Djairam, J. J. Smit, "Development and Implementation of a Maturity Model for Professionalising Maintenance Management", Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM) 2015, ISBN 978-3-319-27062-3 Springer International Publishing, 2016

Co-authored Journal

Ł. Chmura, P. H. F. Morshuis, R. P. Y. Mehairjan, J. J. Smit, "Review of the Residual Life Assessment of High-voltage Cables by Means of Bottom-up an Top-down Analysis—Dutch Experience", Vol.41, No.4: 1-11, High Voltage Engineering April 30, 2015.

Co-author CIGRE Technical Brochure

"IT Strategies for Asset Management of Substations - General Principles", CIGRE WG B3-06 TF05 brochure 576, April 2014.

"Guidelines for the Use of Statistics and Statistical Tools on Life Data", CIGRE WG D1.39 *(active WG, draft document)*

"Expected Impact of Future Grid Concept on Substation Management", CIGRE WG B3.34 (*active WG, draft document)*

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R. P. Y. Mehairjan, D. Djairam, Q. Zhuang, J. J. Smit and A. van Voorden, "Statistical Life Data Analysis For Electricity Distribution Cable Assets - An Asset Management Approach-," in IET IAM International Asset Management Conference 2011, London, 2011.

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R. P. Y. Mehairjan, D. Djairam, Q. Zhuang, A. van Voorden and J. J. Smit, "Statistical Approach to Establish Failure Behaviour on Incomplete Asset Lifetime Data," in Proceedings of IEEE International Condition Monitoring & Diagnostics Conference , Bali, 2012.

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S. A. V. Goerdin, R. P. Y. Mehairjan, A. M. Hanea, J. J. Smit and A. M. van Voordem, "Application of monte Carlo Simulation to Support Risk-based Decision Making in MV Distribution Networks," in 23rd International Conference on Electricity Distribution CIRED, Lyon, 2015.

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Awarded Paper

Outstanding Student Paper Award, IEEE CMD 2014, Jeju, South-Korea

R. P. Y. Mehairjan, F. Steennis, G. C. Montanari, P. Morshuis, D. Djairam and J. Smit, "Experiences with the Introduction of Online Condition Monitoring in Asset Management for Distribution Networks," in IEEE CMD 2014, Jeju, 2014.

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In May 2011, I embarked on a journey in which I committed myself to pursue a part time PhD-research and work at a company the other part of the time. During these years I have been challenged to combine scientific and practical work with each other. In doing so I have learned that social skills, maximization of the mind-set, own personal development and leadership is essential in this combination. Perhaps, I will benefit the most from the latter in future, especially from the soft skills I developed, the patience, perseverance and self-motivation I learned to master.

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My journey continues…

Thank you

Ravish P. Y. Mehairjan

Curriculum Vitae

Ravish Preshant Yashraj Mehairjan was born on 11th of April 1987 in Paramaribo, Suriname. He completed the Algemene Middelbare School (A.M.S.) in Paramaribo, Suriname (2005) and studies Electrical Power Engineering at Anton de Kom University of Suriname where he graduated for his Bachelor of Science degree with " Cum Laude" in 2008. From 2008 to 2010 he studied Electrical Sustainable Power Engineering at the Delft University of Technology in the Netherlands, where he graduated with "Cum Laude" for his Master of Science degree in 2010. After that, in 2011, he joined Stedin Distribution Network Operator (DNO) in Rotterdam as a specialist in Asset and Network Management. Since September 2015 he works as a Lean Six Sigma Blackbelt process improvement and change management professional at Stedin. Along his job at Stedin he started in 2011 with a part-time PhD research at Delft University of Technology at the High Voltage & Asset Management group. He has represented the Netherlands and Stedin in CIGRE working groups B3.06 and B3.34 and as secretary for working group D1.39. In 2014 he has made it into the Top 100 Best Young Professionals of Memory Magazine in the Netherlands.