Eindhoven University of Technology

MASTER

Optimization model for maintenance planning
an affix to asset life cycle planning

Stam, D.J.

Award date:
2018

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain

Master Innovations Science
Department of Industrial Engineering & Innovation Sciences
Technology, Innovation & Society Research Group

Master Sustainable Energy Technology
Department of Electrical Engineering
Electrical Energy Systems Research Group

Optimization model for maintenance planning: an affix to asset life cycle planning

Master Thesis

David Stam

Supervisors:
Prof. Dr. F. (Floortje) Alkemade (TU/e, TIS)
Prof. Dr. ir. J.G. (Han) Slootweg (TU/e, EES)
Dr. N. (Nikolaos) Paterakis (TU/e, EES)
R. (Reiner) Petersen (Liandon)

Eindhoven, December 2018

Preface

It was halfway March 2018 when I started with the final journey of my masters. Now eight and a half months later this thesis probably concludes my career as a student. During this period I have been able to learn and explore a lot, at one of Netherlands its key facilitators when it comes to heat and electricity, Alliander. From the days in the field, running along with the technicians, to the conceptual brainstorming with asset managers, I have been able to do and see it all. Aside from the knowledge I gained during those activities, they were a welcome variation to the sometimes tough process of writing a thesis. Therefore, I want to thank all those people at Alliander for their genuine interest and open-mindedness with respect to my project.

Although there have been many people I spoke to during my time at Alliander, there are several persons I want to thank individually. First of all, I would like to thank Reinder Petersen who trusted me with this assignment and provided valuable input where needed. Secondly, I would like to thank Willem Haanstra and Ihsan Karakoc for their feedback and input during several brainstorm sessions. Those provided me with the conceptual knowledge to put things into perspective. Finally, I would like to thank Jeroen van de Logt, for helping me with the R programming language and understanding the input data needed for this research.

Besides the people at Alliander, I also want to thank my TU/e supervisors. Combining two master programs did put some stress on some aspects of the thesis, but in the end, it seems like we have managed. Nikos, I would like to thank you for your feedback throughout the research, especially on the modelling parts of my research. You provided me with valuable knowledge and it was always a pleasure working with you. Floor, I would like to thank you as well, for making me reflect on my own research from an Innovation Science perspective. Furthermore, you made sure I kept on track and provided me with valuable feedback where needed. Finally, I would like to thank Han Slootweg, Guus Pemen and Onder Nomaler for being part of my graduation committee. Therefore, providing the critical input needed for research to be valuable.

Finally, I would like to thank my friends and family. Especially my parents, for their continued support and trust in my capabilities. During my time as a student, you motivated me to follow my (broad) interests, without ever pushing me into certain directions. Through this freedom, I ended up combining two master programs, thank you for that. By doing so I also learned a lot about myself and the career I would like to pursue.

David Stam

December 2018

Abstract

Introduction

Reinforcements to the electricity grid, sensor installation, facilitating new grid connections and grid maintenance, these are just a couple of the activities carried out by the Dutch distribution system operators (DSOs). Especially now, due to an increased demand for new grid connections to facilitate renewable energy sources (RES) and building projects, the demand for a DSO its resources is high. However, keeping up with this demand turns out to be a challenging and almost impossible task for the DSOs. The current shortage of technical personnel, that is supposed to carry out those activities, makes DSOs look for alternative ways to make sure its technical personnel is deployed as efficiently as possible. Based on the input of one of the Dutch DSOs, Alliander, room for improvement has been identified in the maintenance personnel allocation process. Currently, this allocation process is inconsistent, because different engineers put different maintenance priorities to identical assets. To overcome this problem a more objective allocation process needs to be in place.

Making the allocation process objective, implied that assets should be managed consistently according to organizational standards. In this research, it was tried to objectively quantify some of the organizational standards. Moreover, the aim was to find the optimal balance between some of those standards to make sure assets would be managed consistently. To achieve this, an optimization model has been developed that could make asset management (AM) at Alliander more efficient.

Aside from the development of the optimization model. The importance of an organization its dynamics was also recognized. Especially with respect to innovation and change, because the problem mentioned before will require changes or innovation at Alliander. Therefore, finding important organizational factors that could facilitate change/innovation was also aimed for.

Methodology

In this research, the asset life cycle planning (ALCP) methodology has been used as a starting point. ALCP is a state of the art AM methodology that focuses on the way, Technical, Economical, Compliance, Commercial and Organizational (TECCO), developments can impact the assets lifetime. Moreover, it can also indicate what actions to take when those developments occur. These developments and maintenance go hand in hand. However, the technical deterioration of an asset is currently only monitored subjectively. Leading to inconsistent technical statuses of different assets. To overcome this inconsistency, an optimization model has been developed that gives the optimal maintenance interval based on their technical and economic characteristics.

For this research, failure data regarding 50 kilo Volt (kV) circuit breakers were used as the technical input for the model. Whereas, the cost of different maintenance activities was used from an

economic perspective. By applying several data transpositions and applying optimization software, for each of the different circuit breaker types, the optimal maintenance interval and activities were identified. Besides the optimization through modelling. The organizational characteristics that could contribute to implementing innovations/changes, e.g. the optimization model, were identified as well. This was done by analyzing different literature regarding the impact of change. From this literature, in combination with practical experience, some key characteristics were identified.

Conclusions & recommendations

From the results, it can be concluded that the optimization model could add significant value to the ALCP methodology. Furthermore, a deeper integration of ALCP and the model is possible. By integrating some of the subjectivity of AM into the model. Aside from the optimization, several characteristics were identified that could facilitate change/innovation. Such as, good organizational involvement, attention to job security and being goal oriented. Besides those characteristics, it is advised that a continues improvement (CI) strategy is followed.

The results of this research provided valuable insights and show the potential for data integration in the ALCP methodology. By which the personnel allocation process could be made more consistent. However, the methods and results of this research do leave room for improvement. May it be either in a general scientific context, with respect to Alliander's operations or both. One of these improvements lies in the fact that this research focused on maintenance allocation. In practice, maintenance and inspection are two integrated activities. In recent studies similar optimizations have been done, but for inspections. In order to really capture the full potential of optimization with respect to personnel allocation in AM, an integration of both would be recommended. A second important improvement to be made is the data quality. Although the current data does provide valuable insights, it is highly recommended to make improvements in the data monitoring and processing. This way the underlying failure data becomes more consistent and easier to analyze.

Contents

List of Figures

List of Tables

Acronyms

AGAN	as good as new.
ALCM	asset life cylce management.
ALCP	asset life cycle planning.
AM	asset management.
CI	continues improvement.
DSO	distribution system operator.
EU	European Union.
IDE	integrated development environment.
KA	Klimaatakkoord.
kV	kilo Volt.
OPL	optimization programming language.
PDCA	plan-do-check-act.
RES	renewable energy sources.
RIDM	reliability increase due to maintenance.
SDCA	standardize-do-check-act.
SF6	Sulfur hexafluoride.
TECCO	Technical, Economical, Compliance, Commercial and Organizational.
YCC	yearly conservation cost.
YCT	yearly conservation time.

1. Introduction

1.1 Context

In October 2014, the European leaders adopted the ”2030 climate & energy” framework. This framework was developed to put the European countries on their way towards the 2050 targets of the Paris Agreement. In the framework key European targets for 2030 have been set. Aiming for a reduction of greenhouse gas emissions of, at least, 40% (compared to 1990) and a minimal share of 27% renewable energy (General Secretariat of the European Council, 2014). Each member of the European Union (EU) will have to play its part in achieving those targets. Therefore, the Netherlands has recently created its own roadmap to make sure those targets will be achieved.

In the Dutch roadmap, called the Klimaatakkoord (KA), the European goals have been made more specific. The targets set in the KA for CO_2 reduction are slightly more ambitious than those set by the EU, with 49% per cent to 40% respectively. Additionally the KA shows which sectors will contribute to those CO_2 reductions and to what extent. One of those sectors is the electricity sector, aiming to reduce its yearly CO_2 emissions 20.2 Megatons by 2030 (Rijksoverheid, 2018). This reduction will partially be accomplished by an increased use of renewable energy sources (RES). Two RES that the Dutch government stimulates for the electricity sector are wind turbines and solar panels (Rijksoverheid, 2018). Several plans for new wind parks have been made already and it is expected that the overall wind energy capacity will rise towards 11.5 GW by 2030. In the same period, the total capacity for solar energy is expected to increase towards 20 GW (Rijksoverheid, 2017).

The increase in the amount of RES will impose, and already imposes, serious consequences for the distribution systems operators (DSOs). At this point, the DSOs already lack the technical personnel to meet their workload (Blom, 2018) (ANP, 2017) (Sjors Moolenaar & Natasja de Groot, 2018). With the increasing amount of RES in distributed areas, new problems will occur that put even more stress on the DSOs (Verbong and Geels, 2007). One of those problems is the congestion of the local electricity grid. Meaning that more electricity is produced than the system can transport. Leading, in rare cases, to the disconnection of solar panels (Trommelen, 2016). The future developments will make those cases more likely and will put even more stress on the already demanding workload.

To overcome the increase in workload more technical personnel is being recruited and schooled, but this is a very time-consuming process. Furthermore, it is only solving part of the problem, since the amount of technical personnel is limited. Therefore, the asset management (AM) departments of different DSOs are reconsidering the way they work. With the current availability of data and the wide range of data processing techniques, DSOs feel that their way of working might improve from a more data-driven approach. This feeling is fueled by their current dependence on subjective/experience-based prioritization of maintenance. To illustrate this subjectivity, there have been cases where, dependent on the person, the condition/risk status of an asset and the corresponding maintenance interval differ completely. Resulting in the prioritization of relative unimportant assets, in a field where one wishes to use every man hour to its maximum potential.

Data may provide valuable insights and potentially improve the prioritization process. However, for data driven maintenance to realize its potential it is important that employees adopt and accept the changes in the work processes, this is not trivial. This non-triviality is supported by several studies that identified repulsive behavior at employees during change processes(Hansson et al., 2003)(Jetten et al., 2002).

In this thesis, the potential of data-driven maintenance is explored via a case study at Alliander N.V. Since maintenance is part of AM, one needs to consider the latest theoretical developments in the field of AM. AM a field that focuses on the application of an organizations its resources, to achieve a set of objectives for an asset its lifetime. Where, more recently the notion of risk has also become a more integrated part of AM. Besides considering the latest developments in the AM field, it is also important to consider the goal of the DSOs: a more consistent and efficient maintenance prioritization process. The aim is to provide new insights in the field of AM and show the potential of a more data-driven prioritization approach. However, as the previous paragraphs indicates, success, when implementing a new method, is not guaranteed. The employees have to be managed accordingly in cases of change. Therefore, this research also aimed for the identification of several management implications to facilitate change.

This research is conducted at Alliander N.V. Alliander focuses on managing different parts of the distribution system in the Netherlands. It originated in 2009 after Nuon was forced, by law, to split its energy generation and distribution divisions. The distribution division continued as Alliander (Alliander, 2018). Currently, Alliander N.V. consists of quite some companies itself. Of which, Liandon and Liander are the biggest. Liander is one of the three biggest distribution system operators in the Netherlands. Whereas, Liandon manages the complex medium- and high voltage distribution systems for Tennet and Liander.

1.2 Problem statement

In this thesis the realms of a more data driven approach are explored by a case study. This case study is conducted in collaboration with one of the Dutch DSOs, Liander, and one of its facilitating partners Liandon. The focus of the case study is on the maintenance protocol of Liandon. For this case study, several problems are identified. First, the current AM techniques used by Liandon result in inconsistent maintenance advice. Although, there is currently no measurable data source/reference material available to quantify the inefficiency of this maintenance protocol. There is a general feeling in the organization that the consistency and efficiency of maintenance can and needs to be improved. The inconsistency is caused by the fact that the asset condition determining process allows for significant amounts of subjectivity. To overcome this problem it is tried to provide an AM methodology that includes data to make the condition determining process more objective.

The inclusion of data does introduce a second problem. If a data-driven approach is developed for AM, the boundaries and implications of such an approach are still unknown. Those boundaries need to be consistent with current day literature regarding AM, and, on the on the hand, should suffice the goals of Liandon. Considering that AM allows for the inclusion of company-specific objectives, combining AM theory and business objectives is possible (Arunraj and Maiti, 2007). However, the definition of AM does impose the company to define their objectives from a multidisciplinary perspective (Pudney, 2010):

“Asset management is a multidisciplinary practice that applies human, equipment and financial resources to physical assets over their whole lifecycle to achieve defined asset performance and cost objectives at acceptable levels of risk whilst taking account of the relevant governance, geopolitical, economic, social, demographic and technological regimes.”

When a company defines its objectives within the scope of AM, it preferably, just like Alliander, wants to find the optimal balance between those objectives. Doing so would make the decisions about an asset more consistent. Achieving this optimality in an objective way is, therefore, the goal of this research. The research question corresponding to this goal is the following:

- How could an optimization model be used to make asset management of distribution system operators, more efficient?

Although, finding optimality objectively is the main research goal. It is also deemed important to take the implementation of new methods into account. As mentioned in section 1.1, change management is important in those cases. Since, incorrect change management could lead to resistance of employees. Therefore, the aspect of change with respect to asset management is also taken into account. Resulting in the following list of sub-questions, used to cover all important aspect of this research:

1. What is the state of the art asset management practice?
2. Which objectives of asset management can be used for optimization?
3. How can these objectives be optimized?
4. How can an optimization model be implemented in current asset management practice?
5. How can asset management organizations, like Alliander, facilitate a smooth implementation of innovations, like the optimization model?

Since Liandon aims for a more consistent maintenance/replacement decision process. The focus of this research is on the operational phase of an asset. It is recognized that there are many other decisions that could be made with respect to an asset. However, the underlying problem as explained in section 1.1, is about the allocation of maintenance personnel. Since maintenance personnel is mainly involved in the maintenance or replacement activities of an asset, only the operational phase of an asset was considered. The pre- and post-operational phases fell out of the research scope.

1.3 Scientific and societal relevance

In this research the subjectivity of the maintenance decision process is the main problem. Although, like previously mentioned, there is no quantification of this problem, there is a general feeling at DSOs, or at least, Liandon that the current inclusion of subjectivity leads to inefficient maintenance. To cope with the subjectivity problem, this research proposes a new way of assessing the relevance of maintaining an asset, based on the risk it imposes to the organization. The definition of risk, in this case, is subjective in itself, but is dependent on the organization. The subjectivity problem referred to previously focuses on the subjective notion of risk, that employees have. Especially on the difference between the notion of the employees and the notion of the organization.

Since the definition of risk is subjective it is hard to scientifically generalize the definition. However, throughout literature, one can find similar interpretations of risk when put in the context of AM. The further one wishes to define risk the more case dependent, thus subjective, risk gets. Therefore, the applicability of this research outcome will be subjective in itself, but, since this subjective notion of risk is very similar for other organizations it might still provide valuable insights in the way risk is assessed and managed.

So, when one is aware of the subjectivity risk in itself implies, this research can contribute in several ways. Firstly, the current AM practice at Liandon relies on the subjectivity of maintenance personnel (Appendix A). By quantifying some of the AM objectives and expose those objectives to an optimization. The aim is to reduce the irregularity in the maintenance allocation process. The optimization problem that is addressed in this research is specific for Liandon. However, similar problems could be perceived by other organizations as well. Since it is known that more, similar, organizations work by the same AM protocol as Liandon.

Besides the quantification of AM practice, change management literature has been analyzed. This has been done for two reasons. Firstly, because the outcome of AM strategies could imply changes in the organization, potentially causing resistance from the employees. This is something one wants to avoid. Secondly, the use of optimization in AM would be a change in itself. Both of those potential changes need to be dealt with in an organization. Therefore, it was deemed important to analyze characteristics of an organization that facilitates or initializes progressive change.

Meaning that the outcome of this thesis provides an increment to current AM practice. Aside from the optimization of maintenance allocation, the impact of implementing new methodologies in an organization will be analyzed as well. This provided insights into how to deal and facilitate change within an organization like Liandon.

1.4 Thesis outline

The goal of this research is to answer the main research question. In order to do so several sub-questions have been formulated. These sub-questions will be answered in the different chapters of this thesis. The first sub-question will be answered in Chapter 2. Chapter 2 will also provide some additional theoretical background needed for this research. The second and third sub-question will be answered in Chapters 2,3 and 4. Where Chapter 3 describes the methodological steps taken to answer all different aspects of this research. Whereas, Chapter 4 shows the results of the optimization model. The fourth and fifth sub-question are both answered in Chapter 5. Finally, Chapter 6 rounds everything up by answering the main research question. Besides, it also reflects on the methods and results of this research.

2. Theoretical background

This chapter will discuss the theoretical findings that are deemed important to position this research in scientific literature. Since this research aims to provide new insights into AM it is important to understand it thoroughly. Therefore, this chapter will start off with discussing the concept of AM. Secondly, the latest developments regarding AM will be discussed. From these developments, the asset life cycle planning (ALCP) has been developed by (Ruitenburg, 2017). The ALCP will be discussed and potential expansions on the method are proposed. Finally, theoretical context regarding network reliability modelling is provided.

2.1 Asset management

Introduction

Nowadays, organizations have to think about a wide range of factors when it comes to managing their physical assets. These factors can range from the environmental impact of their operations to the safety of their staff. While keeping their financial situation as optimal as possible. With such a wide range of objectives, it is important that these assets are managed accordingly. A discipline that applies an organization its resources, to achieve a set of objectives for an assets lifetime, while keeping the risks at an acceptable level, is AM (Pudney, 2010).

Due to the multidisciplinarity of AM, some organizations struggle with finding the right approach to prioritize their objectives. Therefore, in 2004 the Publicly Available Specifications 55 (PAS-55) were developed, which can be considered the predecessor of the International Organization of Standardization 55000 (ISO-55000) guidelines (Preshant and Mehairjan, 2017). The ISO-55000 provides general principles that assure a well-structured AM practice. Although the ISO-55000 provides a good general structure to asset managers, the IEC (2015) concluded that those general principles are not specific enough to be applied to the electricity industry. Especially when it comes to a proper framework for risk management (Preshant and Mehairjan, 2017).

The fact that the ISO-55000 is non-specific is a consequence of its wide applicability. Therefore, industry-specific applications of AM theory require more detailed attention. By applying action research for specific cases, researchers have been trying to specify the AM theory for the electricity industry (Pudney, 2010)(Ruitenburg, 2017)(Preshant and Mehairjan, 2017). This is a demanding process, because the complexity of AM in the electricity industry, especially when looking at DSOs, requires a detailed description of objectives and risk. Even when one manages to properly define the objectives and risk, it remains a challenge to create a generally applicable AM methodology.

Since the creation of such a methodology, that is applicable to all assets, is a demanding process. It falls outside the scope of this thesis. However, by doing a case-study, that focuses on one asset, it is tried to contribute to the latest methodological developments in AM. Specifically for the electricity industry. To do so, the general rules of AM will be combined with the latest, electricity industry-specific, developments to create a case-specific methodology.

In the following sections, the focus will first be on specifying general principles covered by AM. After which, the focus will be on analyzing the latest methodological development regarding AM in the electricity industry.

Asset life cycle management

Overcoming the conceptual limitations of asset management

As mentioned in the introduction of this chapter, the way AM is described by the ISO-55000 is not that specific. Although it mentions that one should measure and monitor his/her objectives, it does not say how. Even so, if one wants to change his/her objectives during the assets lifetime the ISO-55000 does not provide any guidelines. In 2010, Pudney already came up with a definition of AM that tackles some of the limitations of the ISO-55000. Ruitenburg (2017) used Pudney's definition to develop the asset life cylce management (ALCM) approach. In the ALCM approach, five key characteristics of AM were identified:

- *It is a multidisciplinary practice*: meaning that all disciplines in the organization, that are relevant for managing the asset, may be involved in order to create maximum value from the assets exploitation.
- *It takes into account the entire lifecycle of an asset*: AM should not stop when the asset design at the beginning is made. Instead, when objectives, regulations, costs, etc., change, one should re-assess the way in which the asset is managed.
- *Its goal is to achieve corporate objectives*: an asset is only valuable when it contributes to the companies goals. Since these goals may change over time, the previous characteristic becomes even more important.
- *Risk and regimes should be taken into account*: where risk says something about the potential impact on company-specific values. Regimes say something about external developments, such as social pressure, changes in regulation or labour union pressure to change the working environment.
- *Ultimately it allocates an organization's resources*: Such as the allocation of the workforce/-money to specific assets.

Overcoming the practical limitations of asset management practice

In Ruitenburg (2017) the ALCP methodology was developed to asses the lifetime impact of an asset. This came forth due to the limitations of the previous approach for AM. The previous approach tried to answer the question, "*when will an asset stop to provide value to the asset owner?*" To do so, often the remaining useful life (RUL) method is used for this (Si et al., 2011). However, Ruitenburg et al. (2014) identified some weakness in this approach.

The first weakness has to do with the multidisciplinarity of AM. When AM is a multidisciplinary practice the determination of one's end-of-life should be as well. However, in current AM practice, most of the times this is not the case and either the technical aspects are analyzed, or a statistical focus on the failure mechanisms is presented. The second weakness is the availability and quality of the available data to do a quantitative analysis of the useful life.

With the ALCP those weaknesses are trying to be solved. The first weakness is solved by making sure the approach is multidisciplinary. This is done by including the Technical, Economical, Compliance, Commercial and Organizational (TECCO) perspectives, so that one analyses the remaining assets lifetime based on these perspectives (Ruitenburg, 2017). All those perspectives should be included in ALCP to assure its multidisciplinarity. How this is done will be explained in the next section. The second weakness is not directly solved in the ALCP methodology. At the time that ALCP was developed the availability of data was limited. Therefore, it was chosen not to use it.

2.2 Asset Life Cycle Planning

The goal of ALCP is to provide insight into the current and future developments regarding an asset and how to manage those developments. To do so, the steps of the ALCP by Ruitenburg (2017) have been used to properly report those developments. In this section, the general principles of those steps will be summarized.

Pre-assessment

The pre-assessment has three main functions. First, it is done to determine whether it is actually useful to do an ALCP for the selected asset. This decision can be impacted based on the available information, performance, criticality or financial impact of the asset itself, but also the amount of change in an organizations environment could influence the need for an ALCP. When all the different factors have been considered, one needs to define the detail of analysis, by defining the boundaries of the asset population involved in the analysis.

The second function of the pre-assessment focuses on the meta-level information of the asset. This may involve department-specific objectives regarding the asset, but also general organizational objectives or developments that might impact or be impacted by the asset.

The third and final aspect of the pre-assessment is the assessment of the current performance of the asset. Since the goal of ALCP is to provide a multidisciplinary perspective on the lifecycle of the asset, it is also important to define the performance of an asset in a multidisciplinary way. To do so the corporate objectives can be quantitatively or qualitatively be defined according to the TECCO perspectives.

Lifetime impacts

When most information about the current performance of an asset is known, the goal is to see which developments may impact the performance of an asset in the future. Throughout (AM) literature there have been many different ways to asses future developments. The methods used for assessing an assets developments are often highly related to one of the TECCO perspectives. Therefore, in order to ensure the multidisciplinarity of ALCP, several of the following methods need to be included in order to asses an assets lifetime impacts (Ruitenburg, 2017):

1. Failure curves (Preshant and Mehairjan, 2017)(Datla and Pandey, 2006)
2. Cost prognoses, often lifecycle costing (LCC) or total cost of ownership (TCO) (Haanstra and Braaksma, 2018)(Roda and Garetti, 2015)
3. Change in regulation (Khanna et al., 2009)
4. Market developments, e.g. if asset production stops.

5. "Others": key performance indicators (KPI's) based on organizations objectives

As mentioned in the last point of the list above, there can be more factors that have an impact on the way an asset is managed, but this is dependent on the objectives of the organization. It is often recommended to communicate with experts within the organization to identify all the lifetime impact factors.

Discussion and evaluation

When the lifetime impacts on the performance of the assets have been identified it is time to take appropriate actions to make sure their performance is guaranteed. These actions can range from new maintenance protocols to the monitoring of a lifetime impact to make sure it is maintained in time. In the end, the goal of the ALCP is to provide an objective overview of the lifetime impacts and potential actions to prevent those impacts. Often it is in the interest of the organization/client to provide some additional information of those actions as well, e.g. cost, time of action, benefits of the action. Again this also depends on the objectives of the client.

After the ALCP have been put together it important to discuss and evaluate the results with the client and other relevant stakeholders. It is important that the findings are supported by the client. Furthermore, it is important that the recommended actions and their implications to the organization are properly communicated. So that the client can understand the outcome of the ALCP.

Expanding asset life cycle planning

The ALCP methodology proposed by Ruitenburg (2017) already mentions that it is important to evaluate the results with the client and other relevant stakeholders. However, slightly more emphasis could be placed on the organizational changes that these results might impose. Since some lifetime impacts may require a change to the organization its way of operation. These changes can be called process innovations (Fondas, 1993). In those cases, there is a large body of literature that substantiates the importance of stakeholder involvement. Although this is briefly mentioned in the ALCP method, it is deemed important to expand on this topic.

Process innovation literature looks at the dynamics and capabilities of an organization that may impact the development or adoption of a new process (Das and Joshi, 2012). Some of the literature focuses more on the organizational factors that are related to an organizations ability to innovate their processes (Matthews et al., 2015)(Piening and Salge, 2015)(Khazanchi et al., 2007)(Das and Joshi, 2012). Whereas, other literature also looks at an organizations capability to change/implement such process innovations (Piening and Salge, 2015)(Vough et al., 2017)(Hameed et al., 2012). The later will be of importance for ALCP since the outcome of the ALCP could imply a change to the organization's operational processes. Therefore, the findings in literature regarding change management and process innovations may be good additions to ALCP

Before analyzing different studies on how to facilitate change. It is important to know if there is an acceptance problem with data/IT related process innovations. A meta analysis looking into the implementation of information technology (IT), confirms that certain people do not accept or even resist to the implementation of IT systems. The researchers identified that people mainly resisted, because they did not see the benefits of the change/process innovation (Cooper and Zmud, 1990). Research by Krovi (1993) also confirms that in order to successfully implement new information systems good use of change theory is necessary.

Change management

As mentioned previously the outcome of ALCP could initialize change in an organization. These changes could be sudden, slow, forced or natural, but they all require adaptation by the employees. To illustrate this, imagine the use of an optimization model by Liandon. The outcome of the model could change the maintenance interval and activities of an asset. Especially with long-term assets, employees have become used to certain routines. Changing those routines could lead to resistance, and could even cause employees to work around the changes. In order to make sure change is adopted to the best of an organization its abilities. Several key findings from the literature regarding change management have been displayed in the following paragraphs.

Schaffer and Thomson (1992) stress the importance of result-driven improvements. Meaning that one should quantify a measurable operational improvement, in order to make sure change adds value to the organization. Furthermore, they mention that activity-centred improvement strategies often rely on the fact that: "*results will take care of themselves*". Therefore, being ineffective as a change strategy. However, continues improvement (CI) strategies, which Schaffer and Thomson (1992) categorizes as an activity-centred improvement strategy, do provide a good environment to adopt and facilitate innovation (Backlund and Sundqvist, 2018; Singh and Singh, 2015; Bhuiyan and Baghel, 2005).

Furthermore, based on articles by Bala and Venkatesh (2013), Ciocoiu et al. (2015), Georgalis et al. (2015), Amarantou et al. (2018) and Straatmann et al. (2018) it can be concluded that the CI strategy incorporates many aspects related to change management. These articles did not necessarily take into account cases that used the CI strategy, but did stress the importance of employees' involvement, perceptions (of justice[1]), relation with management and job security. Of which some are also important aspects of the CI strategies. Therefore, the implementation of the CI strategy for process improvement supplemented with recent insights from change management could improve the incorporation of changes. To summarize, the most important aspects of the CI strategy and literature are enumerated below:

1. **Feedback loop:** Following the CI strategy, include the plan-do-check-act (PDCA) and standardize-do-check-act (SDCA) cycles to facilitate change (Singh and Singh, 2015). Where the PDCA initializes change and the SDCA stabilizes it.

2. **Involvement & perception management:** A positive perception towards change is often related to strong involvement within the organization. In literature several practical implications for good involvement are given:

   (a) **management - employee involvement:**
   Make sure managers build and maintain trust with their employees, in particular when a period of change is due (Amarantou et al., 2018). This also means that an employee should be appreciated or rewarded for innovative incentives. Although employee involvement is a good way to facilitate innovation, do keep in mind that employees might not know all the scopes from management. Therefore, some ideas need to be filtered out before being considered by management (Kesting and Ulhøi, 2010). From a trust perspective, in cases where employee incentives are not implemented, explanatory feedback can be used to remain trust between management and the employees.

   (b) **employee - employee involvement:**
   Within groups of employees, change is more likely to be accepted if opinion leaders have a positive attitude towards change. Opinion leaders are people with similar social status, but due to their strategic positioning, they are able to influence the opinion of others (Lam and Schaubroeck, 2000).

---

[1] **Perception of justice:** whether employees perceive that they are being treated fairly or not.

3. **Quantify goals:** As mentioned previously it is important to quantify goals. This allows for objective reflection, instead of relying on hunches and feelings.

In the end, these key parts to change management, do not only facilitate change but also stimulate bottom-up innovations. Due to the better involvement of personal and their understanding of the corporate goals, their detailed knowledge of the asset could lead to new proposals for improvement.

2.3 System reliability modelling

The reliability of systems has been the interest of many different studies. Of which this thesis is another. Two of the fundamental concepts of system reliability modelling are series and parallel systems (Figure 1) (Billinton and Allan, 1983)(Samaniego, 2007). In the following paragraphs, these two systems will be explained in more detail.

2.3.1 Series system reliability

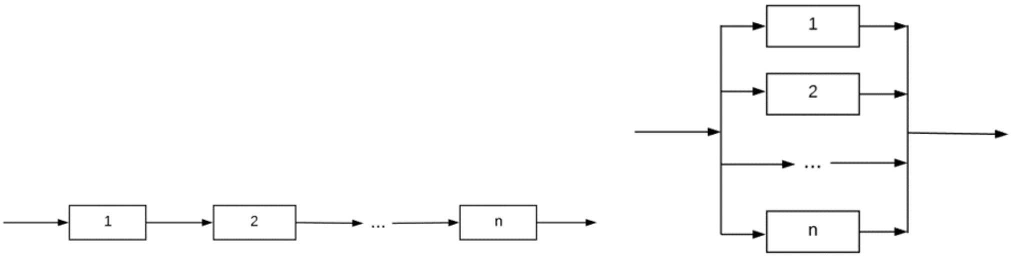
In the situation where one speaks of a series system none of the components of the system is redundant (Figure 1a). Meaning that every part of the system is needed to prevent failure. If one of the system's components fails the entire system will fail. In order to calculate the reliability of a series system (R_s) with n different components the following formula can be used:

$$R_s = \prod_{i=1}^{n} R_i \tag{2.1}$$

However, when the reliability of the system is composed of components that have their own probability distribution the overall reliability becomes a bit more complex. In order to get the reliability of the system in those cases, the probability distributions need to be transformed into reliability functions. In order to do so the probability of individual components ($P_n(t)$) first need to be integrated:

$$Q_n(t) = \int_0^t P_n(t)\, dt \tag{2.2}$$

This will result in the unreliability (Q), which is equal to the cumulative density function (Bagnoli and Bergstrom, 2005). In order to get the reliability function of each component and the entire system, the following two equations are used respectively.



(a) Series system

(b) Parallel system

Figure 1: The two fundamental reliability modelling systems.

$$R_n(t) = 1 - Q_n(t) \tag{2.3}$$

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{2.4}$$

2.3.2 Parallel system reliability

For parallel systems the different components are redundant (Figure 1b). So if one of the components fails the system will still be able to function. The mathematical representation of a parallel system's (R_p) reliability is the following:

$$R_p = 1 - (\prod_{i=1}^{n} Q_i) \tag{2.5}$$

Equation 2.2 & 2.3 are both independent of the system. Therefore, the unreliability over time can be calculated in the same way for both parallel and series system components. Therefore, the unreliability of all the components combined over time (t), is defined as

$$Q_p(t) = \prod_{i=1}^{n} Q_i(t) \tag{2.6}$$

Finally, the formula for the time-dependent reliability in a parallel system is the following:

$$R_p(t) = 1 - Q_p(t) \tag{2.7}$$

Aside from the series and parallel systems in practice there it is not uncommon that systems are both series and parallel combined. In those cases, it is important to identify the series and parallel aspects of the system and calculate them accordingly.

3. Methodology

This research is based on the ALCP methodology as presented in the theory section. The ALCP methodology is relatively new and, so far, only qualitative input has been used. However, the definition of the TECCO perspectives makes it possible to define some of those perspectives quantitatively/subjectively. Since the aim of this research is: "*making asset management more objective*", it is tried to incorporate objectivity in a quantitative way in the ALCP methodology. An explanation of how this is done in this research is presented in this chapter. Furthermore, the end of this chapter expands on the aspect of change and its implementation in ALCP.

Before explaining the most important methods of this research, it is important to show how and where the sub-questions of this research are answered. An overview for the different sub-questions can be found in Table 3.1. The methods used to answer the sub-questions can be found in the second column of Table 3.1. The explanation on how these methods will be used to answer the sub-questions can be found in this chapter. The answers to the sub-questions themselves can be obtained by reading the chapters displayed in the third column of Table 3.1.

3.1 Scope

General principles of asset management are well defined, but measuring and/or valuing of the objectives remains a difficult process (IEC, 2015). Ruitenburg (2017) developed a method that tries to do that in a qualitative way. To measure all aspects of asset management the TECCO perspectives have been developed. These perspectives are highly related to risk management, that defines similar perspectives in order to determine the risk of an asset (Preshant and Mehairjan,

Table 3.1: The methods used for answering the sub-questions and their corresponding chapter(s)

Sub-question	**Methods**	**Chapter(s)**
1. What is the state of the art asset management practice?	- Literature study	Chapter 2
2. Which objectives of asset management can be used for optimization?	- Literature study - Interviews - Data analysis	Chapter 2 Chapter 3
3. How can these objectives be optimized?	- Literature study - Interviews - Optimization modelling	Chapter 3 Chapter 4
4. How can an optimization model be implemented in current asset management practice?	- Literature study - Interviews	Chapter 5
5. How can asset management organizations, like Alliander, facilitate a smooth implementation of innovations, like the optimization model?	- Literature study - Interviews	Chapter 5

2017) (Khan and Haddara, 2003). This shows that literature evolving around assets has a general consensus about what aspects need to be taken into account.

As mentioned before, the general principles of risk have been defined in previous literature as well. However, general methods that define a way to measure and translate those principles to specific asset management strategies are scarce. Based on literature and interviews with experts it has been concluded that one of the main reasons for this is the fact that asset management combines qualitative and quantitative knowledge (Karakoc, 2018)(Chmura, 2014). In several studies methods have been provided to quantify some of the TECCO/risk perspectives (Zhong et al., 2017)(Khan and Haddara, 2003)(Yeddanapudi et al., 2008). In most cases, these studies focus on the technical and economic TECCO perspectives. However, for the other perspectives, the quantification is a lot more difficult. Furthermore, for these perspectives good predictions are hard to make (Karakoc, 2018). For example, case-specific safety issues are hard to quantify objectively. This makes it hard to objectively optimize an ALCP over all TECCO/risk perspectives.

Based on the previous paragraphs it should be acknowledged that AM and its optimization is difficult when both qualitative and quantitative objectives are aimed for. Although optimizing AM all objectives is the final goal of AM, in this research the choice has been made to optimize the ALCP based on the two TECCO perspectives that are generally well quantifiable, the technical and economic perspective. Furthermore, a recent study optimizing inspection/maintenance intervals with technical and economic input data shows the potential of this method (Zhong et al., 2017). In the upcoming section(s) more information about the construction of the optimization model will be presented.

3.2 Optimization model of maintenance interval

3.2.1 Input data

In order to make a suitable optimization model, it is important to use the right input data. For the extraction of the technical- and economic-objectives and their corresponding input data, a method similar to the pre-assessment of ALCP (section 2.2) is used. The objectives are determined through semi-structured interviews with Reinder Petersen. Semi-structured interviews are chosen because they provide the possibility to divert. Since, the interviewee only has a rough idea of the objectives, these diversions allowed for co-exploration of the objectives and their quantification.

Similarly to Zhong et al. (2017), the technical objective is quantified as the reliability of the asset. The data regarding the reliability is provided by Tazelaar et al. (2017), who developed a condition model for 50KV circuit breakers. Showing the reliability of the different circuit breakers and their underlying failure mechanisms.

The definition of the economic objectives deviates slightly from the one proposed by Zhong et al. (2017). For this research the cost structure for maintenance or a new asset is the following:

1. Cost of the material
2. Cost of the personnel
3. Cost of services

In this case potential downtime costs, as considered by Zhong et al. (2017), are not taken into account. This is done, because for 50KV circuit breakers it is assumed that they are redundant. Meaning that there should always another circuit breaker available to temporarily take over.

Furthermore, based on several semi-structured interviews with both the client and several experts of Alliander, it is concluded that the costs (as enumerated) do not provide enough information in itself. From an economical perspectives the client wanted valuable time-related information of a maintenance activity. Therefore, after several brainstorm sessions with experts, the ”yearly conservation cost” concept is developed. An explanation of this concept will be given in the next section.

3.2.2 Optimization model

Based on the requirements of Liandon and the input data provided by Tazelaar et al. (2017) several semi-structured interviews and brainstorm sessions are conducted. This is done to come up with the right technical and economical variables needed for optimizing the maintenance interval. This resulted in two concepts that are used in the objective function of the optimization model. For the technical variable, the RIDM concept is developed. Whereas, for the economical variable the yearly conservation cost (YCC) concept is developed. The calculation method for both concepts are discussed in the following two sections.

Reliability increase due to maintenance

A circuit breaker its reliability is considered to be a series system, as explained in section 2.3.1. Since a failure in one of the failure mechanisms of the circuit breaker would cause the entire circuit breaker to enter a failed state. Therefore, the reliability of a circuit breaker can be calculated according to formulas 2.1 to 2.4. This resulted in formula 3.1, that calculates the general reliability of a circuit breaker, based on the product of a circuit breaker its failure functions. Therefore, first, the reliability functions of the individual failure mechanisms have to be modelled. This is done by applying R-studio its build in cumulative density functions, combined with the input parameters provided by Tazelaar et al. (2017).

Aside from the general reliability function of the circuit breaker. This research also considers maintenance. In order to simulate maintenance the principle of ”resetting” is applied to the reliability formula. ”Resetting” refers to the fact that the age of a failure mechanism is put back to zero. While the age of the circuit breaker does not change. In such a case the failure function is said to be: as good as new (AGAN)(Appendix B). This results in formula 3.2, where $R_{i_{re}}$ indicates a ”reset” failure function. The ”reset” of a function depends on the maintenance scenario that is simulated. Where only the maintained failure mechanisms are ”reset”.

In the end, the difference between the reliability before maintenance (= general reliability function) and the reliability after maintenance is quantified as the RIDM. The steps and formulas used to calculate the RIDM are shown in formulas 3.1 to 3.3. Where n refers to the number of failure mechanisms for a specific circuit breaker. First, the reliability of the circuit breaker before maintenance (R_{cb-bf}) is calculated:

$$R_{cb-bf} = \prod_{i=1}^{n} R_i \tag{3.1}$$

Then the reliability of the circuit breaker after maintenance (R_{cb-af}) is calculated:

$$R_{cb-af} = R_1 \cdot R_{2_{re}} \cdot R_{3_{re}} \cdot ... \cdot R_n \tag{3.2}$$

In the end, to get the RIDM, the reliability before maintenance is subtracted from the reliability after maintenance:

$$RIDM = R_{cb-af} - R_{cb-bf} \tag{3.3}$$

Depending on the circuit breaker and the number of underlying failure mechanisms (n), there are 2^n maintenance scenarios. Where the amount of "reset" ($R_{i_{re}}$) and non-changing (R_i) reliability functions are different for each maintenance scenario. However, based on an interview with maintenance engineer Erik Peerdeman, it is concluded that for certain failure mechanism the corresponding maintenance activity can no longer be conducted. Either due to the lack of knowledge, the complexity of maintenance or the lack of materials. Therefore, for some circuit , the amount of maintenance scenarios is less than 2^n (see Appendix B & C).

When all the maintenance scenarios are known they are simulated over time. This was done because the reliability increase of each maintenance scenario differs with age. So in order to get a matrix with all the values for the RIDM over a time period of 100 years, a nested for loop is used to fill all the cells in the matrix accordingly. Meaning that the calculations above are executed for each maintenance scenario and for each year over a time span of 100 years.

Yearly conservation cost

The yearly conservation cost (YCC) is related to a circuit breaker its in-/decrease in reliability over time. Conceptually the YCC is the cost of a maintenance/replacement activity, divided by the time it takes for the total reliability of a circuit breaker after maintenance, to get back to the same level as before the maintenance/replacement (yearly conservation time (YCT)). Since the reliability is different for each year, the YCT can be different for each year and each maintenance scenario. When put into a formula the YCC can be formulated as follows:

$$YCC(t) = \frac{C_c}{YCT(t)} \tag{3.4}$$

Where C_c is the cost of conservation for a specific maintenance or replacement scenario. The values for C_c were estimated by Boris Ros and Patrick Bos, two (former) experts at liandon, as a contribution to the research by Tazelaar et al. (2017). The value for the YCT is constructed by the algorithm displayed below. Where Rel_a and Rel_b refer to the reliability after and before maintenance/replacement respectively. When all the YCT values are known all the YCC values can be calculated as well. In the end, the YCT and YCC values are simulated and stored according to the same principles as the RIDM values.

```
for t in time do
  x = 0
  while $Rel_a >= Rel_b$ do
    x = x + 1
  end while
  YCT(t) = x
end for
```

Score calculation

To find the most optimal maintenance scenario and interval, an objective function is constructed. In this objective function, named *score*, the different objective variables (RIDM & YCC)) are included. However, to make sure *score* represents the objective accordingly the objective variables are scaled between 0-1. For the RIDM variables, this is not necessary since its values are already between 0-1. For the YCC values the scaling is done separately for each type of circuit breaker according to formula 3.5:

$$YCC(t) = \frac{(C_c - C_{min})}{(YCT(t) * (C_{max} - C_{min}))} \tag{3.5}$$

$$C_{min} = Cost\ of\ maintenance\ scenario\ with\ the\ lowest\ cost$$

$$C_{max} = Cost\ of\ circuit\ breaker\ replacement$$

After both the YCC and RIDM are scaled the score for a specific scenario is calculated. This is done according to formula 3.6. Where the objective is to find the scenario that has the most optimal balance between reliability increase and cost.

$$Score_i = RIDM_i - YCC_i \tag{3.6}$$

$$i = a\ specific\ maintenance\ scenario$$

Technical implementation

The modelling of the RIDM, YCC and YCT is done in R-studio, which is an integrated development environment (IDE) for the R programming language. The choice for R-studio is made for two reasons. Firstly, because R-studio is the environment used by Liandon. Secondly, the R language is well suited for data handling and analysis. Making it a suited language for the purpose of this research (CRAN, 2016).

After the RIDM, YCC and YCT are constructed and calculated in R-studio they need to be saved in excel format. This is needed in order to be used by the optimization software. By using the *write.xlsx* function in R-studio the different values are extracted to excel. After which the excel files are imported by the optimization software.

Model description

For this research, the IBM ILOG CPLEX Optimization Studio was used as the optimization programming language (OPL) IDE. The IBM ILOG CPLEX IDE contains the solvers that are needed for this research (CPLEX, 2018). The overall structure of the model, which will be explained in the following paragraphs, can be applied to all circuit breaker types. Only the input data differs for each circuit breaker.

1. **Assumptions:**
   During this research, several assumptions are made that influence the way maintenance impacts the reliability of an asset. The two main assumptions that are made will be briefly discussed here. First, there is the assumption that the circuit breaker its reliability can be calculated according to the rules of a series system.

   The second assumption is the statement that maintained failure mechanisms are AGAN. Leading to a reset of the reliability function of that failure mechanism. According to several experts at Alliander, it is not very likely that maintenance will lead to an AGAN situation.

2. **Sets:**

$$T = 1..|T| \tag{3.7}$$

$$M = 1..|M| \tag{3.8}$$

3. **Parameters:**
   - $|T|$: set with the number of years one wishes to optimize over.
   - $|M|$: set with the number of possible maintenance scenarios.
   - MinReliability: gives the minimum value for the reliability that is accepted by the client.
   - MinIncrease: gives the minimum RIDM value the client wants to achieve when maintenance is conducted.
   - d: depreciation time for each failure mechanism at each time step.
   - r: reliability for each failure mechanism at each time step.
   - total: gives the circuit breakers total reliability over time.
   - c: cost for each different maintenance scenario.
   - DeprMain: normalized value for maintenance depreciation (YCC).
4. **Decision variables:**
   - Booleans
     - higher: indicates for which maintenance scenario maintenance is conducted.
     - maintained: indicates whether a failure mechanism is maintained at a give time
   - Floats
     - score: used to obtain the objective function, gives the score for all maintenance possibilities.
5. **Objective function:**
   The objective of the model is to find the maintenance scenario with the maximum score. So the score must be maximized.

$$\begin{aligned} &\text{maximize} \quad score \\ &\text{subject to} \quad score = r_{m,t} * maintained_{m,t} - DeprMain_{m,t} * maintained_{m,t} \; (\forall m \in \mathbb{M} \\ &\forall t \in \mathbb{T}) \end{aligned} \tag{3.9}$$

6. **Constraints:**
   (a) Each maintenance scenario can only be conducted once.

$$\sum_{t \in \mathbb{T}} maintained_{m,t} <= 1 \; (\forall m \in \mathbb{M}) \tag{3.10}$$

   (b) When the total reliability drops below the MinReliability value no more maintenance can be conducted.

$$total_t >= MinReliability * maintained_{m,t} \; (\forall m \in \mathbb{M}, \; \forall t \in \mathbb{T}) \tag{3.11}$$

$$\sum_{m_2 \in \mathbb{M}_2, \; t_2 \in \mathbb{T}_2} maintained_{m_2,t_2} >= total_t - MinReliability \; (\forall m \in \mathbb{M}, \; \forall t \in \mathbb{T}) \tag{3.12}$$

   (c) Limiting the amount of highest scores to one, since only one score can be the highest.

$$\sum_{m \in \mathbb{M}} higher_m == 1 \tag{3.13}$$

$$\sum_{t \in \mathbb{T}} score_{m,t} <= 10000 * higher_m \; (\forall m \in \mathbb{M}) \tag{3.14}$$

(d) Maintenance can only be conducted if the reliability increase is at least MinIncrease.

$$r_{m,t} >= MinIncrease * maintained_{m,t} \ (\forall m \in \mathbb{M},\ \forall t \in \mathbb{T}) \tag{3.15}$$

$$\sum_{m_2 \in \mathbb{M}_2,\ t_2 \in \mathbb{T}_2} maintained_{m_2,t_2} >= total_t - MinIncrease \ (\forall m \in \mathbb{M},\ \forall t \in \mathbb{T}) \tag{3.16}$$

3.3 Expanding asset life cycle planning

After the model is developed the expansion of the ALCP was analyzed. As mentioned in section 1.3 the model is expanded in two ways. First of all, by the inclusion of the optimization model. Secondly, some recommendations will be made based on the change management theory.

First of all, ALCP has to be expended by implementing the optimization model. To do so a thorough understanding of ALCP was necessary. This knowledge is obtained through the analysis of literature in the first place. However, besides literature research several expert sessions are conducted. These sessions are conducted with Willem Haanstra, PhD candidate at the University of Twente (UT) on lifecycle Costing in Asset Management, and Ihsan Karakoc, Asset Policy Advisor at Liander Asset Management. During these sessions, the different aspects of ALCP are discussed. Where the emphasis is on the potential relation between the optimization model and the subjective aspects of ALCP.

Secondly, to reduce the potential resistance of employees during change processes, as indicated in the introduction, change management was also researched. By doing a literature review (see section 2.2) the key aspects of good change management are identified. To apply the outcome of the literature study to Alliander several interviews were conducted. Based on those interviews the current way of operation was identified. With the case specific knowledge and the knowledge gained from literature an advice is given. This advice indicates which aspects of literature are most applicable to Alliander. Furthermore, recommendations are given on how to manage/organize an organization to facilitate/stimulate change/innovation.

4. Results

In this chapter, the results of the optimization in IBM CPLEX ILOG will be discussed. However, before showing the results of the optimization the pre-optimization calculations are presented. First, the reliability of a circuit breaker and its underlying failure mechanisms are visualized. Thereafter, the RIDM is visualized based on the reliability function of a circuit breaker. Both are visualized for an Oil-Pneumatic circuit breaker. This is done to give insight into the data transformations conducted to obtain the data needed for optimization. In this case, an Oil-Pneumatic circuit breaker was chosen for the visualization, but the principle is the same for all other circuit breakers. An overview of all the different circuit breakers considered in this research and a their average maintenance needs can be found in Appendix B. In the final section of this chapter, the focus will be on the outcome of the optimization model. There, for each of the different circuit breakers discussed in this thesis, the optimal maintenance interval and scenario for different reliability levels is provided.

4.1 Cicuit breaker reliability

As mentioned in section 3.2 the reliability of circuit breakers was calculated by multiplying the underlying failure functions. The total reliability indicates how probable it is that the circuit breaker enters a failed state. The results of such a calculation can be seen in Figure 2. Where the lower dark blue line indicates the total reliability of the circuit breaker. The other lines show the failure functions for the individual failure mechanisms. In this case, the reliability was modelled for an Oil-Pneumatic circuit breaker.

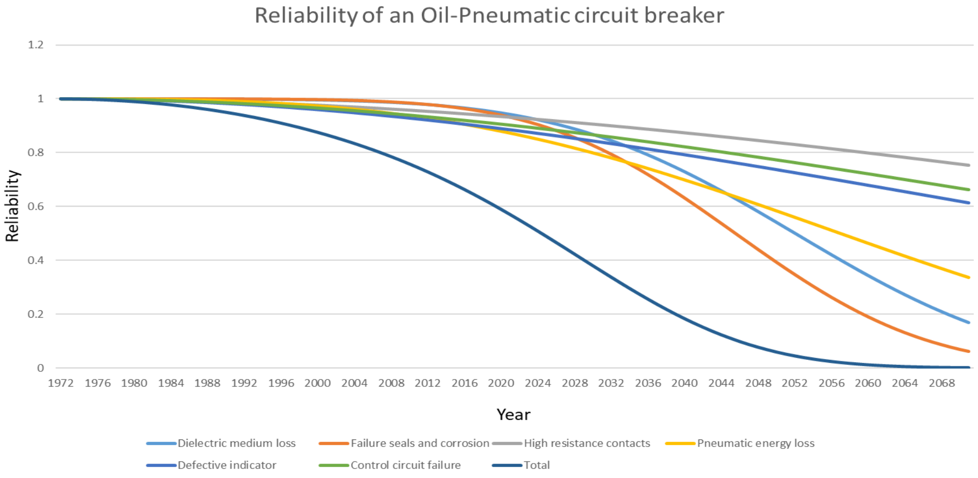


Figure 2: Reliability functions for a pneumatic, oil insulated circuit breaker.

4.2 Circuit breaker's RIDM

The first variable included in the objective function was the RIDM. A visual representation, showing how maintenance affects the overall reliability of the asset is shown in Figure 3. For the represented example, maintenance is conducted on the second and third failure mechanism of this circuit breaker.

The increase in the total reliability function, as can be seen in Figure 3, is defined as the RIDM value. For this specific maintenance scenario and time, the RIDM value is approximately 0.125. Meaning that the total reliability increased with 12.5%. This shows that significant increases in reliability for some of the underlying failure mechanisms, 14% & 48% in this case, do not necessarily lead to big increases in the overall reliability of the circuit breaker. Therefore, especially in the long term, it might be more beneficial to do maintenance on more or all failure mechanisms. However, to find the best option with respect to reliability increase and economic cost the YCC was taken into account as well. Both the RIDM and the YCC have been taken into account in the optimization model to find the best-balanced maintenance option. The results of this optimization will be discussed in the upcoming section.

4.3 Optimal maintenance scenarios

For each of the seven circuit breakers researched, the optimal maintenance interval and scenario were determined. This was done based on two input conditions:

1. The reliability of the circuit breaker was not allowed to be below 60%.
2. The increase in total reliability of the circuit breaker, when maintenance was conducted, needed to be at least 5%.

These conditions were based on common sense together with the client. However, in a future optimization those values may differ for individual circuit breakers. Under the conditions indicated

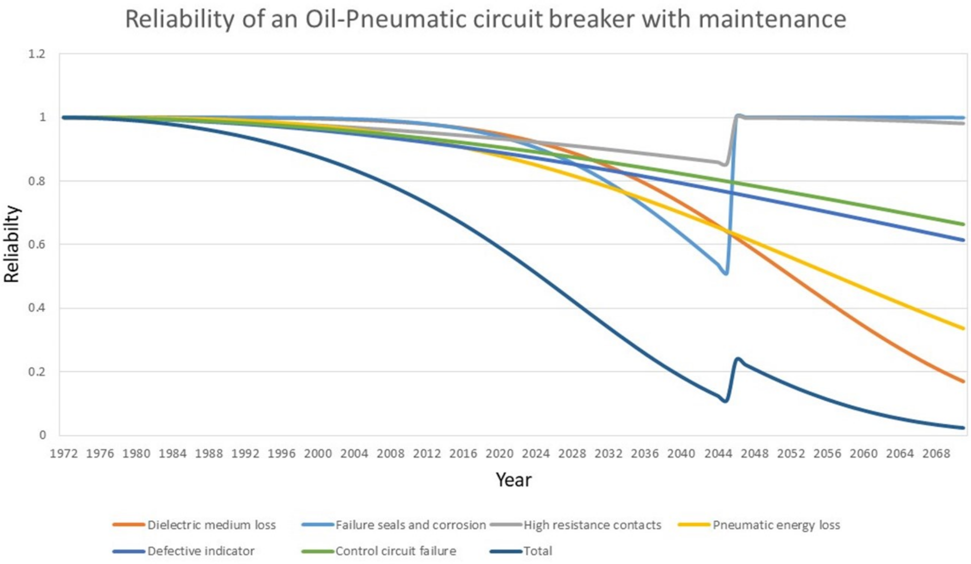


Figure 3: Example, of the RIDM for a pneumatic, oil insulated circuit breaker.

above, the optimal maintenance scenarios for the different circuit breakers were determined. In the following sections the optimal maintenance interval, scenario, RIDM and YCC will be presented for each type of circuit breaker. The failure mechanisms that are being maintained for each scenario can be found in Appendix C. In cases where not all failure mechanisms can be maintained the first (1) scenario represents replacement. In the cases where maintenance is possible, maintenance to all failure mechanisms is cheaper than replacement. Therefore, replacement is not considered in those cases. Finally, to illustrate the effect of different acceptable reliability levels, the optimal scenario was simulated for reliability levels from 90-60% with intervals of 10%.

SF6 - pneumatic

Under the assumption that maintenance leads to an AGAN situation for the SF6-pneumatic circuit breaker, replacement of components causing failure is recommended (scenario 1). Table 4.1 shows that independent of the accepted reliability level, replacement of all components is the best option. It should be mentioned that the years to maintenance, is based on the last year with a reliability above the threshold level. Because the simulation was done with time steps of a year, the reliability level didn't always reach the threshold level exactly. Therefore, the RIDM is 37,1% instead of the expected 40% in the second column of Table 4.1.

SF6 - hydraulic

For the SF6-hydraulic circuit breaker in most cases, the first maintenance scenario turns out to be the best one (Table 4.2). However, only in the case where one would accept a 90% reliability level the optimal maintenance scenario would differ. In that case maintenance scenario 2 would turn out to be the best (see Appendix C).

SF6 - spring

The SF6-Spring circuit breaker shows similar characteristics to the previous SF6 insulated breakers (Table 4.3). Again the most optimal maintenance scenario is scenario 1. Where one would replace all components related to the failure mechanisms (see Appendix B & C).

Oil - pneumatic

For the oil insulated, pneumatic driven circuit breakers it turned out that replacement was the best scenario for all reliability levels (Table 4.4). In this case scenario 1 is the replacement scenario, because for Oil-insulated circuit breaker not all maintenance activities are possible.

Oil - hydraulic

For the Oil-hydraulic circuit breaker also replacement was recommended (Table 4.5). In that sense, it was similar to the Oil-pneumatic breaker. Although, the years to maintenance was quite a bit lower for the Oil-hydraulic breaker. Indicating that the hydraulic drive chains present in Liander its system are less reliable than the pneumatic ones.

Oil - spring

The last Oil insulated circuit breaker has a spring drive chain (Table 4.6). For the Oil-spring breaker, an acceptability level of 90% is also the only case that does not need a replacement. In that case maintenance scenario 50 turned out to be the more favourable scenario.

Air - pneumatic

The final circuit breaker that was considered in this research was the Air-pneumatic one (Table 4.7). For this specific breaker only the lower reliability levels of 60 & 70% a replacement was indicated as the most optimal scenario. For the higher reliability levels maintenance scenario 9 turned out to be the most optimal one. The large difference in the YCC indicates the underlying reason for the preference of scenario 9. Since this affects the score calculation used in the optimization.

General findings

Aside from the circuit breaker specific information some general trends can be identified. One of these trends is that the years to maintenance for SF6 insulated breakers is, in general, lower than for the breakers with different insulation. This is caused by one of the underlying failure mechanism for SF6 breakers: SF6 leakage. Which occurs in SF6 insulated breakers and tends to drop in reliability rather quickly compared to the other failure mechanisms. Therefore, leading to the identified behaviour compared to other breakers.

Table 4.1: Optimization results, for a SF6-pneumatic circuit breaker, for different reliability thresholds.

	60%	70%	80%	90%
Years to maintenance	27	24	20	15
Maintenance scenario	1	1	1	1
YCC	1448	1622	1931	2534
RIDM	37,1%	28,2%	17,9%	8,5%

Table 4.2: Optimization results, for a SF6-hydraulic circuit breaker, for different reliability thresholds.

	60%	70%	80%	90%
years to maintenance	23	20	17	13
Maintenance scenario	1	1	1	2
YCC	1689	1931	2253	3119
RIDM	39,9%	28,8%	19,1%	8,7%

Table 4.3: Optimization results, for a SF6-spring circuit breaker, for different reliability thresholds.

	60%	70%	80%	90%
years to maintenance	25	21	17	11
Maintenance scenario	1	1	1	1
YCC	2506	2962	3620	5430
RIDM	38,9%	28,2%	19,1%	9,1%

Table 4.4: Optimization results, for an Oil-pneumatic circuit breaker, for different reliability thresholds, exclusive non-maintainable failure mechanisms

	60%	70%	80%	90%
years to maintenance	48	42	35	26
Maintenance scenario	1	1	1	1
YCC	2041	2336	2778	3704
RIDM	39,1%	28,7%	19,0%	9,8%

Table 4.5: Optimization results, for an Oil-hydraulic circuit breaker, for different reliability thresholds, exclusive non-maintainable failure mechanisms

	60%	70%	80%	90%
years to maintenance	27	24	20	15
Maintenance scenario	1	1	1	1
YCC	3571	4000	4762	6250
RIDM	37,0 %	28,2%	18,1%	8,7%

Table 4.6: Optimization results, for an Oil-spring circuit breaker, for different reliability thresholds, exclusive non-maintainable failure mechanisms

	60%	70%	80%	90%
years to maintenance	42	34	25	14
Maintenance scenario	1	1	1	50
YCC	2326	2857	4000	3259
RIDM	39,1 %	29,0 %	19,4%	8,9%

Table 4.7: Optimization results, for an Air-pneumatic circuit breaker, for different reliability thresholds, exclusive non-maintainable failure mechanisms

	60%	70%	80%	90%
Years to maintenance	56	48	39	28
Maintenance scenario	1	1	2	2
YCC	1786	2083	371	517
RIDM	39,6%	29,6%	18,0%	8,9%

5. The affix to asset life cycle planning

In this section, the expansion of the ALCP will be discussed. This will be done in two ways. First of all, the implementation of the optimization model into ALCP will be discussed. Thereafter, the aspect of change will be discussed with respect to ALCP. The relation between change and ALCP has already been briefly discussed in section 2.2. However, the practical implications of change theory will be discussed here.

5.1 Implementing the optimization model into ALCP

The goal of this research was to make AM more objective, with the focus on the operational phase of an asset. To do so the ALCP methodology was taken as the state of the art. From the analysis of the methodology, it was concluded that for *technical* and *economical* TECCO perspectives it would be possible to objectively quantify them. The quantification of those perspectives resulted in the optimization model. However, for the *compliance*, *commercial* and *organizational* perspectives this wasn't the case. Therefore, these aspects were mostly left out of the model, except for some organizational aspects[1].

To combine the perspectives, quantitative and qualitative, back together it is important to have a deeper understanding of the ALCP methodology. The goal of ALCP is to identify the main lifetime impacts for each of the TECCO perspectives. Meaning that one looks for changes in the way an asset is operated with respect to the current situation. This approach assumes operational standards, for each of the TECCO perspectives, to be in place at the time of analysis. In order to see how the optimization model relates to the changing environment, it is important to understand its relationship to the current operational standards first.

The operational standards relate to the optimization model in two ways. First of all, some standards can influence the model directly. For example, by a change in the reliability functions or replacement cost. Secondly, a change in the qualitative TECCO perspective could change the expert its opinion about the acceptable reliability level. This reliability level, provided by experts, has to be used as input for the model. In the previous chapter the results were displayed for different thresholds (90-60%). However, the actual threshold level can differ for each circuit breaker and need to be determined by experts. Therefore, some of the TECCO indirectly influence the outcome of the optimization model, because the experts base the acceptable reliability level on:

---

[1] The available knowledge and materials were taken into account, which are organizational aspects of the ALCP

1. Safety conditions
2. Number of clients connected
3. Specific regulations
4. Internal or external environmental policies
5. Impact on grid availability
6. Others

These variables can all be categorized in one of the TECCO perspectives. Meaning that the TECCO perspectives also indirectly influence the outcome of the optimization model. However, these variables do not capture the entire scope of the TECCO perspectives. Since the ALCP focuses on the entire life cycle, some of the TECCO standards do no influence the operational part of the asset its lifetime (Figure 4). Therefore, they are not related to the optimization model. Furthermore, some operational objectives are unrelated to the reliability threshold, but just state a way of operation, e.g. the use of recyclable materials. This shows that the optimization model and the TECCO perspectives can be integrated to some extent, but parts of the ALCP methodology will not be influenced by the use of an optimization model.

Knowing how the optimization model relates to the initial, TECCO, operational standards the model can now be related to changing TECCO perspectives. In a changing environment, those perspectives are still related to the model in the same way. Meaning that they could change the reliability threshold as mentioned before (Figure 4). These reliability changes are indicated as dots in Figure 4. Aside from changes to the reliability functions or thresholds, some of the changes in operational standards are independent. Meaning that a change in a TECCO perspective does not

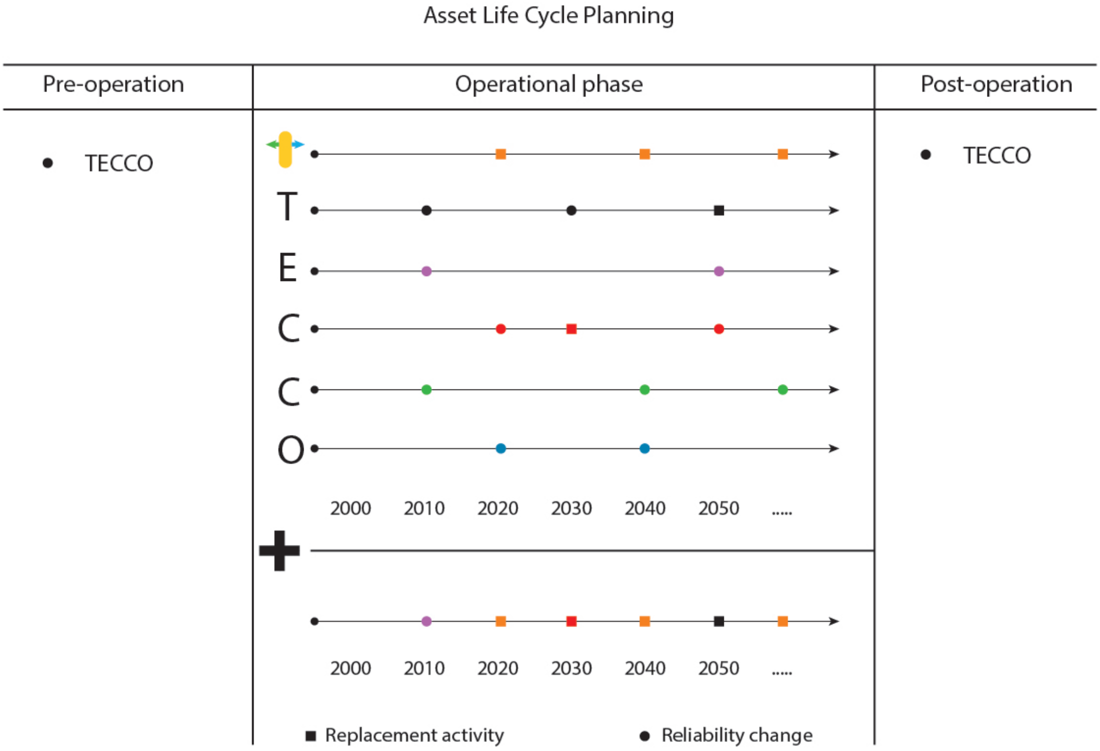


Figure 4: Integration of the optimization model in ALCP

affect the reliability, but does impact the operational phase of the asset. For example, if a new law prohibits the use of SF6 gas, obliging the DSOs to replace all SF6 insulated circuit breakers within ten years. Whereas, the optimization model proposed maintenance after twelve years. In such a case a change in the TECCO perspective can cause an early replacement activity that was not proposed by the optimization model (✝). These replacement activities are indicated as squares in Figure 4.

Summarizing, it can be said that some of the TECCO, defined operational conditions can directly influence the optimization. Either by directly influencing the MinIncrease function of the model (Equation 5.1). Or by changing the cost or reliability function of a circuit breaker. On the other hand, there will remain developments that are independent of the model and still need to be taken into account. In the end, all those developments and the model can be used to define the best moment to do an intervention to the breaker. The visual representation of this concept can be seen in Figure 4. Concluding it can be said that the optimization model could become part of the ALCP methodology, but the ALCP methodology will remain bigger than the model itself.

$$MinIncrease = safety \cdot w_1 + nr.clients \cdot w_2 + regulations \cdot w_3 + ... + other_n \cdot w_n \tag{5.1}$$

$$w_i = \text{weight factors expert assign to certain operational conditions}$$

5.2 Change management and ALCP

As mentioned in section 2.2 the outcome of the ALCP could impact the way maintenance and assets are managed. Aside from the outcome of the ALCP, new methods such as data analysis and optimization modelling could also require more specific input. Requiring the maintenance personnel to actively gather data. The way of dealing with those changes is only marginally touched upon in ALCP theory. Therefore, a literature review has been conducted in section 2.2 to expand on the topic of change. Based on the review in combination with several interviews, conducted with different people throughout Alliander, several recommendations can be made on how to expand ALCP. In the follow paragraphs the most important recommendation will be presented. These recommendations are based on the 50kV circuit breaker used in this research. However, it is believed that they are more generally applicable.

Based on the outcome of the literature review and interviews, several things can be recommended. The most important one has to do with the management of perceptions and the creation of involvement. Currently technicians feel that quite some improvements could be made, for example, in the decision making process assigning maintenance priority. They did not know that several people higher in the organization are working on this. This made the technicians question "what all those people in office" are actually doing. Based on the literature regarding involvement it would be recommended to improve the communication between technicians and process analysts. It is expected that this will improve the quality of the proposals by process analysts. Furthermore, it would improve the perception of technicians towards "those people in office". Which also makes them more likely to adopt future changes.

Aside from change management, it is also important to keep the goals of change in mind. For example, a new software tool could provide interesting insights. However, one should question if one needs those insights in order to achieve the goals. During this research and the interviews and meetings that were conducted/attended, a lack in such goal oriented decision making was not directly identified. Although they were not identified, it is still recommended to reflect on ones decisions from time to time.

Similar to the goal oriented change management, the CI strategy is also recommended based on literature. It requires the organization to implement two feedback loops that make sure change is implemented correctly. First one implements the PDCA loop. Whereafter, one implements the SDCA loop in order to make sure change standardized. This touches upon the first and most important recommendation of involvement. By checking with technical personnel if the changes are implemented correctly, involvement is also stimulated. Currently there have been cases within Alliander where good feedback loops have been used. It is recommended to also do this with respect to future improvements, e.g. for 50kV circuit breakers.

5.3 Practical implications

Based on the results of the optimization model and the recommendations made in this chapter. It is interesting to know how the daily practice of maintenance personnel is influenced. In this section it is assumed that the results from this research are implemented at Alliander. Based on this assumption the changes in daily practice will be illustrated. It should be noted that AM is a complex field and many different people are involved, the changes described in this section are only a small part of AM.

First and foremost, the implementation of the optimization model would change the maintenance and inspection planning. Meaning that assets are no longer inspected every six years as is currently the case (see Appendix B), but instead the inspection interval becomes dynamic. Meaning that the inspection interval is determined based on the age and status of the asset. Furthermore, one would plan preventive maintenance moments, based on population characteristics. In those cases, internal parts of the assets can be replaced, even though from the outside no clear deterioration can be detected. This might feel counter intuitive for some maintenance engineers, because they do not see or measure deterioration.

In cases where maintenance feels counter intuitive to maintenance engineers, the recommended increase in involvement becomes important. Good and frequent communication between process analysts and maintenance personnel would facilitate the implementation of these new procedures. By informing the maintenance personnel about the data and the corresponding decision process they will better understand certain maintenance decisions. Whereas, on the other hand, they can provide valuable feedback on the correctness of the new approach.

From CI theory these feedback sessions are also supported. In practice this could mean that process analysts and maintenance personnel have a feedback session, for example, every month. Where they would discuss the correctness of the preventive maintenance strategy. Furthermore, the process analysts can inform the maintenance personnel about the latest developments in the asset population. Whereby, the mutual understanding and knowledge regarding maintenance planning increases.

Concluding, the implementation of the results may lead to dynamic maintenance planning. This may feel counter intuitive for maintenance personnel, but by regular feedback sessions the mutual understanding of the maintenance planning should be increased. Aside from the dynamic maintenance planning and regular feedback sessions, the changes with respect to the actual maintenance activity of maintenance personnel, will be limited.

6. Conclusions, Discussion & Recommendations

In this chapter, the methods and results of this research will be interpreted in several ways. First of all, the most important conclusions of this research will be drawn. Secondly, the input, methods and results of this research were reflected upon. Finally, recommendations were made. Those recommendations ranged from company-specific improvements to potential ways of extending this research.

6.1 Conclusion

As stated in the introduction of this research, the increasing work pressure in combination with inefficient maintenance allocation can imply serious consequences for the DSOs. Currently, the DSOs are putting a lot of effort into the recruitment of new technical staff. Although a more efficient maintenance allocation process might also solve part of this problem.

This thesis shows the potential of an optimization model in the maintenance allocation process. Based on an asset its technical and economical characteristics the model gives the best maintenance activities and interval for different circuit breakers. With this information one could improve the allocation process of technicians. Making sure they go to assets that really need maintenance. Instead of unnecessary maintenance based on wrongful interpretation of inspections, which currently happens occasionally.

Aside from the objective technical and economical perspectives. This research also shows how the optimization model can be integrated with the other TECCO perspectives. Therefore, providing an extension to the current ALCP methodology. This extension can be used by future researchers and practitioners of asset management. Especially those who want to look into a more data driven asset management strategy.

Concluding it can be said that an optimization model could become an integrated part of the latest AM methodology, ALCP. Where it provides the optimal maintenance scenario and its corresponding maintenance interval from an asset its technical and economical perspectives. As can be seen in the Tables in section 4.3. In order to make sure maintenance personnel will not repel against the data driven maintenance interval. It is important to make them understand the data and the construction of the maintenance interval. For example, it should be clear to them why one wants to maintain a certain Oil-pneumatic circuit breaker after 48 years. This is achieved by doing regular feedback sessions, following the CI strategy. These feedback sessions increase the involvement in the organization, which makes sure there is a mutual understanding, between process analysts and maintenance personnel, about why and how the optimal maintenance interval is as it is. Thereby, making sure that maintenance personnel will not repel against data driven maintenance, but instead become eager to improve its outcome.

6.2 Discussion

In this section, the results, assumptions and quality of the research are reflected. The reflection will be based on the input, methods and output used in this research.

First of all, as mentioned by Tazelaar et al. (2017) and their internal documentation at Alliander. The use of physical principles in combination with statistics reduces the need for data. This way it was possible for them to provide information about the failure rate of different circuit breakers and their underlying failure mechanisms. Although, the model provides useful information, the authors mention the importance of better data monitoring. Especially for some failure mechanisms, the way the data was reported was lacking in quality. Therefore, the quality of some reliability functions might be low. This was also confirmed through a reflective interview with technicians. They mentioned that the current maintenance intervals proposed by the model were to long, especially for SF6 leakage. Meaning that one should consider this when interpreting the results of the optimization. Besides the data quality, several assumptions have been made during the creation of the model. These assumptions are part of previous research by Tazelaar et al. (2017), but should be taken into account by the user of the optimization model.

Secondly, for maintenance activities, it is assumed that, when maintenance is conducted, the reliability of failure mechanisms is "as good as new". Based on interviews with experts it was concluded that it is unlikely for this to be the case. The actual factor of reliability that can be achieved with maintenance is unknown. In future research assumptions can be done to investigate the impact of imperfect repairs. Research by Kijima (1989) would be a good starting point if one wishes to investigate imperfect repairs.

Thirdly, the optimization model optimizes the maintenance interval for new circuit breakers. Therefore, the optimal maintenance interval for the different circuit breakers is based on the fact that they are placed new. However, some of the circuit breakers are more than 40 years old. They have been subject to several maintenance activities. The documentation of all those activities is not available. Meaning that it won't be possible to determine their reliability at this point in time. For some of the relative new breakers, where documentation is available, one could potentially incorporate the conducted maintenance and alter the reliability accordingly. This means that for the old circuit breaker this model is not applicable. It will be mainly applicable to the newer breakers, which, in most cases, are SF6 insulated.

Fourthly, for each maintenance scenario, it was only possible to simulate one maintenance activity. Therefore, the potential long-term financial benefits of maintenance are not captured to their full potential. To illustrate this, imagine the following: for an SF6-pneumatic breaker, SF6 leakage is a very dominant failure mechanism. So in order to increase the overall reliability of the breaker, maintenance on SF6 leakage has the most impact. So it could be possible that if one conducts maintenance on SF6-leakage three times, the score becomes higher than that of replacement. However, in the current optimization model, it is not possible to simulate several subsequent maintenance activities. This way a bias towards circuit breaker replacement is created.

Lastly, this research focused on the operational phase of assets. AM is more than just the operation. Like, choosing the right asset based on pre-defined characteristics or their recyclability. These aspects have not been considered in this research. Although some aspects could also be applied to these phases, e.g. the failure behaviour could be used as input for deciding which asset to use.

6.3 Recommendations

Finally, aside from the improvements mentioned in the discussion, some recommendations are given with respect to the scientific background of this research. To give the reader an idea of how to build on this research from a scientific perspective. Furthermore, some recommendations for Liandon are given on how to potentially incorporate this research. This also includes ways to improve the reliability of the research outcome.

6.3.1 General recommendations

In this research, objectively quantifiable aspects of ALCP have been used to develop an optimization model. In the end, the optimization model was implemented back into the ALCP methodology. During this process, it was mentioned that some of the TECCO perspectives determine the acceptable reliability level in the optimization model. Currently, this would need to be determined by experts. Using experts is not a bad thing, but could impose a similar inconsistency that started this research in the first place. Therefore, it would be recommended to use multi-criteria analysis (MCA). By including many expert opinions in the MCA a general consensus about the importance of the TECCO perspectives can be created. Which in the end can be used to customize the acceptable reliability level for each circuit breaker in the system. Summarizing, it is important to find a good methodology to combine subjective and objective data in a consistent way. To do so, MCA might be a good option.

The current optimization model mainly focuses on replacement activities. Aside from replacement activities also inspections are conducted. The failure data of an asset could also be used for inspection optimization as has been done by Zhong et al. (2017). Doing so would allow for optimization of the personnel allocation over the entire operational lifetime of an asset. Furthermore, inspection input can improve the failure function accuracy for individual assets (Tazelaar et al., 2017). Which allows for individualizing of the reliability functions for circuit breakers.

6.3.2 Recommendations for Liandon

Besides the more general methodological recommendations made in the previous section, there are also some case-specific recommendations for Liandon. These recommendations are based on the difference between the current way of working at Liandon and the methodology used in this research.

First of all, this research assumes maintenance to be a one-time activity. Although in practice small maintenance activities are conducted during every inspection. For the bigger maintenance activities, this is not the case. Those are only conducted by Liandon if a failure occurs or inspection indicates a bad condition. The condition indicated by inspection is part of the subjectivity problem discussed in this research. To overcome this, Liandon could rely completely on the optimization model to indicate the point of big maintenance. However, this is not recommended at this point, because the reliability of the model could still be improved. Therefore, it is recommended to use the model next to the current condition monitoring process. They both provide valuable information, where the current process of Liandon captures a wider range of failure mechanisms than the model. Indicating that the current "subjective" methodology still provides valuable information. Future improvements to the model, as recommended in the next paragraph, could put more emphasis on the model its recommendations. The opinion that the model needs to be improved in order to be valuable, is shared by several technicians.

On the other side, the proper documentation of inspections could really improve the accuracy of the reliability functions. Therefore, it is also recommended that the data quality is improved.

Detailed recommendations with regard to this aspect have already been done by Tazelaar et al. (2017) in company-specific documentation. The integration of those aspects in the inspection would increase the model quality significantly.

Furthermore, it is highly recommended to analyze the failure functions in more detail and relate them with inspection intervals. For quite some failure mechanisms the reliability decreases exponentially, but the current inspection interval does not. This highly increases the possibility that failure is not detected in time.

It should be said that the model can provide valuable insights. Together with its integration in the ALCP methodology, it can provide well-founded preventive maintenance strategies. However, making these models and integrating them into current methodologies can be a difficult and time-consuming process. Where aspects of change management also play an important role in their acceptance and integration in the organization. Therefore, Liandon should definitely consider if such an extensive model provides enough value. Since the investments in such a methodology can be significant, whereas the benefit mainly lies in the potential improvement in failure prevention. Where in the case of 50kV circuit breakers, that are often placed in n-1 redundancy, one could question if (minor) failure prevention, that is considered in this research (Appendix B), should be a goal in itself. Summarizing, consider if these models provide enough value, given the goals one has in mind.

Finally, during some of the cooperation days with the maintenance personnel, it was noticed that for them it is unclear what is being done with the inspection data they generate. From what has been identified in change management theory, it might be helpful to increase the involvement throughout departments. Since the changes proposed by management need to be understood by the people that execute them. Otherwise, the effect of changes could be significantly less.

Bibliography

Alliander (2018). Een bedrijf met 100 jaar ervaring — Alliander. Retrieved 14-08-2018 from `https://www.alliander.com/nl/over-alliander/bedrijfsprofiel/geschiedenis`. 2

Amarantou, V., Kazakopoulou, S., Chatzoudes, D., and Chatzoglou, P. (2018). Resistance to change: an empirical investigation of its antecedents. *Journal of Organizational Change Management*, 31(2):426–450. 9

ANP (2017). Tekort aan technici bij netbeheerder Alliander — NU - Het laatste nieuws het eerst op NU.nl. Retrieved 27-06-2018 from `https://www.nu.nl/economie/4526154/tekort-technici-bij-netbeheerder-alliander-.html`. 1

Arunraj, N. and Maiti, J. (2007). Risk-based maintenanceTechniques and applications. *Journal of Hazardous Materials*, 142(3):653–661. 2

Backlund, F. and Sundqvist, E. (2018). Continuous improvement: challenges for the project-based organization. *International Journal of Quality and Reliability Management*, 35(7):1306–1320. 9

Bagnoli, M. and Bergstrom, T. (2005). Log-concave probability and its applications. *Economic Theory*, 26(2):445–469. 10

Bala, H. and Venkatesh, V. (2013). Changes in employees'job characteristics during an enterprise system implementation: A latent growth modeling perspective. *MIS quarterly*, 37(4). 9

Bhuiyan, N. and Baghel, A. (2005). An overview of continuous improvement: From the past to the present. *Management Decision*, 43(5):761–771. 9

Billinton, R. and Allan, R. N. (1983). *Reliability Evaluation of Engineering Systems*. Springer US, Boston, MA. 10

Blom, R. (2018). Nieuwbouwwoningen vaker te laat opgeleverd door een groeiend tekort aan monteurs — De Volkskrant. Retrieved 27-06-2018 from `https://www.volkskrant.nl/economie/nieuwbouwwoningen-vaker-te-laat-opgeleverd-door-een-groeiend-tekort-aan-monteurs~b3c6ed52/`. 1

Braaksma, A. (2012). *Asset information for FMEA-based maintenance*. University of Groningen, SOM research school. 39

Chmura, L. A. (2014). *Life-Cycle Assessment of High-Voltage Assets using Statistical Tools*. TU Delft. 14

Ciocoiu, L., Hubbard, E.-M., and Siemieniuch, C. E. (2015). Implementation of remote condition monitoring system for predictive mainte- nance: an organisational challenge. In *the International Conference on Ergonomics & Human Factors*, pages 449–453, Daventry. Taylor and Francis. 9

Cooper, R. B. and Zmud, R. W. (1990). Information Technology Implementation Research: A Technological Diffusion Approach. *Management Science*, 36(2):123–139. 8

CPLEX (2018). IBM CPLEX Optimizer. Retrieved 20-09-2018 from `http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/index.html`. 17

CRAN (2016). R: What is R? Retrieved 13-08-2018 from `https://www.r-project.org/about.html`. 17

Das, S. R. and Joshi, M. P. (2012). Process innovativeness and firm performance in technology service firms: The effect of external and internal contingencies. *IEEE Transactions on Engineering Management*, 59(3):401–414. 8

Datla, S. V. and Pandey, M. D. (2006). Estimation of life expectancy of wood poles in electrical distribution networks. *Structural Safety*, 28(3):304–319. 7

Fondas, N. (1993). Process Innovation: Reengineering Work Through Information Technology. *Academy of Management Perspectives*, 7(2):100–103. 8

General Secretariat of the European Council (2014). European Council (23 and 24 October 2014) Conclusions. Technical report, European Union, Brussels. 1

Georgalis, J., Samaratunge, R., Kimberley, N., and Lu, Y. (2015). Change process characteristics and resistance to organisational change: The role of employee perceptions of justice. *Australian Journal of Management*, 40(1):89–113. 9

Haanstra, W. and Braaksma, J. (2018). Life Cycle Costing in physical Asset Management: a multiple case study. In *Paper at The Twentieth International Working Seminar on Production Economics*, page 12, Innsbruck. 7

Hameed, M. A., Counsell, S., and Swift, S. (2012). A conceptual model for the process of IT innovation adoption in organizations. *Journal of Engineering and Technology Management - JET-M*, 29(3):358–390. 8

Hansson, J., Backlund, F., and Lycke, L. (2003). Managing commitment: increasing the odds for successful implementation of TQM, TPM or RCM. *International Journal of Quality & Reliability Management*, 20(9):162–181. 2

IEC (2015). Strategic asset management of power networks. *International Electrotechnical Commission*. 5, 13

Jetten, J., O'Brien, A., and Trindall, N. (2002). Changing identity: Predicting adjustment to organizational restructure as a function of subgroup and superordinate identification. *British Journal of Social Psychology*, 41(2):281–297. 2

Karakoc, I. (2018). Personal Interview. 14

Kesting, P. and Ulhøi, J. P. (2010). Employee-driven innovation: Extending the license to foster innovation. *Management Decision*, 48(1):65–84. 9

Khan, F. I. and Haddara, M. M. (2003). Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning. *Journal of Loss Prevention in the Process Industries*, 16(6):561–573. 14

Khanna, M., Deltas, G., and Harrington, D. R. (2009). Adoption of pollution prevention techniques: The role of management systems and regulatory pressures. *Environmental and Resource Economics*, 44(1):85–106. 7

Khazanchi, S., Lewis, M. W., and Boyer, K. K. (2007). Innovation-supportive culture: The impact of organizational values on process innovation. *Journal of Operations Management*, 25(4):871–884. 8

Kijima, M. (1989). Some results for repairable systems with general repair. *Journal of Applied Probability*, 26(01):89–102. 32

Krovi, R. (1993). Identifying the causes of resistance to IS implementation: A change theory perspective. *Information & Management*, 25(6):327–335. 8

Lam, S. S. and Schaubroeck, J. (2000). A field experiment testing frontline opinion leaders as change agents. *Journal of Applied Psychology*, 85(6):987–995. 9

Matthews, R. L., Tan, K. H., and Marzec, P. E. (2015). Organisational ambidexterity within process improvement: An exploratory study of four project-oriented firms. *Journal of Manufacturing Technology Management*, 26(4):458–476. 8

Piening, E. P. and Salge, T. O. (2015). Understanding the antecedents, contingencies, and performance implications of process innovation: A dynamic capabilities perspective. *Journal of Product Innovation Management*, 32(1):80–97. 8

Preshant, R. and Mehairjan, Y. (2017). *Risk Based Maintenance in Electricity Network Organisations.* Springer International Publishing. 5, 7, 13

Pudney, S. (2010). *Asset Renewal Desicion Modelling with Application to the Water Utility Industry (Ph.D. Thesis).* PhD thesis, Queensland University of Technology. 2, 5

Rijksoverheid (2017). Transitiepad Kracht en licht c.q. Elektriciteit — Publicatie — Klimaatakkoord. Retrieved 27-06-2018 from `https://www.klimaatakkoord.nl/elektriciteit/documenten/publicaties/2017/06/15/10-pager-elektriciteit`. 1

Rijksoverheid (2018). Elektriciteit — Klimaatakkoord. Retrieved 12-07-2018 from `https://www.klimaatakkoord.nl/elektriciteit`. 1

Roda, I. and Garetti, M. (2015). Application of a performance-driven total cost of ownership (TCO) evaluation model for physical asset management. In *Lecture Notes in Mechanical Engineering*, volume 20, pages 11–23. Springer, Cham. 7

Ruitenburg, R. (2017). *Manoeuvring physical assets into the future: Planning for predictable and preparing for unpredictable change in Asset Life Cycle Management.* University of Twente, Enschede. 5, 6, 7, 8, 13

Ruitenburg, R. J., Braaksma, A. J., and Van Dongen, L. A. (2014). A multidisciplinary, expert-based approach for the identification of lifetime impacts in Asset Life Cycle Management. *Procedia CIRP*, 22(1):204–212. 6

Samaniego, F. J. (2007). *System Signatures and their Applications in Engineering Reliability*, volume 110 of *International Series In Operations Research & Management Science.* Springer US, Boston, MA. 10

Schaffer, R. H. and Thomson, H. A. (1992). Successful change programs begin with results. *Harvard Business Review*, 70(1):80–89. 9

Si, X. S., Wang, W., Hu, C. H., and Zhou, D. H. (2011). Remaining useful life estimation - A review on the statistical data driven approaches. *European Journal of Operational Research*, 213(1):1–14. 6

Singh, J. and Singh, H. (2015). Continuous improvement philosophy literature review and directions. *Benchmarking*, 22(1):75–119. 9

Sjors Moolenaar & Natasja de Groot (2018). Nieuwbouw maanden later opgeleverd, kopers de dupe. Retrieved 27-06-2018 from `https://www.ad.nl/economie/nieuwbouw-maanden-later-opgeleverd-kopers-de-dupe~acaeb069/`. 1

Straatmann, T., Nolte, J. K., and Seggewiss, B. J. (2018). Psychological processes linking organizational commitment and change-supportive intentions. *Personnel Review*, 47(2):403–424. 9

Tazelaar, E., Breteler, D., Van Tongeren, J., and Stijl, R. (2017). Combining statistics and physics to rank circuit breakers on condition. *CIRED - Open Access Proceedings Journal*, 2017(1):58–61. 14, 15, 16, 32, 33, 34, 42, 43

Trommelen, J. (2016). Stroomnet kan zonnepanelen-hausse in Groningen niet aan. Retrieved 27-06-2018 from `https://www.volkskrant.nl/nieuws-achtergrond/stroomnet-kan-zonnepanelen-hausse-in-groningen-niet-aan~bf9a7416/`. 1

Verbong, G. and Geels, F. (2007). The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960-2004). *Energy Policy*, 35(2):1025–1037. 1

Vough, H. C., Bindl, U. K., and Parker, S. K. (2017). Proactivity routines: The role of social processes in how employees self-initiate change. *Human Relations*, 70(10):1191–1216. 8

Yeddanapudi, S. R. K., Li, Y., McCalley, J. D., Chowdhury, A. A., and Jewell, W. T. (2008). Risk-based allocation of distribution system maintenance resources. *IEEE Transactions on Power Systems*, 23(2):287–295. 14

Zhong, J., Li, W., Wang, C., Yu, J., and Xu, R. (2017). Determining Optimal Inspection Intervals in Maintenance Considering Equipment Aging Failures. *IEEE Transactions on Power Systems*, 32(2):1474–1482. 14, 33

A. Case study background

Background information is provided for two reasons. First, the background information is the contextual framework of this research, which provided the base for some of the decision made in this research. Furthermore, the background information is necessary for reflection. As mentioned in ALCP theory, reflection and evaluation of the changes are important. However, in order to discuss change, it is important to understand both the old and the potential new situation. In this section the current protocols used by Liandon are discussed.

A.1 Asset management at Liandon

Current protocol

As mentioned previously Liandon is part of Alliander N.V. and manages the complex medium- and high voltage networks for Tennet and Liander. This means that Liandon has to make sure the different network components in those networks are functioning. In general, one can speak of three types of components:

1. *Primary*: these components are necessary for the transportation of energy, e.g. transformers, circuit breakers, lines, etc.
2. *Secondary*: these components are used for signalling, controlling or measuring the function of the primary grid components, e.g. relays.
3. *Tertiary*: these components facilitate the primary and secondary components, e.g. the terrain, the buildings, etc.

All those different components have different maintenance intervals, but the overall method to determine those intervals is the same. Before explaining this method in more detail it should be mentioned that a shift is made from asset management to maintenance. The two are highly related and maintenance can be considered an important part of asset management. Maintenance is the management of an asset during its operational lifetime. In this research general AM principles are used, but since maintenance is a big part of AM both principles may get intertwined sometimes.

For the maintenance intervals currently a Failure Mode Effect and Criticality Analysis (FMECA) is used. The FMECA is a method that uses qualitative and quantitative data to determine the main failure modes, their effects and risks. According to Braaksma (2012) FME(C)A's are often used to come up with preventive maintenance strategies. This is also the case for Liandon. Where the FMECA has been used to come up with a preventive inspection interval. During the inspection, the condition of an asset is monitored according to a checklist. This checklist is based on the different aspects of the FMECA. When the condition is registered a maintenance engineer assigns a condition code to the asset. Stating the urge of maintenance and the interval of maintenance, if it is necessary. In the end, the condition code determines how maintenance personnel is allocated. Since, both the condition monitoring and condition code allocation are sensitive to personal subjectivity, the risk of each asset is very dependent on the person assessing it.

B. Circuit Breakers

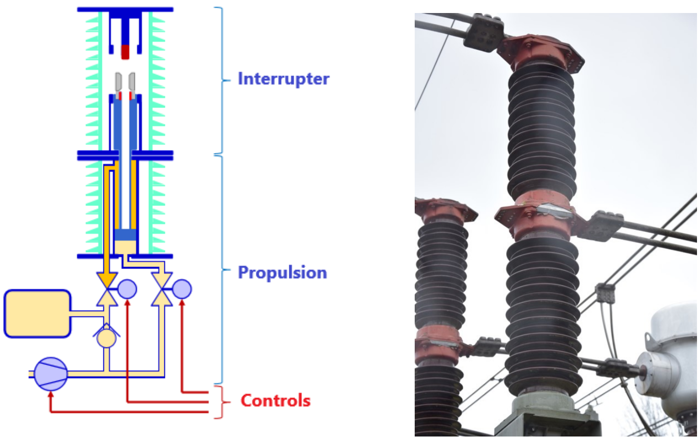
B.1 The 50 kV circuit breaker

In this research, the focus was on the asset and maintenance management protocol for the 50kV circuit breaker (*Figure 5*). In this section, the function of a 50kV CB and its maintenance protocol will be discussed.

What is a 50kV circuit breaker?

In general, a circuit breaker its function is to break the flow of power. For a 50kV circuit breaker, this is the same, although it is able to break power flows with a voltage up to 50kV. A circuit breaker has three main components (*Figure 5a*):

1. *Interrupter*:
   The part of the circuit breaker that extinguishes the arc. This is done by the use of an extinguishing agent, e.g. oil, SF6, vacuum.
2. *Propulsion*:
   The part of the circuit breaker that makes sure a movable contact in the interrupter section is pulled down. Making sure the conducting surfaces are no longer in contact. The propulsion is done by pneumatic, hydraulic or spring based systems.



(a) Schematic representation (b) In field representation

Figure 5: 50kV circuit breaker

3. *Controls*:
   In order for the propulsion to take place, they need a signal from the control system. This system comes from secondary network equipment that measures the voltage levels in the system. If those voltage levels are out of bounds the controls will activate the circuit breaker.

Maintenance protocol

For the 50kV circuit breaker, the maintenance protocol has been constructed according to the general Liandon protocol. This means that a FMECA was constructed to identify the main failure mechanisms. Based on the FMECA the inspection interval has been set to six years. When six years have passed an engineer will do an inspection and basic maintenance if necessary. Aside from that, the checklist is filled in, indicating the, mainly qualitative, condition of the circuit breaker. Based on the inspection results a maintenance engineer assigns a condition code to the circuit breaker. Based on the condition code the next maintenance/inspection moment is determined. In cases of good operation the inspection interval will be the six years mentioned earlier. In bad or mediocre conditions the inspection/maintenance interval will be shorter than six years.

B.2 50 kV Circuit breakers in Liandon's control

For this research, the different types of 50kV circuit breakers under Liandon its control have been researched. In total there were seven different types of circuit breakers based on the different drive-chains (pneumatic, spring & hydraulic) and insulating mediums (Air, Oil & SF6). For both oil and SF6-gas insulated circuit breakers under Liandon's control, breakers can occur with all the mentioned drive-chains. However, for air insulated breakers, only pneumatic drive chains are used. Resulting in the following seven types of circuit breakers under Liandon's control:

1. Air - Pneumatic
2. SF6 - Pneumatic
3. SF6 - Hydraulic
4. SF6 - Spring
5. Oil - Pneumatic
6. Oil - Hydraulic
7. Oil - Spring

For each of the circuit breakers, based on their drive-chain and insulating medium different failure mechanisms occur. In the upcoming sections, the failure mechanisms and the corresponding maintenance activities will be discussed. This will be done for every drive-chain and insulating medium separately. For each of the maintenance activities, it is assumed that after maintenance the failure mechanism is AGAN. This has certain implications on the modelling process.

Based on the failure mechanisms for each drive-chain and different insulating media, the failure mechanisms and corresponding maintenance scenarios per circuit breaker can be derived (see Table B.1). This information is based on the report by Tazelaar et al. (2017) and the experts (Boris Ros & Patrick Bos) they consulted. For all failure mechanisms, it is assumed that the proposed maintenance activity will reset the failure function of the given failure mechanism back to its initial "new" condition. However, based on the interview with maintenance engineer Erik Peerdeman it was concluded that the execution of some of those maintenance activities is no longer possible.

This is either due to the lack of materials, knowledge or complexity of the maintenance. For each failure mechanism and the corresponding maintenance activity it will be mentioned if it still executable and why (not).

Before explaining the failure mechanisms it is important to explain the meaning of failure in this case. According to Tazelaar et al. (2017) the underlying data explaining the failures, mainly consist of minor failures. Meaning that failure doesn't necessarily mean that the circuit breaker stops working, but it indicates that it indirectly can cause the circuit breaker to stop working. For example, the leaking of an insulating medium. If a minor failure is not maintained it can mitigate to a major failure, thus the interruption of a circuit breakers operation.

Pneumatic drive-chain

Loss of stored energy

For the pneumatic drive-chain, one minor failure category has been specified. This category specifies the cases where some of the stored pneumatic energy is lost. This can be caused by leaks, slippage or breakage. According to the experts, this almost never happens. Therefore, no information regarding the cost of this failure was known. However, since the failure of the pneumatic drive-chain is similar to that of the hydraulic drive-chain, the specifications of the later were used for the pneumatic drive-chain.

Maintainability

For the pneumatic drive chain, independent of the isolating medium, the loss of stored energy can still be maintained.

Hydraulic drive-chain

Loss of stored energy

As mentioned in the previous paragraph the hydraulic and pneumatic drive-chain are highly related. Therefore, the failure category for the hydraulic drive-chain is similar to that of the pneumatic drive-chain. In the case of the hydraulic drive-chain, this means that in most cases the bearing bushes and seals quail due to dehydration or usage, causing leakage. More specifically, this is often caused by a failure in the accumulator. Most of the time the wear and tear of the gasket/seal causes this. So by replacing the bushes or seals this failure can be solved or prevented.

Maintainability

For the main type of Oil-hydraulic circuit breakers in the system of Liandon (EIB-AE70) the hydraulic drive-chain cannot be maintained. This is due to the tight casing of the drive-chain. This makes any type of maintenance to the primary components of the Oil-hydraulic circuit breakers very hard and not worth the effort. For the SF6-Hydraulic breakers most of the population are in gas insulated substations (GIS) instead of air-insulated substations (AIS). Meaning that their hydraulic drive-chain is different from the Oil-hydraulic one. Therefore, maintenance to SF6-hydraulic systems should still be possible.

Spring drive-chain

Failure between operating mechanism and interruption

For the spring drive-chain, two failure categories have been identified. First, there is the failure between the operating mechanism and interruption of the power. In practice, this often means that a mechanical part breaks due to metal fatigue. Although, the experts mention that this almost never happens, which is confirmed by the data. To solve or prevent this failure mechanism the broken/fatigue part is replaced or repaired.

Maintainability

Withing the knowledge of the maintenance engineer, maintenance to the spring drive-chain should still be possible.

Loss of stored energy

The second maintenance category also focuses on the leakage, slippage or breakage of the spring. However, in practice, this failure often occurs due to the fact that the secondary relay doesn't function properly. Meaning that in most cases the relay of the spring needs to be replaced in order to overcome the failure.

Maintainability

Withing the knowledge of the maintenance engineer, maintenance to the spring drive-chain should still be possible.

Air insulated circuit breaker

High resistance contacts

For air insulated circuit breakers the main insulator related failure has to do with the resistance of the contacts. Meaning that wear, tear or contamination of the contacts due to corrosion causes the resistance of the interrupter's contacts to increase. This can be solved by cleaning or replacing the contacts. Although, for air insulated circuit breakers the contacts are often replaced. Due to special deviations in the contact-pressure.

Maintainability

For air insulated breakers, maintenance to fix the resistance of contacts is no longer possible. Due to the fact, that for all air insulated breakers, materials are no longer available.

Oil insulated circuit breaker

Dielectric medium loss

For oil insulated circuit breakers three failure categories were identified. First of all, there is the loss of the oil. This means that throughout time the oil has leaked or has been contaminated. Causing the insulating quality of the oil to decrease. To solve these types of failures the oil is replaced.

Maintainability

As mentioned previously for Oil-hydraulic this is not possible. For the Oil-spring and Oil-pneumatic breaker, this should still be possible.

Failure of seals, gaskets or rupture of the porcelain disk

The second category has to do with the failure of the seals, gaskets or rupture of the porcelain disk. In general, if oil is leaking from the breaker, it can be categorized in this failure mechanism. In most cases, it turns out that the gasket is leaking. Replacing the gasket will solve or prevent this failure from happening.

Maintainability

As mentioned previously for Oil-hydraulic this is not possible. For the Oil-spring and Oil-pneumatic breaker, this should still be possible.

High resistance contacts

Finally, there is also the same failure category as for the air insulated circuit breakers. Where the resistance of the interrupter's contacts increases. In this case, the contacts are being cleaned instead of replaced.

Maintainability

This is not possible for all Oil insulated circuit breakers, because materials are no longer supplied.

SF6 insulated circuit breaker

Loss of gas pressure

For the SF6 insulated circuit breakers, one failure category has been identified. The failure is caused by the leakage of the SF6 gas in the insulator. Due to corrosion, wear and tear or vibrations the gasket becomes fragile and leakage of the SF6 gas can occur. To solve this failure temporarily, one can refill the insulator with SF6 gas, but in this case replacement of the gasket was considered. This was done because a replacement will come closer to an ”as good as new” situation, which is assumed.

Maintainability

Although some types of SF6 breakers are being replaced, maintenance should still be possible.

Secondary failures

Stuck, broken or defective indicator

Aside from the failures that have to do with the insulator or the drive-chain, there are two failure categories that apply to all the different circuit breakers. This is because these failures occur in the secondary components related to the circuit breaker. The first category focuses on the fact that the position (open or closed) of the breaker is no longer reported. This is often caused by a stuck relay. By replacing or rewiring the relay this failure can be solved.

Maintainability

Because this is related to the secondary components of the circuit breakers, it generally should be possible to replace a relay.

Communication/control circuit failure

Finally, there is one category that takes in account any failure with the communication between the circuit breaker and business control. To solve this the engineer will need to find the problem himself. Although, often the wiring is the cause of failure. So often, by replacing the wiring this problem can be solved.

Maintainability

This is very case dependent, but if the problem is found it is assumed that it can be solved.

Table B.1: Circuit breakers and their corresponding failure mechanisms

	SF6 - pneum	SF6 - hyraul	SF6 - spring	Oil - pneum	Oil - hydraul	Oil - spring	Air - pneum
Stored energy loss - pneumatic	x			x			x
Stored energy loss - hydraulic		x			x		
Stored energy loss - spring			x			x	
Failure linkage drive interrupter			x			x	
High resistance contacts - air							x
High resistance contacts - oil				x	x	x	
Dielectric medium loss				x	x	x	
Failure seals and corrosion				x	x	x	
Loss of gas pressure	x	x	x				
Defective indicator	x	x	x	x	x	x	x
Control circuit failure	x	x	x	x	x	x	x

C. Maintenance scenarios

C.1 SF6 - pneumatic

Table C.1: SF6-pneumatic: Maintained failure mechanisms for each optimal scenario.

nr.	**Pneumatic energy loss**	**Loss of gass pressure**	**Defective indicator**	**Control circuit failure**
1	1	1	1	1
2	1	1	1	0
3	1	1	0	1
4	1	1	0	0
5	1	0	1	1
6	1	0	1	0
7	1	0	0	1
8	1	0	0	0
9	0	1	1	1
10	0	1	1	0
11	0	1	0	1
12	0	1	0	0
13	0	0	1	1
14	0	0	1	0
15	0	0	0	1

C.2 SF6 - hydraulic

Table C.2: SF6-hydraulic: Maintained failure mechanisms for each optimal scenario.

nr.	**Hydraulic energy loss**	**Loss of gass pressure**	**Defective indicator**	**Control circuit failure**
1	1	1	1	1
2	1	1	1	0
3	1	1	0	1
4	1	1	0	0
5	1	0	1	1
6	1	0	1	0
7	1	0	0	1
8	1	0	0	0
9	0	1	1	1
10	0	1	1	0
11	0	1	0	1
12	0	1	0	0
13	0	0	1	1
14	0	0	1	0
15	0	0	0	1

C.3 SF6 - spring

Table C.3: SF6-spring: Maintained failure mechanisms for each optimal scenario.

nr.	Spring energy loss	Failure linkage drive	Loss of gass pressure	Defective indicator	Control circuit failure	Control circuit failure
1	1	1	1	1	1	1
2	1	1	1	1	0	1
3	1	1	1	0	1	0
4	1	1	1	0	0	1
5	1	1	0	1	1	0
6	1	1	0	1	0	1
7	1	1	0	0	1	0
8	1	1	0	0	0	1
9	1	0	1	1	1	0
10	1	0	1	1	0	1
11	1	0	1	0	1	0
12	1	0	1	0	0	1
13	1	0	0	1	1	0
14	1	0	0	1	0	1
15	1	0	0	0	1	0
16	1	0	0	0	0	1
17	0	1	1	1	1	0
18	0	1	1	1	0	1
19	0	1	1	0	1	0
20	0	1	1	0	0	1
21	0	1	0	1	1	0
22	0	1	0	1	0	1
23	0	1	0	0	1	0
24	0	1	0	0	0	1
25	0	0	1	1	1	0
26	0	0	1	1	0	1
27	0	0	1	0	1	0
28	0	0	1	0	0	1
29	0	0	0	1	1	0
30	0	0	0	1	0	1
31	0	0	0	0	1	0

C.4 Oil - pneumatic

Table C.4: Oil-pneumatic: Maintained failure mechanisms for each optimal scenario.

nr.	**Pneumatic energy loss**	**High resistance contacts**	**Dielectric medium loss**	**Failure seals & corrosion**	**Defective indicator**	**Control circuit failure**
1	1	1	1	1	1	1
2	1	1	0	1	1	1
3	1	1	0	1	1	0
4	1	1	0	1	0	1
5	1	1	0	1	0	0
6	1	1	0	0	1	1
7	1	1	0	0	1	0
8	1	1	0	0	0	1
9	1	1	0	0	0	0
10	1	0	0	1	1	1
11	1	0	0	1	1	0
12	1	0	0	1	0	1
13	1	0	0	1	0	0
14	1	0	0	0	1	1
15	1	0	0	0	1	0
16	1	0	0	0	0	1
17	1	0	0	0	0	0
18	0	1	0	1	1	1
19	0	1	0	1	1	0
20	0	1	0	1	0	1
21	0	1	0	1	0	0
22	0	1	0	0	1	1
23	0	1	0	0	1	0
24	0	1	0	0	0	1
25	0	1	0	0	0	0
26	0	0	0	1	1	1
27	0	0	0	1	1	0
28	0	0	0	1	0	1
29	0	0	0	1	0	0
30	0	0	0	0	1	1
31	0	0	0	0	1	0

C.5 Oil - hydraulic

Table C.5: Oil-hydraulic: Maintained failure mechanisms for each optimal scenario.

nr.	**Hydraulic energy loss**	**High resistance contacts**	**Dielectric medium loss**	**Failure seals & corrosion**	**Defective indicator**	**Control circuit failure**
1	1	1	1	1	1	1
2	0	0	0	0	1	1
3	0	0	0	0	1	0
4	0	0	0	0	0	1

C.6 Oil - spring

Table C.6: Oil-spring: Maintained failure mechanisms for each optimal scenario.

nr.	**Spring energy loss**	**Failure linkage drive chain**	**High resistance contacts**	**Dielectric medium loss**	**Failure seals & corrosion**	**Defective indicator**	**Control circuit failure**
1	1	1	1	1	1	1	1
2	1	1	0	1	1	1	1
3	1	1	0	1	1	1	0
4	1	1	0	1	1	0	1
5	1	1	0	1	1	0	0
6	1	1	0	1	0	1	1
7	1	1	0	1	0	1	0
8	1	1	0	1	0	0	1
9	1	1	0	1	0	0	0
10	1	1	0	0	1	1	1
11	1	1	0	0	1	1	0
12	1	1	0	0	1	0	1
13	1	1	0	0	1	0	0
14	1	1	0	0	0	1	1
15	1	1	0	0	0	1	0
16	1	1	0	0	0	0	1
17	1	1	0	0	0	0	0
18	1	0	0	1	1	1	1
19	1	0	0	1	1	1	0
20	1	0	0	1	1	0	1
21	1	0	0	1	1	0	0
22	1	0	0	1	0	1	1
23	1	0	0	1	0	1	0
24	1	0	0	1	0	0	1
25	1	0	0	1	0	0	0
26	1	0	0	0	1	1	1
27	1	0	0	0	1	1	0
28	1	0	0	0	1	0	1
29	1	0	0	0	1	0	0
30	1	0	0	0	0	1	1
31	1	0	0	0	0	1	0
32	1	0	0	0	0	0	1
33	1	0	0	0	0	0	0
34	0	1	0	1	1	1	1
35	0	1	0	1	1	1	0

Table C.7: Continued.

nr.	**Spring energy loss**	**Failure linkage drive chain**	**High resistance contacts**	**Dielectric medium loss**	**Failure seals & corrosion**	**Defective indicator**	**Control circuit failure**
36	0	1	0	1	1	0	1
37	0	1	0	1	1	0	0
38	0	1	0	1	0	1	1
39	0	1	0	1	0	1	0
40	0	1	0	1	0	0	1
41	0	1	0	1	0	0	0
42	0	1	0	0	1	1	1
43	0	1	0	0	1	1	0
44	0	1	0	0	1	0	1
45	0	1	0	0	1	0	0
46	0	1	0	0	0	1	1
47	0	1	0	0	0	1	0
48	0	1	0	0	0	0	1
49	0	1	0	0	0	0	0
50	0	0	0	1	1	1	1
51	0	0	0	1	1	1	0
52	0	0	0	1	1	0	1
53	0	0	0	1	1	0	0
54	0	0	0	1	0	1	1
55	0	0	0	1	0	1	0
56	0	0	0	1	0	0	1
57	0	0	0	1	0	0	0
58	0	0	0	0	1	1	1
59	0	0	0	0	1	1	0
60	0	0	0	0	1	0	1
61	0	0	0	0	1	0	0
62	0	0	0	0	0	1	1
63	0	0	0	0	0	1	0
64	0	0	0	0	0	0	1

C.7 Air - pneumatic

Table C.7: Air-pneumatic: Maintained failure mechanisms for each optimal scenario.

nr	**Pneumatic energy loss**	**High resistance contacts**	**Defective indicator**	**Conctrol circuit failure**
1	1	1	1	1
2	0	1	1	1
3	0	1	1	0
4	0	1	0	1
5	0	1	0	0
6	0	0	1	1
7	0	0	1	0
8	0	0	0	1