Productized maintenance framework for utilities

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Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo April 27, 2020

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Abstract of the master's thesis

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Title Productized maintenance framework for utilities

Degree programme Automation and Electrical Engineering

Major Electrical Power and Energy Engineering **Code of major** ELEC3024

Supervisor Prof. Matti Lehtonen

Advisors MSc Juha Haikonen, MSc Teemu Heusala

Date April 27, 2020 **Number of pages** 76 **Language** English

Abstract

In recent years, developments in energy politics have put electricity distribution network operators under increasing cost pressure due to constantly increasing reliability requirements set by the Finnish Energy Authority. One of the most important measures for achieving a sufficient level of reliability is well-coordinated maintenance. Network maintenance is also mandatory according to Electrical Safety Law, and network operators must prepare a maintenance program.

Although the maintenance program must include detailed maintenance measures, it has been recognized, that some of the smaller network companies from Trimble customer base haven't been able to deploy the Trimble NIS maintenance application. The objective of this Master's thesis was to develop a maintenance framework for the maintenance application. The maintenance framework is a service package intended for smaller network companies. The maintenance framework includes predefined features and configurations to ensure easy deployment and efficient use of the maintenance application.

The development of the maintenance framework is based on an extensive literature review considering legislation, network reliability and implementation of maintenance strategies and practices. To ensure the compliance and functionality of the maintenance framework, a needs assessment and necessary user tests were conducted with the pilot customers.

As a result of this thesis, the maintenance framework was successfully compiled. Based on the user acceptance testing, the framework is ready to be delivered, and will be marketed for small network companies. Further development is possibly needed in order to expand of the customer segment to medium-sized network companies.

Keywords NIS, DMS, reliability, network maintenance, asset management, preventive maintenance, reactive maintenance, reliability centered maintenance, condition index, condition management, distribution network, condition hierarchy, maintenance strategy

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Diplomityön tiivistelmä

Tekijä Mikael Aikio

Työn nimi Productized maintenance framework for utilities

Koulutusohjelma Automation and Electrical Engineering

Pääaine Electrical Power and Energy Engineering **Pääaineen koodi** ELEC3024

Työn valvoja ja ohjaaja Prof. Matti Lehtonen

Päivämäärä April 27, 2020 **Sivumäärä** 76 **Kieli** Englanti

Tiivistelmä

Viime vuosina energiapolitiikan kehitys on asettanut jakeluverkkoyhtiöille lisää kustannuspaineita. Verkkojen toimivarmuuskriteereitä nostetaan jatkuvasti säännöksillä. Yksi tärkeimmistä toimenpiteistä riittävän toimivarmuuden saavuttamiseksi on hyvin koordinoitu kunnossapito. Myös sähköturvallisuuslaki edellyttää laitteiston kunnossapitoa, ja verkkoyhtiöiden on laadittava kunnossapito-ohjelma. Vaikka kunnossapito-ohjelma sisältää yksityiskohtaiset toimenpiteet verkon eri osien kunnossapitoon, on käynyt ilmi, että osalla Trimblen asiakaskunnan pienemmistä verkkoyhtiöistä on ollut hankaluuksia Trimble NIS:in kunnossapitosovelluksen käyttöönotossa.

Tämän diplomityön tavoitteena oli kehittää kunnossapitopaketti Trimble NIS ohjelmistoon. Kunnossapitopaketti on pienemmille jakeluverkkoyhtöille tarkoitettu palvelupaketti, joka sisältää tarvittavat määritykset kunnossapitosovelluksen helpon käyttöönoton ja tehokkaan käytön varmistamiseksi.

Kunnossapitopaketti perustuu laajaan kirjallisuuskatsaukseen, jossa tarkastellaan lainsäädäntöä, verkon toimivarmuutta sekä kunnossapitostrategioiden ja -toimenpiteiden soveltamista verkon eri osissa. Kunnossapitopaketin vaatimustenmukaisuuden ja toimivuuden varmistamiseksi suoritettiin tarvekartoitus sekä tarvittavat käyttäjätestit pilottiasiakkaiden kanssa.

Diplomityön tuloksena tuotettiin onnistuneesti kunnossapidon palvelupaketti. Käyttäjätestien ja asiakaspalautteen perusteella kunnossapitopaketti on toimitusvalmis, ja sitä markkinoidaan pienille verkkoyhtiöille. Mahdollista jatkokehitystä tarvitaan asiakassegmentin laajentamiseksi keskisuuriin verkkoyhtiöihin.

Avainsanat NIS, DMS, reliability, network maintenance, asset management, preventive maintenance, reactive maintenance, reliability centered maintenance, condition index, condition management, distribution network, condition hierarchy, maintenance strategy

Preface

This thesis is done on a topic given by Trimble Solutions Oy.

I would like to thank Juha Haikonen and Teemu Heusala, who acted as the thesis supervisors and gave me valuable advice during the project. I would also like to thank the companies that took part in the pilot project, Kemin Energia ja Vesi Oy and Raahen Energia Oy.

In addition, I would like to thank Professor Matti Lehtonen, the thesis examiner, for his good advice and comments.

Otaniemi, 15.4.2020

Mikael Aikio

Contents

Symbols and abbreviations

Symbols

$CIC_{k,l}^{HV}$	The CIC-value for a high-voltage distribution network in year k, in monetary value of year l, euro
$CIC_{k,l}^{MV}$	The CIC-value for a medium-voltage distribution network in year k, in monetary value of year l, euro
$CIC_{ref,l}$	The reference CIC-value for year l, euro
CPI_{2006}	Consumer price index in 2006
CPI_{l-1}	Consumer price index in year $l-1$
CPI_k	Consumer price index in year k
DAR_k	Average energy-weighted interruption number due to DAR in year k, number
$HSAR_k$	Average energy-weighted interruption number due to HSAR in year k, number
$IN_{p,k}$	Average energy-weighted interruption number due to planned interruptions in year k, number
$IN_{u,k}$	Average energy-weighted interruption number due to unplanned interruptions in year k, number
$IT_{p,k}$	Average energy-weighted interruption time due to planned interruptions in year k, hours
$IT_{u,k}$	Average energy-weighted interruption time due to unplanned interruptions in year k, hours
K_{intr}	Interruption costs
K_{inv}	Investment costs
K_{loss}	Cost of losses
K_{mms}	Maintenance costs
m	Number of client/connection points supplied by certain voltage level
N_i	Number of customers affected by the permanent interruption i
n_i	Number of interruptions at client/connection point i
N_T	Total number of customers in the area under review
r_i	Total duration of the permanent interruption i
$R(t)$	The reliability of a component at time t
RP_i	Retention period of component i
RV_i	Replacement value of component i
$RVSD_{i,k}$	Corrected straight-line depreciation of component i for the year k
t_j	Duration of interruption j at client/connection point i
T_k	Amount of hours in year k
T	Planning or holding period
V	Voltage
W_i	Annual energy transferred for client/connection point i
W_k	Annual energy delivered to the customers by the network operator in year k, kWh
W_k	Annual energy delivered to the customers by the network operator in year k, kWh

W_t	Annual energy delivered to the customers by the network operator in year t, kWh
W_T	Total annual energy transferred at certain voltage level
W	Power
Wh	Energy
λ	Failure rate

Abbreviations

CAIDI	Customer Average Interruption Duration Index
CBM	Condition-based Maintenance
CIC	Customer Interruption Costs
CPI	Consumer Price Index
DAR	Delayed Auto-Reclosing
DMS	Distribution Management System
DSO	Distribution System Operator
HSAR	High-Speed Auto-Reclosing
HV	High-Voltage
HVDC	High-Voltage Direct Current
ICT	Information and Communication Technology
IT	Information Technology
LV	Low-Voltage
MV	Medium-Voltage
NIM	Network Investment Management
NIS	Network Information System
RCM	Reliability Centered Maintenance
SAIDI	System Avearage interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
SQL	Structured Query Language
TBM	time-based Maintenance
TSO	Transmission System Operator
UAT	User Acceptance Testing
UTG	Utility To Go

1 Introduction

In recent years, developments in energy politics have put electricity distribution network operators under increasing cost pressure due to constantly increasing reliability requirements set by the Finnish Energy Authority (*Energiavirasto*) for electricity networks. One of the most important measures for achieving a sufficient level of reliability is well-coordinated maintenance. Network maintenance requires significant investments, and reducing maintenance for mere cost reasons can lead to impaired reliability and higher interruption costs. Numerous studies have been devoted to considering different maintenance strategies and their effect on network reliability and cost-effectiveness [1] [2] [3] [4] [5]. Network operators can choose the most appropriate maintenance strategies for different parts of the network, and these decisions can be supported by different methods, such as classifying component criticality and calculating customer interruption costs (CIC). In addition, maintenance planning is commonly guided by network recommendations [6].

Various IT solutions, including network information systems (NIS) and distribution management systems (DMS), are used to support network operations. Up to 87% of the Finnish distribution network operators use either Trimble DMS or Trimble NIS, or both. Together, they form an information system that is used for network modeling, planning, maintenance, power system analysis, supervision and control. Trimble NIS includes a maintenance application offering tools for versatile network maintenance. Maintenance programs and practices are always company specific. For example, the service and inspection intervals, condition classification and maintenance actions of two network operators can differ greatly, depending on the network size, structure and location.

Although network operators are required to have detailed maintenance programs, it has been recognized by Trimble Solutions Oy [7] that some smaller network companies have not been able to deploy the maintenance application. This means that the maintenance process is not controlled through the information system. This can be explained by several reasons. Since transferring the maintenance program to the information system and learning to use the maintenance application can be laborious, continuing with the existing maintenance practices may feel easier. Moreover, implementing the maintenance program into the maintenance application may also require renewals. In addition, some network operators may not have a clear picture of the direction in which they want to develop their maintenance. Therefore, the objective of this thesis is to develop a framework for the maintenance application of Trimble NIS. The developed maintenance framework is a service package intended for smaller network companies, including all the needed features and configurations for efficient use of the maintenance application. The framework is developed in a pilot project involving two network companies. In order to develop this solution, the thesis will evaluate current network maintenance practices in terms of legislation, network reliability and the functionalities of the maintenance application. To ensure the compliance and functionality of the maintenance framework, a needs assessment and user tests are conducted with the pilot customers.

The scope of the thesis is limited to typical components and maintenance actions of medium-voltage (MV) and low-voltage (LV) networks, such as overhead lines, utility poles, distribution cabinets and distribution substations. Detailed maintenance of high-voltage (HV) network components, such as substations, is excluded from the scope, since many smaller distribution network operators do not own HV networks. Moreover, the maintenance of HV networks is usually performed by external contractors.

The maintenance framework includes predefined features, configurations, installation scripts, a user manual and user training to ensure easy deployment and efficient use of the maintenance application. The predefined features consist of maintenance actions and condition classifications for MV and LV networks. The installation package ensures easy delivery of the maintenance framework, including all the predefined features and configurations.

The rest of this thesis is divided into ten chapters. Chapter 2 discusses the effect of legislation and regulatory control on network maintenance. Chapter 3 reviews the factors affecting network reliability and interruptions. Chapter 4 evaluates different maintenance strategies and their implementation. Chapter 5 outlines the most common maintenance actions and the recommended maintenance intervals for distribution networks. Chapter 6 describes the most important features of the Trimble NIS maintenance application and their usage in the maintenance process. Chapter 7 describes the methodology and results of the requirements analysis. Chapter 8 provides the product specifications for the maintenance framework, including the product description, as well as evaluation of the business case and user personas. Chapter 9 describes the development of the maintenance framework, including predefined features, parametrization, installation package and documentation. Chapter 10 provides the results of the thesis, including project evaluation, testing results and customer feedback. Chapter 11 concludes the thesis by summarizing the pilot project, the role and cost effects of maintenance in distribution network operation, as well as evaluates the sales potential of the maintenance framework, and suggests directions for further development of the framework.

2 Background of network maintenance

Network maintenance is a vital tool in network condition- and risk management. The purpose of the network maintenance is to establish a secure and reliable network. Well coordinated maintenance will also minimize long term total costs of network operation by reducing the interruption related costs.

Network operation is business, so optimizing the operating costs is justified. Insufficient investments to the maintenance will increase interruption related costs and impair safety, but investing too much will increase the operating costs, which is not desirable for the business.

Network maintenance is very often profitable business, but it is also mandatory according to the law and regulations. Lots of money is invested in the maintenance, but the benefits are hard to model, so optimizing the maintenance for different parts of the network can be challenging. Finnish union, Sener ry, has compiled recommendations for the network maintenance, which have been the guideline for many network companies over the years. Sener ry operates in connection with the Finnish Energy (*Energiateollisuus ry*).

In this section, basic network structure and operation, and the most important laws and regulations in terms of network operation and maintenance will be reviewed. Regulatory control and its effects to network operation and maintenance will also be discussed.

2.1 Power system

Electric power system consists of production, transmission, distribution and consumption. In Finland, there exists about 120 companies that produce electricity, and over 400 power plants, half of which are hydro power plants [8]. Electricity is delivered to consumers through nationwide 110 kV-400 kV transmission grid and distribution networks that operate at multiple voltage levels. The single most important part of the electricity network is substation, where high-voltage, typically 110 kV, is transformed to 20 kV for radial distribution.

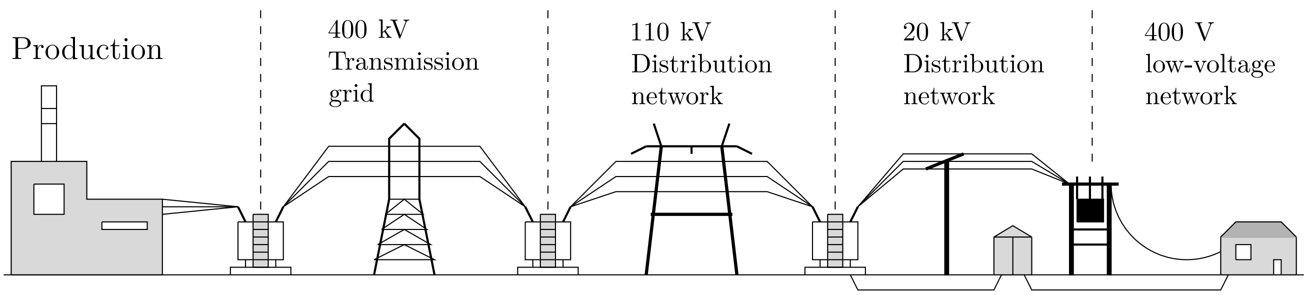

Figure 1: Simplified power system structure.

Electricity network consists of primary components and secondary components. Primary components include transmission lines, transformers and switching devices. Secondary components include protective devices, auxiliary voltage systems, control-, monitoring-, measurement-, and ICT-devices. Secondary devices are vital to the operation of power system, even though they don't physically contribute to the transmission of electrical energy.

2.1.1 Transmission grid

Finnish transmission grid operates at voltage levels of 110 kV, 220 kV and 400 kV. The grid comprises of 14600 kilometers of transmission lines and almost 120 substations. It is managed by the Finnish transmission system operator (TSO) Fingrid Oyj. About 77% of all electricity transmitted in Finland flows through the transmission grid. Majority of the transmission grid is built as a looped network for added reliability and smaller transmission losses. [9]

Finnish power system is also part of the inter-Nordic power system together with Sweden, Norway and Denmark. Furthermore, Russian and Estonian power systems are connected the Finnish powers system through HVDC transmission links. [9]

2.1.2 Distribution network

Finnish distribution networks are owned by several network companies. Distribution network usually consists of high-voltage regional network, substations, medium-voltage network, distribution substations and low-voltage network. Operating voltages are commonly 110 kV, 20 kV and 0,4 kV respectively.

Majority of medium-voltage networks consists of overhead lines, large cities excluded. However, in recent years the usage of underground cables has increased due to the Electricity Market Law. The objective is to make the network weather-proof for greater reliability. The cabling degree of MV and LV networks is expected to reach 54% and 70% respectively by the end of year 2036 [10].

The essential parts of MV networks are usually built as a looped networks. This increases reliability and makes the outage planning and management easier. In sparsely populated areas networks are usually radial because the building costs of a looped network are much higher than the financial gains from the reduced interruption and operating costs. Majority of distribution networks are located in areas where the increase of power transfer is not necessary. In such areas it is appropriate to focus on maintaining and improving reliability, and wise scheduling of the replacement investments. In growth centers the power demand can increase 30-50 % in ten years, so major investments are mandatory. [11]

2.1.3 Distribution network operation

In Finland, electricity network business is subject to license. The licenses are granted by the Finnish Energy Authority. Parallel networks are not built in Finland, so electricity network operation forms a natural monopoly. Therefore, it is strictly controlled by legislation and regulations. A network operator has obligations towards its network. These include network maintenance and development. In addition, a network operator shall connect production and consumption to its network. [11]

Operations and investments in the network have a significant impact in the price of electricity paid by the customer. The distribution fee is 15-50% of the electricity price [12, p. 17]. The objective of a network operator is to ensure efficient use of the network. It is essentially about maintaining and developing the quality, safety, customer service and economy of electricity. In practice, this means network planning and control, interruption management, network status monitoring and network maintenance.

Network planning is a one-off task, which is strongly guided by town planning and land use, especially in the urban conditions. The life cycle of a network is long, so future needs and statutory requirements are carefully considered at the planning phase. Because of the long technical life of network components, long-term planning of a distribution network plays an important role in a successful network strategy. The long-term planning seeks to outline how much investments to the network should be made in order to fulfill the statutory requirements. The network planning also has a major impact on network reliability, which can be improved by choosing more reliable components and by changing the network topology. [12]

The planning and implementation of network operations is directed by the operations manager. The core operations include planning and implementation of switching-operations, network supervision, interruption management and implementation of network maintenance. Frequently, the operations team also contributes to the network development by suggesting improvements. The operations are controlled from the control room or equivalent workstation. [12]

Network planning, operations and maintenance are carried out with the help of different IT solutions such as SCADA, NIS and DMS. Trimble NIS and Trimble DMS are discussed in more detail in section 6.

2.2 Legislation

The obligations of a distribution network operator are defined in the Electrical Safety Law and the Electricity Market Law. The purpose of these laws is to ensure safe, reliable and unbiased distribution of electricity.

In this section, the most important regulations considering the network maintenance will be reviewed. The legislation in certain European countries will also be discussed to determine, if the maintenance framework could possibly be implemented to foreign markets.

2.2.1 Electrical Safety Law

The purpose of the Electrical Safety Law is to ensure the safe use of electrical equipment and installations, to prevent the harmful effects of electromagnetic interference caused by the use of electricity, and to protect the rights of parties that have suffered damage. Furthermore, the purpose of the law is to ensure the compliance and free movement of electrical equipment in the Finnish market. The law is applied to electrical equipment and installations used for the production, transmission, distribution or use of electricity, and whose electrical or electromagnetic properties may present a risk of damage or interference. [13]

The 6 § of the law defines the general requirements for electrical equipment and installations. The electrical equipment and installations shall be designed, constructed, produced and repaired, and they shall be maintained and used in accordance with their intended use so that:

1. they do not endanger the life, health or property of anyone;
2. they do not cause unreasonable interference electronically or electromagnetically;
3. their operation is not easily disturbed electrically or electromagnetically [13].

Electrical equipment are divided into different categories with regard to their certification and periodic inspection requirements and to their maintenance program requirements. According to the 44 § of the law, electricity networks belong to class 3 electrical equipment, which include the distribution, transmission and other electricity networks of a network operator. A maintenance program is required by the law for class 3 electrical equipment. The 48 § of the law states that the maintenance program must adequately take care of different parts of the network and the maintenance actions performed. The implementation and monitoring of the maintenance plan is primarily under the control of the network operator.

According to the 49 § of the law, a periodic inspection must be performed to class 3 electrical equipment every five years. The 50 § of the law defines the content and conductor of the inspection. The periodic inspection shall, to a sufficient extent, ensure by random sampling or by any other appropriate means that:

1. the electrical equipment is safe to operate, the maintenance is sufficient to maintain safety, and the equipment has been subjected to the maintenance plan;
2. the tools, blueprints, diagrams and instructions for operating and maintaining the electrical equipment are available;

3. there are appropriate inspection reports on the extension and modification of the electrical equipment [13].

The periodic inspection may be carried out by an authorized body referred to in the 75 § or by an authorized inspector. The inspector's authorization is carried out by the Finnish Safety and Chemicals Agency *Tukes*.

2.2.2 Electricity Market Law

Finnish electricity market is controlled by the Electricity Market Law to ensure effective and sustainable operation at the national and regional markets, and at the internal market of the European Union. The purpose of the law is to guarantee reliability, competitive price of electricity and reasonable service principles to all consumers. The law is applied to electricity market, which consists of production, importation, exportation and distribution of electricity. [14]

With the reform of the Electricity Market Law in 2013, requirements for the reliability and quality of the electricity supply were clarified. According to the market law, a network company is under an obligation to secure and maintain the quality of electricity through network maintenance and development. The network development obligations are listed in the 19 § of the law, which states that the electricity network must be designed, constructed and maintained so that:

1. the electricity network meets the quality requirements for network operation and the technical quality of electricity transmission and distribution is otherwise good;
2. the electricity network and the network services function reliably and securely when exposed to normal and expected climatic, mechanical and other external disturbances;
3. the electricity network and the network services operate as reliably as possible in the event of disturbances during normal operation and in the event of an emergency referred to in the Emergency Act (1552/2011);
4. the electricity network operates in a compatible manner with the power system and may be connected to another electricity network, if necessary;
5. eligible sites and power plants can be connected to the electricity network;
6. the network operator is otherwise able to fulfill its obligations imposed by this Act [14].

The most important requirements from the perspective of network maintenance and condition management are 1 and 2. These requirements have been clarified in the 28 § and 51 § of the law. The network operator must be prepared for disturbances during normal operation and emergency situations, and shall prepare a contingency plan which must be updated every three years. Quality requirements state that the distribution network must not cause interruptions of more than six hours in town planning area and interruptions of more than 36 hours in other areas by 2028. Moreover, customer interruption costs (CIC) were increased, which also drives network companies for improved reliability.

The 52 § of the law states that the network operator shall prepare a development plan, which must be updated every two years. The plan must include detailed measures, that will systematically and sustainably improve reliability and fulfill the requirements stated in the 51 § of the law. Further instructions for the preparation of the plan are specified in the regulation 823/002/2013 [15]. Development of network condition management is important part of the plan. The development plan and any amendments made to it, shall be submitted to the Energy Authority (Energiavirasto).

2.3 Regulatory control

In addition to the Electricity Market Law and the Electric Safety Law, companies operating in a monopoly position in the electricity sector are under the supervision of the Energy Authority. The reliability requirements of the network are constantly being increased by regulations. It is required that the investments made by network operators are reasonable and operation is efficient [16]. At the same time, the pricing must be reasonable. Regulatory control has a significant impact on the operation of network companies, and therefore on the network maintenance.

2.3.1 Control methods

The pricing of network companies is regulated by the Energy Authority's control methods over four-year monitoring periods. The control methods apply to distribution network operators and high-voltage distribution network operators. The Energy Authority acts as a national regulator in the Finnish electricity market. The rights and jurisdiction of the Energy Authority are stated in the separate control law 2013/590 [17].

In the latest control model, the control methods have been set for the fourth and fifth monitoring periods, which span over 1.1.2016 - 31.12.2019 and 1.1.2020 - 31.12.2023 respectively. With the control methods, a reasonable profit is set for the network companies. The realized return is corrected using depreciation, expenses and incentives. The reasonable profit is subtracted from the corrected realized return, and it results in a surplus or a deficit. A possible surplus realized during the monitoring period must be evened out during the next monitoring period. Summary of the control methods and the incentives for the fourth and the fifth monitoring period is presented in figure 2. [18]

The control of network companies is open to consumers and the media. At the end of each monitoring period the Energy Authority shall publish the final report, which includes the calculations made by the network operators [19, p. 1].

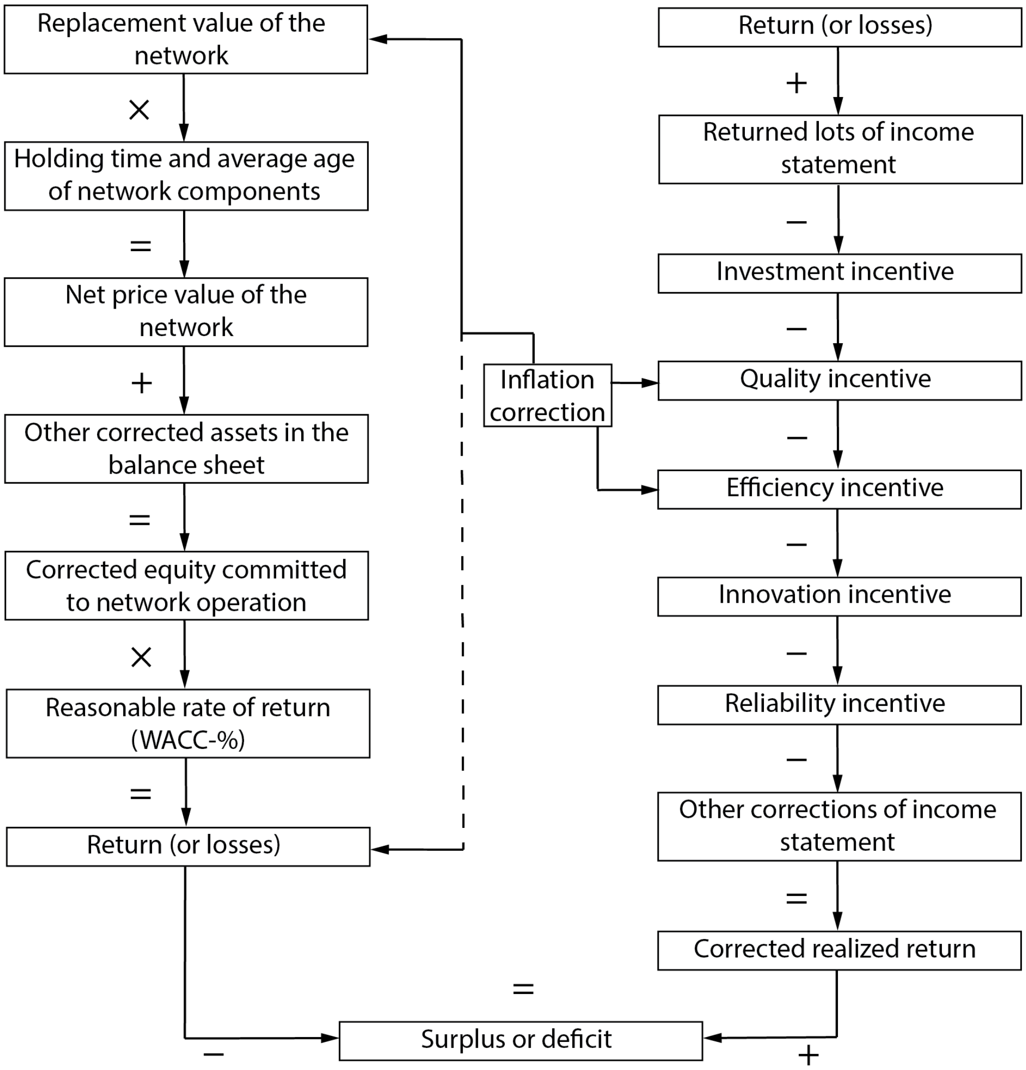

Figure 2: Control methods for the fourth and fifth monitoring periods.

2.3.2 Incentives

The Energy Authority has defined various incentives for network companies to direct and develop their operation. Incentives can be used to systematically correct the realized return in a positive way for the network operator. The additional income generated by the incentives will allow for replacement and acquisition investments, which increase the value of the network assets, which in turn has a positive effect on the maximum allowable profit [18]. The most important incentive from the perspective of network maintenance is the quality incentive.

The purpose of the quality incentive is to encourage network operators to develop the quality of electricity transmission and distribution. A network operator is encouraged to achieve at least the level of reliability required by the Electricity

Market Law. The Energy Authority's objective is also to guide network operators to improve the quality of electricity transmission and distribution beyond the minimum legal requirements on their own initiative. The quality of electricity distribution is measured by the number and duration of interruptions. Interruptions and the related costs are discussed in more detail in section 3.3. Network operators report the interruption costs annually to the Energy Authority, and they are compared to the operator's calculated reference costs. If the interruption costs are lower than the reference costs, the allowed return is increased. In turn, if the interruption costs are higher than the reference costs, the allowed return is deducted. In the new quality incentive, full interruption costs are used instead of the previous half costs, which further emphasizes the importance of the incentive. Since network maintenance has a significant role in preventing interruptions and ensuring the quality of electricity distribution, the effect of maintenance shows directly through the quality incentive. [18]

The purpose of the investment incentive is to encourage network operators to invest in a cost-effective manner. It also allows for replacement investments. The incentive allows network operators an annual depreciation level according to the chosen retention period. Calculated straight-line depreciation is always allowed as long as a component is in actual use. This means that the straight-line depreciation is calculated for a component even after the chosen retention period if the component is still in use. Therefore, the investment incentive enables full depreciation of the replacement costs of the network components. For components that have exceeded their retention period, straight-line depreciation is obtained in proportion to the residual value of the components dismantled before reaching their chosen retention periods. [18]

For network component i, the corrected straight-line depreciation for year k can be calculated with the following equation [18, p. 65]:

$$RVSD_{i,k} = \frac{RV_i}{RP_i} * \frac{CPI_k}{CPI_{2006}} \tag{1}$$

where

$RVSD_{i,k}$	=	Corrected straight-line depreciation of component i for year k
RV_i	=	Replacement value of component i
RP_i	=	Retention period of component i
CPI_k	=	Consumer price index in year k
CPI_{2006}	=	Consumer price index in 2006

The efficiency incentive directs network operators to become more efficient and to allocate resources as efficiently as possible. The incentive consists of a general efficiency objective and a company-specific efficiency objective. The efficiency incentive guides network maintenance so, that the resources invested in it are managed as efficiently as possible in terms of the network operating costs. [18]

The purpose of the innovation incentive is to encourage network operators to develop and use innovative technical and operational solutions in its operations. A network operator may incur research and development costs even before new technologies and practices are fully deployed and exploited [18, p. 93]. The innovation incentive has been developed to compensate these costs. New technical solutions are also likely to have an impact on network condition management, for example as more advanced condition monitoring methods are developed.

The purpose of the reliability incentive is to enable network operators to meet statutory reliability criteria within the legal timeframe. Some network operators will have to make very substantial replacement investments and maintenance work in order to meet the statutory criteria within the deadline. The incentive is used to compensate these costs. [18, p. 94]

2.4 Network operation abroad

In addition to Finland, Trimble NIS is used in several foreign countries. Biggest market segments are in Sweden and Germany. There exists about 170 distribution system operators (DSO) in Sweden and over 900 in Germany [20, p. 11].

Regional laws of the EU member states are based on EU directives and regulations. Therefore, the same requirements apply in all EU member states. The most important EU directives and regulations considering electricity network operation are the Electricity Directive (2019/944) and the Electricity Regulation (2019/943) on the internal market for electricity [21] [22]. In Sweden, regulations considering electricity generation, transmission, use and safety are stated in the Electricity Act (1997:857). In Germany, the corresponding law is the Energy Industry Act. The leading regulatory authority for the Swedish energy markets is the Swedish Energy Markets Inspectorate (*Energimarknadsinspektionen*). For the German energy markets, the leading regulatory authority is The Federal Network Agency (*Bundesnetzagentur*).

According to the report published by the European Commission, even within each member state, big differences exist in the number, size and governance of the DSOs [20, p. 5]. There are also differences in the design of distribution networks between different network operators: Medium-voltages vary and there can be multiple, three or four wires are used, the star point grounding methods differ, and there are differences in the application of local automation and switchgear [12, p. 14]. Finnish electricity distribution practice is largely based on the German tradition, but in some cases the solutions are simpler [12, p. 14]. In continental Europe, the practices are often similar, although the medium-voltage level varies. From the perspective of network maintenance, the differences between countries may not be large. The basic components of the networks are the same, and reliability of the networks must be maintained at the level required by the EU legislation. For example, the maintenance guidelines of the Swedish TSO *Svenska Kraftnät* are very similar to those in Finland [23] [24].

Based on the reviewed legislation and network operation practices, the maintenance framework could possibly be marketed abroad, at least for the existing customers. However, this will require more detailed analysis of the foreign network companies, and possibly a pilot project, where a needs assessment and a detailed research of the foreign maintenance practices is conducted.

3 Network reliability

The reliability of electricity networks and the quality of electricity are of paramount importance for the operation of society. The reliability of electricity network refers to the ability of a network to function under different load or fault conditions, when viewed in a long term [10]. The quality of electricity, in turn, consists of security of supply and quality of voltage. The quality of electricity supply is influenced by the entire operation of the network company: Network planning, operations, maintenance and customer service.

Majority of the interruptions experienced by the consumers are caused by distribution network faults. A distribution network is more prone to faults than other networks because of its structure and operating environment. A large part of distribution networks are placed so, that they are susceptible to external disturbances such as falling trees or earthmoving.

Network operators are divided into three categories; city, conurbanation, and sparsely populated type network operators. The division is affected by the amount of energy delivered, the length of the network and the number of customers, as well as the degree of underground cabling in the MV network.

The Energy Authority monitors and supervises the security of electricity supply based on the development obligations and the quality requirements under the Electricity Market Law. The supervision is based on annual key figures collected from network operators. The collection and publication of reliability figures provides a public and unbiased tool for comparison of network operators. The Energy Authority also monitors the implementation of the development plans. The regulation concerning network operation key figures was revised in 2016 by regulation 2167/002/2016 [19].

3.1 Interruptions

The properties of distribution voltage for LV and MV networks are defined in the standard SFS-EN 50160. Interruption refers to a situation where the voltage is less than 1% of the nominal voltage U_n. The interruption may, at a minimum, affect only one customer, but at its most extensive it can affect the entire transmission grid and its associated distribution networks.

Interruption is deemed to commence when it is brought to the attention of a network operator. For MV and HV networks, the interruption information is almost invariably acquired from SCADA or DMS. For low-voltage networks, the interruption information may also come from a customer. [25]

In standard SFS-EN 50160, interruptions are divided to unplanned outages and planned outages. Unplanned outage is caused by a network fault or an erroneous switching. Usually less than 35% of the outages are permanent interruptions. In city areas, permanent interruptions account for more than 60% of the outages due to the high volume of underground cabling [26]. During a permanent interruption, the operations manager isolates the fault location, possibly identifies the fault, directs the repair personnel and restores the network to normal operation. At its fastest, the fault isolation is done in minutes.

The interruption is counted as high-speed auto-reclosing (HSAR) if it lasts for about one second and as delayed auto-reclosing (DAR) if it lasts less than three minutes. In sparsely populated areas and conurbation, HSAR can clear about 50% and DAR approximately 15% of all faults. [26]

Planned outage is a pre-planned work on the distribution network, that has been notified to the customer in advance. It is counted as unplanned outage if it hasn't been notified to the customer in advance.

3.2 Interruption causes

The Finnish Energy publishes the yearly interruption statistics. Interruption statistics were thoroughly revised at the beginning of 2015. Data collection became client point specific and regional division according to the reliability into the plan area and the area outside the plan area.

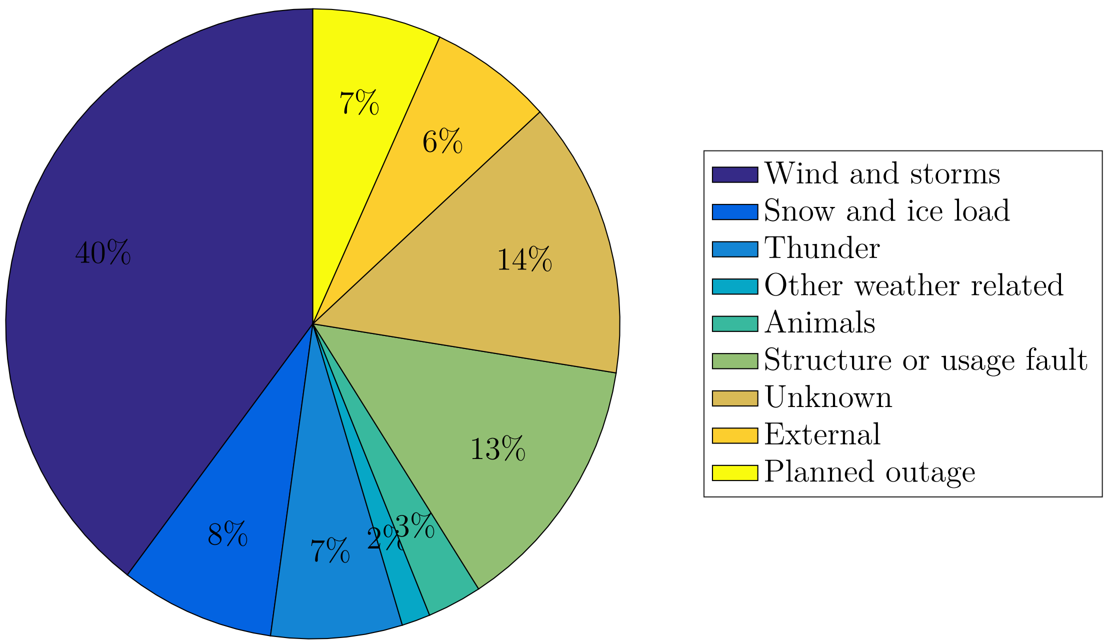

Figure 3: The distribution of interruptions by cause [26].

The statistics collect information on distribution networks both on an interruption basis and on a client point basis. Outage information is collected about network operation and maintenance events, of which the cause, location, type, time and extent of the outage are declared. On a client point basis, the annual outage times and numbers divided to unplanned and planned outages are declared. [26]

In 2018, Finns experienced an average of 6.12 interruptions (SAIFI) with an average duration of approximately 0.6 hours (SAIDI). The interruption statistics for 2018 are based on the interruption data of 59 distribution network operators. The statistics cover 96.6% of the length of distribution networks in Finland. [26]

The distribution of outages by cause in 2018 is presented in figure 3. Natural phenomena remain the largest cause of interruptions in the Finnish distribution network, accounting for more than 57 % of the outage numbers. About 13 % of the outages were caused by structural or operational faults and 7% were planned outages. The outage numbers and times vary from year to year. For example, major storms or other natural phenomena can cause annual peaks to outage times. In 2011, *Tapani* and *Hannu*-storms damaged the electricity network over large areas and caused long interruptions, which in turn led to tighter reliability requirements.

A distribution network consists of network components. Failure of a single network component can result in an outage. The reliability of the system can be evaluated by knowing the characteristics and failure rates of the network components. Factors affecting failure rates include operating conditions, external factors, component structural properties, and service life. Component lifetimes have long been set at recommended values, beyond which component reliability is rapidly reduced. It is generally suggested that the reliability of network components follow the so-called *bathtub curve*, where the failure rate is initially high due to possible manufacturing or installation errors [27, p. 56]. In the second stage, the failure rate remains low during the natural life of the component. In the third stage, the failure rate starts to increase again due to the natural aging of the component.

The structure and properties of equipment insulation will change over the life cycle. Insulators may be subject to mechanical, thermal, chemical or electrical stresses in the short and long term, which impair the electrical strength of the insulator. Naturally, the structure of the insulation also contributes to the life cycle of the insulator. The plastic insulation of underground cables becomes brittle and undergoes various mechanical stresses during its life cycle. These stresses reduce the reliability of the cables. One of the most important properties of plastics is the partial discharge resistance. As a result of mechanical pull or bumping, microscopic cavities may be formed in the cable, which may result in partial discharge channels. In addition to heat radiation, low temperatures can damage cables. [28]

Well coordinated network maintenance can greatly reduce the outage numbers. Regular inspections and services improve the reliability of components and maximizes their service life. Clearing of the line areas can help to prevent weather related outages in areas, where the underground cabling is not economically sensible.

3.3 Outage related costs

A network operator is obliged to pay various compensations for interruptions experienced by the customer. These compensations are called standard compensations and customer interruption costs (CIC). CICs are not paid for the end user. A network operator shall pay the standard compensation to the end user for any interruption in the supply of electricity, unless he can prove that the cause of the interruption was an unavoidable obstacle beyond the control of the operator [14].

Standard compensations are paid for interruptions of more than 12 hours. The standard compensations due to interruption of electricity distribution or supply are defined in the 100 § of the Electricity Market Law. The amount of the compensation depends on the outage time and the amount of annual transfer fees paid by the customer according to table 1. Standard compensation will not be paid for the part exceeding €2000 [14].

Outage time (h)	Standard compensation
12...24	10 %
24...72	25 %
72...120	50 %
120...192	100 %
192...288	150 %
288...	200 %

Table 1: Standard compensations [14].

CIC-values are based on the number and duration of interruptions and the interruption unit prices. A network operator shall report these key figures to the Energy Authority, and they are used in the quality incentive. In the fourth and fifth monitoring period, interruptions caused by MV distribution networks that are taken into account are:

- the number and duration of planned outages
- the number and duration of unplanned outages
- the number of delayed auto-reclosings (DAR)
- the number of high-speed auto-reclosings (HSAR) [18, p. 67].

Since 2013, the Energy Authority has also been collecting the interruption information of high-voltage distribution networks. In the fourth monitoring period, only the number and duration of planned and unplanned outages are taken into account. In the fifth monitoring period, the number of DARs and HSARs shall also be reported. [18, p. 67]

Unit prices of the CIC-values are presented in table 2. The unit price values are based on a study commissioned by the Energy Authority [29]. The unit prices in the table are in 2005 monetary values. For the calculation of the reference values and realized interruption costs, unit prices shall be corrected to the monetary value of each year by the consumer price index (CPI).

Unplanned outage		Planned outage		Delayed auto-reclosing (DAR)	High-speed auto-reclosing (HSAR)
$c_{E,u}$	$c_{W,u}$	$c_{E,p}$	$c_{W,p}$	c_{DAR}	c_{HSAR}
€/kWh	€/kW	€/kWh	€/kW	€/kW	€/kW
11,1	1,1	6,8	0,5	1,1	0,55

Table 2: Unit prices of the CIC-values.

In the incentives, CIC-values are energy-weighted. This allows customers with different electricity consumption to be more accurately included in the CIC calculations. The collected key figures and their calculation is explained in the regulation 2167/002/2016 [19]. According to the regulation, energy-weighted interruption numbers and times used in the CIC calculations are calculated with the following two equations:

$$IN = \frac{\sum_{i=1}^{m} W_i n_i}{W_T} \tag{2}$$

$$IT = \frac{\sum_{i=1}^{m} W_i \left(\sum_{j=1}^{n} t_j \right)}{W_T} \tag{3}$$

where

n_i	=	Number of interruptions at client/connection point i
t_j	=	Duration of interruption j at client/connection point i
W_i	=	Annual energy transferred for client/connection point i
W_T	=	Total annual energy transferred at certain voltage level
m	=	Number of client/connection points supplied by certain voltage level

Equations 2 and 3 can be used to calculate energy-weighted key figures for HV, MV and LV networks. For HV networks, connection points are used instead of client points.

The CIC-values are calculated by multiplying the values in table 2 by the energy-weighted interruption numbers of the network operator, and then multiplying them by the average power transferred or by the annual energy. The CIC-value for a MV distribution network can be calculated with the following equation:

$$CIC_{k,l}^{MV} = \begin{pmatrix} IT_{u,k} * c_{E,u} & + & IN_{u,k} * c_{W,u} & + \\ IT_{p,k} * c_{E,p} & + & IN_{p,k} * c_{W,p} & + \\ DAR_k * c_{DAR} & + & HSAR_k * c_{HSAR} \end{pmatrix} * \left(\frac{W_k}{T_k}\right) * \left(\frac{CPI_{l-1}}{CPI_{2004}}\right) \tag{4}$$

where

$CIC_{k,l}^{MV}$	=	The CIC-value for a medium-voltage distribution network in year k, in monetary value of year l, euro
$IT_{u,k}$	=	Average energy-weighted interruption time due to unplanned interruptions in year k, hours
$IN_{u,k}$	=	Average energy-weighted interruption number due to unplanned interruptions in year k, number
$IT_{p,k}$	=	Average energy-weighted interruption time due to planned interruptions in year k, hours
$IN_{p,k}$	=	Average energy-weighted interruption number due to planned interruptions in year k, number
DAR_k	=	Average energy-weighted interruption number due to DAR in year k, number
$HSAR_k$	=	Average energy-weighted interruption number due to HSAR in year k, number
CPI_{l-1}	=	Consumer price index in year $l-1$
W_k	=	Annual energy delivered to the customers by the network operator in year k, kWh
T_k	=	Amount of hours in year k

For HV distribution networks, the CIC-value ($CIC_{k,l}^{HV}$) is calculated in same way as in equation 4, but the interruption times and numbers are not energy-weighted. Further, in the fourth monitoring period interruptions due to DAR or HSAR are not included in the calculation of CIC-values.

Calculation of the CIC reference level is based on a report prepared by Lappeenranta University of Technology and Tampere University of Technology [30]. The reference level for interruption costs shall be the average of the realized interruption costs incurred for the network operator during the previous two monitoring periods. In the fourth monitoring period, the reference level is the average interruption cost of years 2008-2015 [19].

The reference level takes into account major interruptions, as the costs incurred are compensated for the network operator. The reference level shall be corrected by the annual energy delivered to the customers to make the reference level of interruption costs comparable to that of the realized CIC-value in terms of the transferred energy. The reference CIC-value for a MV distribution network can be calculated with the following equation:

$$CIC_{ref,l} = \frac{\sum_{k=2008}^{2015}\left[CIC_{k,l}^{MV} * \left(\frac{W_k}{W_t}\right)\right]}{8} \tag{5}$$

For HV distribution networks, the reference values are calculated in same way as in equation 5, but $CIC_{k,l}^{HV}$ is used instead of $CIC_{k,l}^{MV}$. In the fifth monitoring period, the calculation of the reference level shall take into account the interruptions caused by the netwok operator's high-voltage distribution network.

$$CIC_{ref,l} = \frac{\sum_{k=2012}^{2019}\left[CIC_{k,l}^{MV} * \left(\frac{W_k}{W_t}\right)\right]}{8} + \frac{\sum_{k=2013}^{2019}\left[CIC_{k,l}^{HV} * \left(\frac{W_k}{W_t}\right)\right]}{7} \tag{6}$$

For HV distribution network operator, the reference value is the second term of equation 6. It is to be noted that in the case of high-voltage distribution network, only CIC-values of years 2013-2019 are considered. Variables in equations 5 and 6 are:

$CIC_{ref,l}$	=	The reference CIC-value for year l, euro
$CIC_{k,l}^{MV}$	=	The CIC-value for a medium-voltage distribution network in year k, in monetary value of year l, euro
$CIC_{k,l}^{HV}$	=	The CIC-value for a high-voltage distribution network in year k, in monetary value of year l, euro
W_k	=	Annual energy delivered to the customers by the network operator in year k, kWh
W_t	=	Annual energy delivered to the customers by the network operator in year t, kWh

In the calculation of the quality incentive, the realized interruption costs are subtracted from the reference costs. The maximum effect of the quality incentive has been moderated by setting limits to the incentive. If the difference between realized interruption costs and reference costs is greater than the treshold, it won't affect the calculation of corrected return.

In the calculation of realized corrected return, the quality incentive effect taken into account may not exceed 15% of the network operator's reasonable profit for the year [18, p. 75]. This applies to the quality bonus for quality improvement and the quality sanction for quality degradation. In spite of its simplicity, the interruption costs associated with the quality incentive are a good financial incentive to accelerate the development of network companies.

The calculation of CIC-values can also be used to determine the optimal maintenance strategy. The cost of component failure can be compared to the annual maintenance cost. The comparison can be also used as a part of the criticality classification. Maintenance strategies and criticality classes will be discussed in section 4.

3.4 Other reliability figures

In addition to the interruption times and costs, the reliability of electricity distribution is described by reliability figures that are defined in the standard IEEE 1366-2012. The use of standard figures significantly improves the ability to compare different network operators. Equally, comparability even between network operators in different countries is facilitated. The figures in the standard are not energy-weighted, and thus are not useful as such in the control methods. However, they are useful in the overall assessment of the network reliability.

The figures can be divided to customer and power based figures. In this section the most commonly used customer-based figures, SAIDI, SAIFI and CAIDI, will be reviewed. The figures are usually calculated over a calendar year. The calculation of these figures is defined in the interruption statistics published by the Finnish Energy. [26].

SAIDI (System Average interruption Duration Index) tells the average total duration of interruptions over a certain time period:

$$SAIDI = \frac{\sum_i r_i N_i}{N_T} \tag{7}$$

where

r_i	=	Total duration of the permanent interruption i
N_i	=	Number of customers affected by the permanent interruption i
N_T	=	Total number of customers in the area under review

SAIFI (System Average Interruption Frequency Index) tells the average number of interruptions per customer:

$$SAIFI = \frac{\sum_i N_i}{N_T} \tag{8}$$

CAIDI (Customer Average Interruption Duration Index) tells the average duration of permanent interruption experienced by the customer. It can be defined as the ratio of SAIDI and SAIFI:

$$CAIDI = \frac{\sum_i r_i N_i}{\sum_i N_i} = \frac{SAIDI}{SAIFI} \tag{9}$$

The above-mentioned figures describe the status of the whole distribution network. Prior to the regulation 1730/002/2015, which was later replaced by the regulation 2167/002/2016, transformer circuit specific figures were also collected. These figures are called T-SAIFI, T-SAIDI and T-CAIDI. There will be no further elaboration on how to calculate these.

3.5 Network development

The quality requirements defined in the Electricity Market Law will come into effect gradually: By the end of year 2019 at least 50 %, and by the end of year 2023 at least 75 % of the distribution network client points must meet the requirements respectively. The remaining end users will have to meet the quality requirements by the end of year 2028.

The challenges of meeting the reliability requirements include changes in network type and topology, as decades old MV overhead lines crossing forests may no longer be appropriate to meet the requirements. In many cases, the electricity user base may also have changed significantly from decades ago, so changes in network structure and topology will be necessary for reasons other than improving reliability. [31]

The fulfillment of these requirements is monitored by development plans discussed in section 2.2.2. Network operators submitted their third plans by June 30, 2018. According to the development plans, as of January 1, 2018, 74 % of all client points meet the quality requirements. In town planning areas 87 % of the client points meet the quality requirements. Outside the town planning area, quality requirements are met in 38 % of the client points. In total, the quality requirements are not met in 920,000 client points. [10]

According to the development plans, the focus of reliability measures will be in the densely populated urban areas during the first third of the transition period, after which the focus will shift to sparsely populated areas. The procedure will help a greater number of client points to meet the reliability requirements, but differences in reliability between urban and sparsely populated areas are likely to increase. According to the development plans, network operators will, in total, spend €633 million annually on replacement investments and approximately €53 million annually for maintenance [10, p. 42]. In total, approximately €9,7 billion will be invested in the electricity distribution network in 2014-2028 [10, p. 42]. The number does not include e.g measurement devices and IT-system investments.

The underground cable network meets the reliability requirements, so over the next 15 years many network operators are concentrating a large part of their network investments on underground cabling of the distribution network. The development of underground cabling degree according to the development plans is presented in table 3. While underground cabling is an effective way to improve the reliability, it is not always the most cost-effective way. The local conditions and operating environment of the network operator have a significant impact on the profitability and applicability of underground cabling. A large underground cable network can also raise other challenges, such as reactive power and earth-fault current management.

For rural network operators, the MV underground cabling rate is expected to rise to an average of only 26 %. Particularly in a rural environment, network operators consider that they fulfill the quality requirements to a substantial degree by other means than underground cabling. For example, network operators can move overhead lines alongside roads and invest in network maintenance. The purpose of the Electricity Market Law and the incentives is therefore not to require complete underground cabling, but to leave it to the network operators to decide on the most cost-effective measures required by the increasing reliability requirements.

Currently around 34 % of the MV distribution network length is the most high-risk i.e overhead lines in the forest. There are 18 % of MV overhead lines alongside the roads and 21 % of MV overhead lines located outside the forests or off-road. Correspondingly 24 % of the LV network length is overhead lines in the forest, 16 % alongside the roads, and 13 % located outside the forests or off-road. [10, p. 44]

Year	Underground cabling degree of MV network (%)	Underground cabling degree of LV network (%)
2014	15	41
2015	17	41
2016	19	42
2017	23	44
2018	27	47
2019	30	49
2020	34	52
2023	42	58
2028	51	67
2032	53	69
2036	54	70

Table 3: Underground cabling degree according to the development plans [10].

The investments and the results achieved in the previous two years have been reported in the development plans. The operations correspond to those reported by distribution network operators in their long-term plans, i.e. MV and LV network cabling and the related transformer and substation projects. Investments reported in 2018 for the previous two years (2016-2017) totalled €1,344 billion. The network has been modified to meet the reliability requirements for approximately 26,000 km. Of this, the MV network accounted for 14,000 km and the LV network accounted for 12,000 km. The reliability requirements were fulfilled in additional 233,000 client points. [10]

Legislation and control methods aim to improve the reliability of distribution networks. The requirements of the Electricity Market Law guide network operators to improve the structural reliability of electricity networks. One of the most straightforward ways is the underground cabling, though widened line areas, effective forest management, increased automation and high-quality maintenance can be cost-effective ways to meet operational quality standards in some environments. Reliability elements in control methods include quality incentive, reliability incentive and the treatment of standard compensations as operational costs. The effects of control methods will probably only be visible in the longer term in terms of reliability.

4 Network condition management

Network condition management refers to the asset management and related support activities that control the current state of the network and its development. The principles, guidelines, goals, and operating models that guide the asset management are referred to as asset management policy or strategy. Practical, asset-related actions under the strategy are referred to as network maintenance. In addition to the network components, network maintenance includes clearing of the line areas and the management of side-by forest. [32]

The purpose of network maintenance is to establish a secure and reliable network and to minimize the overall cost of the network. In addition, the maintenance process provides valuable information about the network, which aims to ensure the planned service life of the network components. Network maintenance is also mandatory according to law.

Network maintenance costs include clearing of line areas, tree care, pole inspections, flight inspections, substation, distribution substation, distribution cabinet and other inspections, and service and repair costs.

4.1 Asset management

Asset management is a broad concept and is widely defined in various studies. Generally it refers to any activity that monitors and maintains an asset and maximizes the return of the asset. This may refer to material assets or immaterial assets, i.e. immaterial capital. [33]

Two international standards, PAS 55 and ISO 55001, are widely used in the asset management [32, p. 13]. Implementing and effectively utilizing asset management requires a disciplined approach and commitment from the entire organization. Investing in asset management has a big impact on a long term, especially in a network company, where asset management has a major impact on the condition and reliability of the network and and further, operating costs.

4.1.1 Network assets

The capital tied up in electricity networks is very high and the network components have a long lifetime, which emphasizes the importance of systematic and long-term asset management. The value of the network assets is adjusted in the control methods to match the net present value. The adjusted net present value is calculated from the adjusted replacement value, which is determined by the component unit prices. The Energy Authority publishes the unit prices and the holding times of the components for different monitoring periods. The adjusted net present value of the network is one of the key figures reported to the Energy Authority, and it effectively affects the allowed revenue of network companies. It is possible to implement a network value calculation in Trimble NIS. [18]

Asset management in network companies refers to the operating models and principles created and used by the company in relation with the development, maintenance and operation of the network. In network companies, asset management can be divided into three main parts: development planning, maintenance and network operation [12, p. 215]. IT-systems, such as Trimble NIS, are closely linked to the asset management process.

4.1.2 Life cycle management

Estimating the life cycle cost of network components is sensible from the perspective of network maintenance. In the life cycle of a component, the total cost of the component is compared to the holding time. When choosing a component, the price is often used as a major justification. However, it is possible that a cheap component will prove more expensive when looking at the entire life cycle.

In the planning phase, the aim is to achieve a low-cost, technically feasible solution. The total cost over the planning or holding period T consists of the investment, loss, interruption and maintenance costs at time t, which are sought to be minimized in accordance with equation 10 [12, p. 63].

$$\begin{aligned} &min \int_0^T (K_{inv}(t) + K_{loss}(t) + K_{intr}(t) + K_{mms}(t)) = \\ &min \sum_{t=1}^{T} [K_{inv}(t) + K_{loss}(t) + K_{out}(t) + K_{mms}(t)] \end{aligned} \tag{10}$$

where

T	=	Planning or holding period
K_{inv}	=	Investment costs
K_{loss}	=	Cost of losses
K_{intr}	=	Interruption costs
K_{mms}	=	Maintenance costs

The way in which equation 10 is minimized is greatly influenced by the operating strategy chosen by the network company. This also directly affects the valuation of the maintenance component and the interruption cost component in total cost optimization.

4.2 Maintenance

Maintenance is defined in the standard SFS-EN 13306 as follows: Maintenance is the sum of all technical, administrative and management measures intended to maintain or restore the object to a state where it is capable of performing the required function throughout its life cycle.

Network maintenance is an essential part of the reliability and safety of electrical equipment and installations. It is also partly mandatory under the Electricity Market Law and the Electricity Safety Law. For example, a network operator must prepare a maintenance plan that adequately covers different parts of the network. With adequate condition inspections and maintenance programs, a distribution company may verify to the Electric Safety Authority that the prescribed requirements for network safety, condition and monitoring are met.

The maintenance strategies and the maintenance program are mainly determined by the network operator. At least the following issues must be considered when designing effective maintenance: uptime, downtime, reliability planning, quality, maintenance actions, and cost optimization. There are various recommendations to support the preparation of the maintenance program. For example, Sener ry's network recommendations and electric cards ST 96.01 and ST 96.02 contain instructions for the inspections, maintenance, and preparation of the maintenance program.

4.2.1 Maintenance strategies

The maintenance strategies of electricity networks can be divided into two main categories: Preventive and reactive maintenance. The classification of maintenance strategies is presented in figure 4. Compared to industrial maintenance, where many maintenance strategies come from, the special features of distribution network maintenance are line objects, long distances, minor condition monitoring and fault management strategies.

In preventive maintenance, the functionality of network components is maintained and faults are prevented by regular services and inspections. Faults can also be prevented by performing maintenance on the basis of condition or observations. In addition, preventive maintenance aims to extend the life of the network components. Most commonly, preventive maintenance is performed through various condition inspections that identify network components and devices that may, by failing, impair the security and reliability of the network. Condition inspections also gather information on the current status of the electricity network, which can be used as a basis for planning future investments. [34]

According to the standard SFS-EN 13306, preventive maintenance is divided into time-based (TBM) and condition-based maintenance (CBM). In TBM, the condition of the equipment is inspected at regular intervals, without taking into account the results of previous inspections and measurements. Maintenance services such as

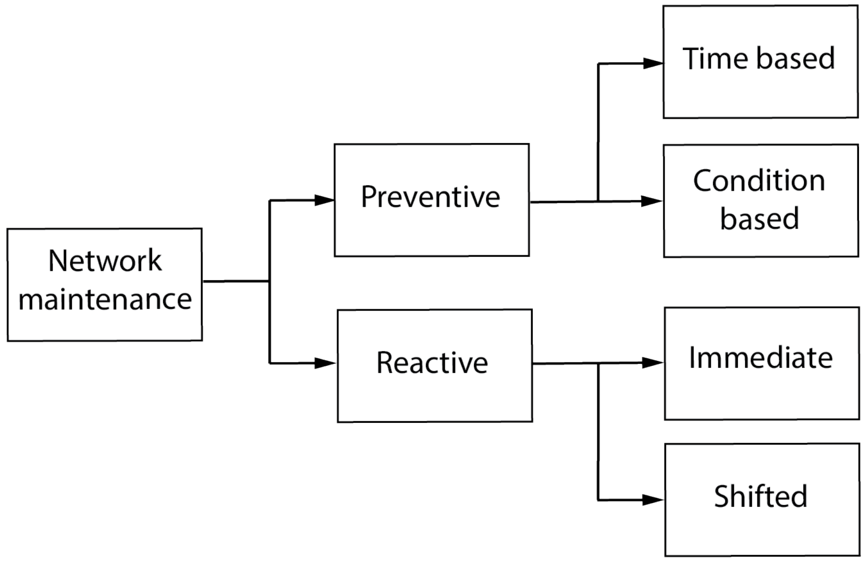

Figure 4: Classification of maintenance strategies.

adjustments, cleaning, greasing, oil changes, and other similar activities are a part of the time-based maintenance. CBM is based on the results of condition monitoring, inspections and measurements. In proactive maintenance, the results of condition monitoring and inspections are used to predict the failure of the equipment. Proactive maintenance aims to correct minor deviations and incipient faults. [34]

In the preventive maintenance of distribution networks, a periodic inspection interval has generally been used, with inspections and maintenance being carried out at regular intervals. Recommendations and standards also direct network companies towards the time-based maintenance. Nowadays, with many years of maintenance data accumulated, there has been a shift towards condition-based maintenance. The collected maintenance data can be used together with other data to form network condition index, so that maintenance actions and inspections can primarily target the weaker parts of the network and equipment. Condition-based maintenance usually results in financial savings when well-maintained network components are not inspected too often. [12]

In reactive maintenance, a component found to be defective shall be repaired to its original condition. If the component malfunctions and the fault is located at a critical part of the network, it will cause a power outage or a security problem requiring immediate repair. On the other hand, if the failure is not at a critical point of the network and does not endanger the environment or customers, the repair can be shifted to a suitable time. [34]

The maintenance strategy to be used for the network components must be separately specified. Reliability-centered maintenance (RCM) can be used to keep a balance between preventive and corrective maintenance [3]. Several studies have shown, that RCM is a cost-efficient solution for the maintenance of power systems [3] [1] [2]. RCM aims to direct maintenance resources according to the criticality of the component. The criticality class of a component describes the damage caused by component failure. Failure of a highly critical component causes widespread network interruptions and thus increases interruption costs, which further leads to an adverse reputation and customer harm. In reliability calculations, component failure models are traditionally based on exponent distribution [5]. Generally, the reliability of a component is predicted by the following equation [27, p. 57] [3]:

$$R(t) = e^{-\lambda t} \tag{11}$$

where

$R(t)$	=	The reliability of a component at time t (hours)
t	=	Time period (hours)
λ	=	Failure rate (failures/hour)

The failure rate λ is a constant for any given operation conditions. For individual components, it can be determined from large failure and damage statistics and test programs. [27, p. 57]. Some studies have been devoted to advanced failure rate models [5] [35]. These models utilize operational stresses and environmental factors of the network components.

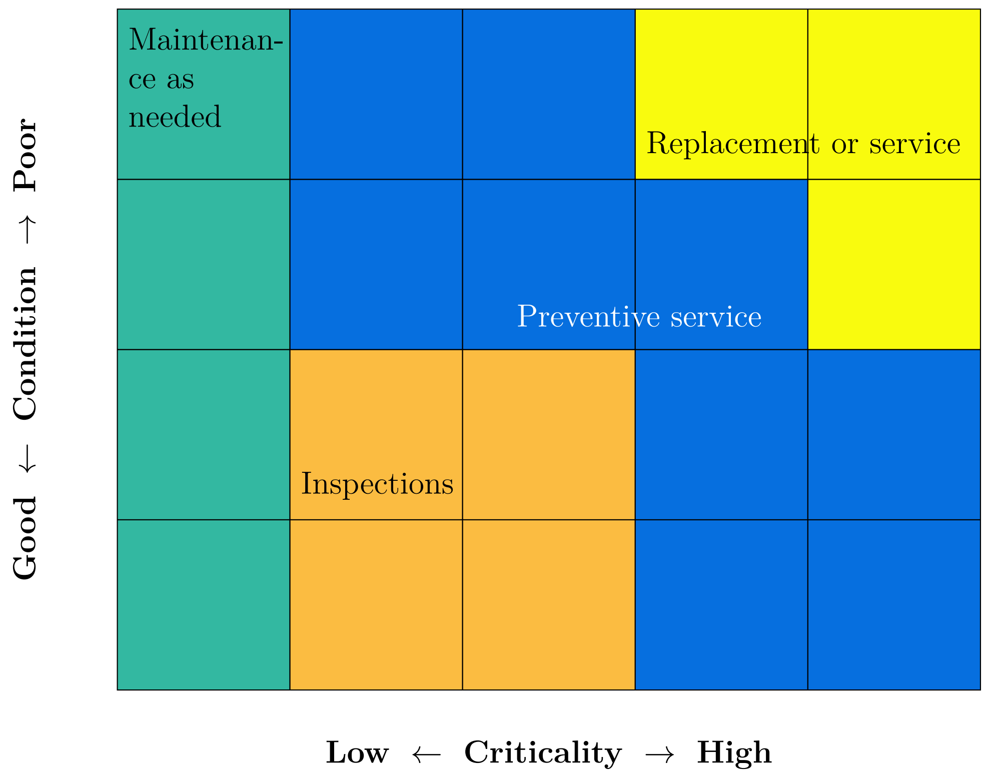

Figure 5: Principle of the reliability-centered maintenance (RCM).

Figure 5 illustrates typical maintenance procedures of RCM based on the importance and condition of the components. Naturally, more inspections and services are performed on critical parts of a network, while the maintenance of a component which failure causes only minor interruptions, is practically corrective maintenance. Components are classified according to the wishes of the network operator. The criticality classification should be simple enough, so that its application is clear.

4.2.2 Criticality classes

The planning and implementation of condition management in a network company is guided by the boundary conditions of security, business and network reliability. The maintenance strategies for different parts of the network and the maintenance programs based on the strategies are designed to achieve safety, reliability and cost-effectiveness. Different requirements can be set for the criticality classes to determine the optimal maintenance program.

When choosing the maintenance strategy for a network component, its criticality class must first be determined. After this, a specific maintenance strategy or a combination of strategies can be determined for each criticality class. The criticality classification can be defined entirely on a company-basis. Typically, a grading scale of at least three levels is used:

- Class I
  - High usability, reliability and security
  - Complete preventive maintenance program
  - Continuous condition monitoring
  - Unpredictable faults and disturbances are prevented
- Class II
  - Good usability and reliability
  - Component level failures can occur
  - Necessary maintenance program and inspections
- Class III
  - Low criticality
  - Low security or financial impact
  - Failures can be allowed
  - Necessary maintenance program and inspections [32, p. 17-18].

Network components can be divided into criticality classes according to their location, role and type [32, p. 18]. In the electricity network, the single most important component is the main transformer located at the substation. It acts as a node in the transmission grid, through which large amounts of power are supplied to a large part of the distribution network. Its failure often results in significant direct and indirect costs for the network operator. In this case, regular services and inspections are used to prevent faults or malfunctions.

Often the importance and criticality of the components will decrease when going towards smaller voltage level, smaller customer base and lower power. Faults can be allowed for individual LV components, so that the component is repaired only when the fault occurs (reactive maintenance).

Criticality classification of the network components is the basis for managing component usability, condition and life cycle. It provides a good basis for planning and developing maintenance actions and repairs. Criticality classification methods can be different and can be applied freely, depending on the objective of the network company and the type of assets. In the maintenance framework, the emphasis will be on a three level grading scale, and MV and LV components.

4.2.3 Condition classes

Network maintenance data is gathered during inspections and services. To fully utilize the gathered data in condition management, the quality of data must be ensured. Therefore, a clear and effective condition classification is needed.

During visual inspections, various observations are recorded. Most of the observations consider the condition of network assets. Recognising the faults, such as structural defects is clear, but determining the general condition of a component by visual inspection can be hard. The inspector must be able to identify small deviations and incipient faults, and must be able to classify them according to urgency and criticality. Therefore, the use of technical diagnostic measures has increased in distribution networks [4]. Visual inspection is followed by appropriate measures, such as targeted examinations and servicing or repair actions.

Like the criticality classification, the condition classification is freely determined by the company. Some companies may use numerical values, while some may use text values. One of the main focuses of the maintenance framework is the condition classification. Condition classes and their development is discussed in more detail in sections 6.2.1 and 9.2.

Clearly defined condition classes enable network operators to effectively manage their maintenance resources and to plan future actions. For example, the network information system can be used to search for incipient faults on all MV columns and to plan the necessary maintenance actions. In Trimble NIS, specific corrective actions are determined for different faults or malfunctions. Performing the corrective action will change the condition value of the component. It is also possible to evaluate the maintenance costs by linking existing price lists to the maintenance actions.

Trimble NIS also includes a condition index tool, which can be used to combine type and condition information of individual components into one arbitrary value. Type or attribute information in general include age, manufacturer, structure, model and location. Similarly, condition data gathered during inspections, such as the external condition of the distribution cabinet, pole tilt, or cleanliness of the transformer, is stored in the component property data. The condition index tool combines maintenance information and attributes into a single index that can be used in network lifecycle management, maintenance and investment monitoring and planning.

4.2.4 Maintenance programs

According to the Electrical Safety Law, a network operator must ensure that a maintenance program is prepared for the class 3 electrical equipment, which include the distribution network, transmission network and other similar electricity network. The network operator is also responsible for ensuring that the maintenance program is followed. While preparing the maintenance program, various things such as operational environment and criticality classes of the network components must be considered.

The main purpose of the maintenance program is to maintain safety and reliability. Maintenance programs are supported by component-specific inspection results from the network condition inspections. The requirements for inspections of electrical installations were complemented in 2017 by *Tukes* guideline 16/2017. The guideline emphasizes the importance of network maintenance and specifically the maintenance program. According to the guideline, the maintenance program should include the following service, maintenance, and repair actions:

- Adequate condition and fault monitoring and repair
- Basic protection and mechanical protection
- Fault protection
- Measures to prevent fire and explosion
- Overhead line safety distances, line area clearing and climbing prevention
- Condition and decay inspection of electric poles
- Locking and warning signs for electrical installations
- Earthings and potential equalizations [36, p. 3].

There are various recommendations to support the preparation of the maintenance program. For example, network recommendation TA 1:97 by Sener ry defines inspection and service intervals for different parts of the network, as well as the recommended maintenance actions.

Electric cards ST 96.01 and ST 96.02 contain instructions for the inspections, services, and preparation of a maintenance program for the electrical equipment. It is stated that the maintenance program shall include the dates of periodic inspections, services, measurements and testing by the operator, and information on when a statutory periodic inspection shall be ordered and performed [37] [38].

The electric card ST 96.03.02 specifies the inspection and service intervals for different parts of electricity distribution systems. Both Sener ry's network recommendation and the above-mentioned electric cards have been used in the development of the maintenance framework.

5 Maintenance actions of distribution networks

Maintenance actions of distribution networks consists of inspections, repair works and scheduled services. The primary purpose of these actions is to provide an accurate and consistent picture of the current state of the network and to maintain the reliability of supply. Up-to-date maintenance data is important for effective maintenance and its planning.

Inspection means the process of evaluating and sorting out the condition and conformity of a network component by making observations and conducting appropriate tests and measurements. Inspections of a distribution network are roughly divided into MV and LV inspections, and decay inspections of the utility poles. If a network operator owns HV networks, maintenance of HV network assets, such as substations, is particularly important. For example, many substations are subject to monthly inspections, but for other parts of the network the inspection interval is considerably longer, usually several years. Visual inspections are usually carried out by the network operator. The components to be visually inspected are predetermined and the results of inspections will be documented for follow-up, possible repairs and periodic inspection.

In Trimble NIS, defects found during inspections are fixed by corrective maintenance actions. In time-based maintenance, deficiencies classified as faults are addressed to prevent major interruptions. Corrective actions are also part of reactive maintenance, where the component faults are fixed as they become known to the network operator.

Scheduled services aim to maintain reliability of network components. The more critical the component is in terms of power distribution, the more frequent its service interval. Services are usually performed on distribution substation and substation switchgear and transformers. Part of the services, measurements and tests are often done by an external contractor on behalf of the network operator, as they require specialized expertise and equipment such as testing of protection relays, disconnectors and circuit breakers [38].

5.1 Maintenance intervals

Since there are no specific regulations for the maintenance actions carried out by a network operator, the operator must determine the maintenance actions to be performed, the frequency of inspections and services and the related documentation. The frequency of inspections and services is affected by manufacturer's instructions, the results of previous inspections, and the age and criticality class of a network component. Some studies have focused on determining optimal maintenance intervals of electricity networks [39] [40]. As a general rule, a distribution network is divided into maintenance areas and each part of the network is inspected once every six years.

Sener ry's network recommendation TA 1:97 gives directive inspection intervals for the following network components:

- high-voltage overhead lines, air insulated switchgear, protective relays and earthings: 3 years
- medium-voltage overhead lines, distribution substations, switchgear and earthings: 6 years
- high-voltage and medium-voltage overcurrent and earth fault relays: without self-monitoring 3 years, with self-monitoring 6 years
- Condition and overcurrent and earth fault protection of low-voltage network and distribution cabinets: 6 years
- Measurement of earthing impedance: One conductor 6 years, multiple conductors 12 years
- Decay inspections of wooden poles: Initial inspection in 25-30 years and then, depending of the level of decay, every 5-10 years [6].

According to the Electrical Safety Law, a periodic inspection must be performed to class 3 electrical equipment every five years. The periodic inspection shall be ordered by the distribution system operator and may be carried out by an authorized body or by an authorized inspector. For the requirements of the periodic inspection, see section 2.2.1.

5.2 Overhead lines and utility poles

Overhead lines have an estimated life span of 35 to 50 years, depending on the type of conductor and environmental conditions [18]. According to the recommendations, MV and LV overhead lines should be inspected every six years. MV lines can be inspected by flight inspection or from the ground by foot, ATV or snow mobile. Flight inspections are usually conducted with a helicopter that collects 3D and laser images of the lines and line areas [41, p. 48]. Currently the collected data is so accurate, that it is possible to determine safety distances based on it [41, p. 48]. This way the clearing of line areas can be targeted more accurately.

During an overhead line inspection, attention is paid to the condition and tension of the conductors, but also to the utility poles and pole structures, as well as to the environment and safety distances. When checking the safety distances, attention should be paid to the distance between the trees and the conductors, and the distances from buildings, other conductors and roads. The safety distances between earth wires and trees must also be sufficient. Inspections of MV and LV lines will in principle check the same objects, but there might be few exceptions. [42]

The most common conductor metals are copper, aluminum, aluminum alloys and steel. In MV networks, the most common conductor materials are aluminum alloy (AlMgSi) and steel reinforced aluminum (*feral*). The conductor types have been standardized (SFS 2430, SFS 3819 and SFS 4080). The steel aluminum conductors have been given names defining the cross-section of the wire. The most common conductors used in MV networks are *Sparrow*, *Raven* and *Pigeon*. Covered conductors have been developed to reduce the space required by overhead lines. In LV networks, very common and well-know conductor is the AMKA, where polyethylene covered phase conductors are twisted around the neutral wire. In MV networks, the most common covered conductors are so called PAS-conductors, where the phase conductors are covered with plastic insulation. [43]

Line areas are usually cleared periodically, but also if needed. Clearing of the line areas is one of the most important maintenance actions of overhead lines. It reduces faults caused by snow loads, for example, when young trees near the line are removed. Clearing includes clearing of undergrowth, tree branches and spreading of the line area. The average clearing interval on a MV line is 3 to 4 years. On MV lines, the distance between tree branches and conductors must be at least 2.5 meters and the width of the line area should be at least 10 meters. The exception is PAS-conductors, which have a narrower line area of 6 meters. On LV lines, the clearing interval is approximately 2 to 5 years and the distance between branches and conductors should be at least one meter and the width of the line area at least 3 meters. Clearing of the undergrowth is best done in snow-free conditions, while spreading of the line are is best done in winter when there are no leaves in the trees. [42]

Visual inspection of the utility poles is usually performed in conjunction with the overhead line inspection. The inspection targets include insulators, guy wires, earthings, support structures, clamps, top covers, warning plates and other markings. Insulators are checked for broken plates and other mechanical damages. If the insulators are very dirty, they should be cleaned to prevent electrical breakdowns. Tension and general condition of the guy wires are inspected. Also the anchoring, strain insulators, clamps and markings of the guy wires are checked. General condition of the earthing wires are checked. Condition and correctness of labels, warning signs and other markings are checked and possibly fixed during the inspection. [44]

Decay inspections are normally done to wooden poles that are over 25 years old, as the network recommendation suggests [6]. If decay is suspected during the visual inspection, the bottom part of the pole should be inspected by tapping it with a hammer, so that rotten poles can be detected. If the condition of a single pole is bad, it is replaced or a root support is installed, but if the general condition of the poles in a line part is poor, it is common practice to replace all of the poles [12, p. 229].

5.3 Underground cables and distribution cabinets

In underground cable network, the condition inspections focus mainly on the above-ground parts of the network, such as distribution cabinets, cable terminals, cable shieldings, earthings and cable markings. The condition of MV cables can be monitored by insulation resistance and partial discharge measurements [12, p. 230]. These measurements are not usually performed for LV cables. Thermal imaging of distribution cabinets is used to search for loose connections and other faults.

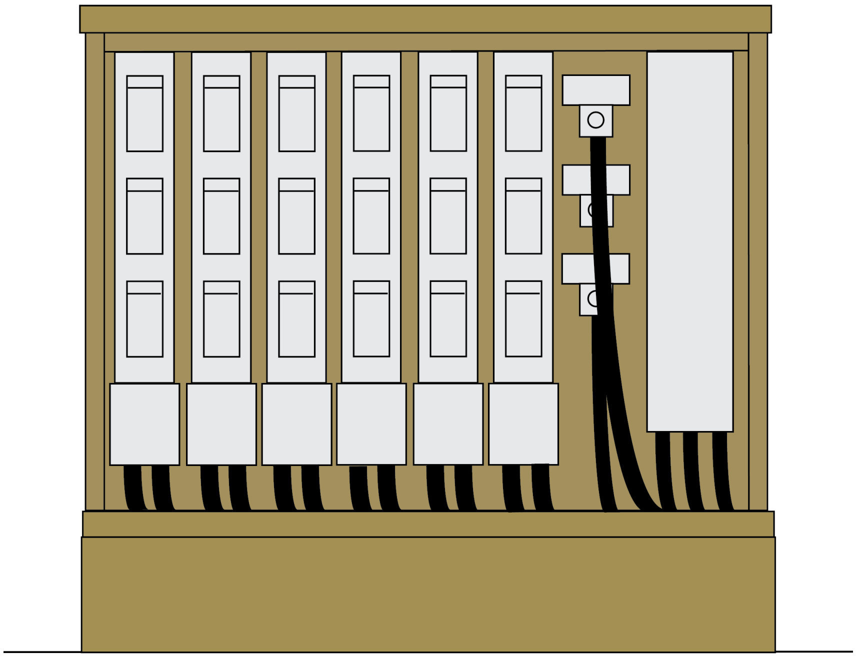

Figure 6: Distribution cabinet and its switchgear.

During a distribution cabinet inspection, the environment, foundation, labels and markings, locking and the general condition of the cabinet are checked. Small service works, such as greasing the lock and door hinges are usually done during the inspection. The inside condition of the cabined is checked for dirt and possible undergrowth. Validity of the main diagram is checked and the general condition of the switchgear, including circuit breaker, fuses, markings, cable terminals, contact shieldings and earthings are checked. [45]

Basic service tasks include testing and greasing the main switch and fuse-switches, tightening the cable connections and cleaning the cabinet. These tasks usually require the distribution cabinet to be de-energized.

5.4 Distribution substations

Distribution network usually includes pole transformers and park and property substations, where medium-voltage is converted to low-voltage. The voltage of the MV network is usually 10 kV or 20 kV, and the voltage of the LV network is usually 400 volts, but nowadays the distribution voltage of 1000 volts has become increasingly common.

A distribution substation consists of a medium-voltage connection, one or more distribution transformers, low-voltage feeders, protective devices and any auxiliary voltage equipment [12, p. 157]. In sparsely populated areas, pole transformers are commonly used, while in urban areas, park and property transformers are used. According to the unit prices of an electricity distribution network for 2016 - 2023 published by the Energy Authority, the service life of a distribution substation is more than 30 years [18]. The inspections of distribution substations can be divided into pole transformer inspections and park and property substation inspections, since the inspected objects of pole transformers and park and property substations differ somewhat.

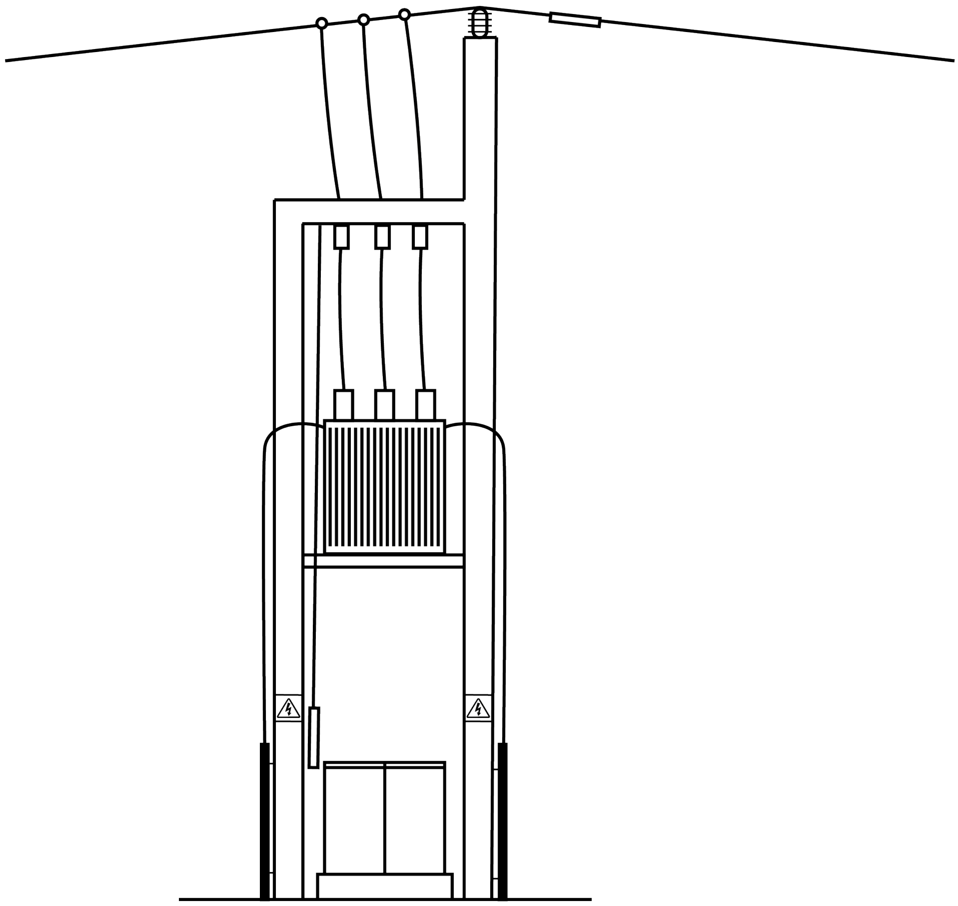

Figure 7: Pole transformer.

Visual inspections of distribution substations may be carried out on their own or in conjunction with the overhead line inspections. The inspection of a distribution substation requires special expertise and the number of inspected objects is large, so a separate inspection is often done to avoid slowing down the overhead line inspection. Pole transformer inspections are usually performed in conjunction with the overhead line inspection, especially if they include a pole decay inspection. Visual inspections can be done while the distribution substation is energized, but many repair and maintenance works, such as periodic service, requires the substation to be de-energized. Power-free maintenance works cause the least interruptions to customers if they are done during the summer months, while the power loads are low.

The visual inspection should begin by checking the environment, labels and markings, warning signs, locking, foundation and the general condition of the distribution substation building. General cleanliness and dustiness of the substation spaces are checked. Also the power sockets, lightning and ventilation are checked. A distribution substation must have all the necessary documentation and diagrams showing transformer fuse sizes, cables, outputs and operating instructions for the switchgear and other equipment. In the case of pole transformers, specific items to be inspected are warning signs, animal enclosures and disconnector markings that may be separate from the pole transformer. Safety distances, switchgear exchange routes and contact shieldings are checked. A distribution substation should include the safety equipment, such as temporary earthings and working protection. Replacement fuses and their replacement equipment should also be available at the substation. In addition, a substation must have fire extinguishing equipment and first aid instructions. [45]

After the general inspection, the condition of the MV and LV switchgear, including disconnectors, switches, fuses, cable terminals, lead-ins, insulators and earthings are checked. Attention should paid be to the cleanliness of cable terminals and insulators. Cable terminals should also be checked for possible oil leakages. Connections of the cables and busbars are checked. If a distribution substation includes SF_6 (sulfur hexafluoride insulated) switchgear, the pressure of the SF_6 gas should be checked. Protective devices, such as relays, indicators, current transformers and surge arresters are checked for any deviations. [45]

During some inspections, test and measurements are performed. These include testing the switches, disconnectors, fuses and relays, and measuring currents, voltages and earthing series impedance [45]. Switchgear testing usually requires the distribution substation to be de-energized, so they are not performed during the visual inspections.

Distribution transformer is the single most important component of a distribution substation, so special attention is paid to its maintenance. Visual inspection of the transformer consists of checking cleanliness of the transformer space, surface treatment of the transformer, insulators, possible oil leakages, oil level of the transformer tank, temperature of the transformer and position of the tap changer [45].

Service works of a distribution substation consist of cleaning the substation, changing air filters and doing repair works, such as painting the substation building. For pole transformers, periodic disconnector services are performed. Switchgear services are performed according to the manufacturer's instructions. These usually include testing the device's functionality, and for example greasing the mechanical parts of a disconnector. Adding oil to the cable terminals, tightening cable and busbar connections and cleaning the switchgear are also done during the periodic service. The distribution transformer is cleaned and possibly painted. Oil is added to the oil tank, and oil samples are taken. Functionality of the tap changer is also checked. If the transformer has reached the end of its life cycle, it is replaced.

5.5 Substations

A substation is the most important part of a distribution network. high-voltage, usually 110 kV, is converted to 20 kV in a substation supplying the MV network. The size and location of a substation largely defines the length and dimensioning of the MV lines. A substation acts as a versatile distribution center of the network, where most of the protective relays and other automation devices of the network are located. Several feeders can be connected to the HV switching station of a substation instead of just one radial feeder. This provides alternative feeding directions for the substation and, depending on the structure of the busbar, allows for the looped usage of the HV network. Improving or maintaining the quality of electricity supply is usually the key reason for building a new substation. [12]

The design of a substation is fundamentally influenced by whether it is solely responsible for distributing electricity, whether it is connected to a power plant or whether it is merely a network switching or transforming station. Substation design is a complex process that requires consideration of transmitted power, voltages, amount of transformers, location, feeder arrangements, reliability, dimensioning of the switchgear etc. The placement and simplicity of a substation depends greatly on the power transmitted through the substation, the type of the network and the amount of feeders the substation is associated with. [43, p. 96-97]

A switching station connects wires of the same voltage level and substation connects wires of different voltage levels. A substation usually consist of HV and MV switching stations, one or more main transformers and auxiliary voltage system. Compensation devices, such as reactors, are also usually located at substations. Switching devices consist of circuit breakers and disconnectors. Circuit breakers, unlike disconnectors, are capable of switching off and closing the load and fault currents. Disconnectors are used to de-energize the switchgear components for safe service or maintenance. Traditional air-insulated switching stations are used in sparsely populated areas. SF_6 gas-insulated switching stations are largely used in urban areas, since they require less space. The service life of a substation is 30-45 years. [12]

Usually the network operator visits substations monthly or every few months for visual inspection. During the inspection, attention is paid to the substation environment, transformers, equipment condition, lighting, oil levels and oil leaks as well as measuring devices and signal lights. Due to the high cost and criticality, main transformers usually have a special maintenance program. Main transformers have a lot of auxiliary components, including monitoring and protective devices. The loading of the transformers is constantly monitored, and oil samples are taken frequently. All the maintenance and service tasks of the transformer require special training. [42]

A more extensive visual inspection is carried out annually to check the condition of switchgear and auxiliary systems, and to check for the presence of occupational safety equipment and instructions. The annual inspection shall also include an examination of the existence and correctness of the documentation and diagrams. The actual periodic service and operational tests are usually performed by specially trained personnel. The aim is to schedule the services during the summer months, when customers are least affected. Due to the large number of substation components and the specialized expertise required in their maintenance, detailed inspection or service programs will not be reviewed in this context.

6 Maintenance in Trimble NIS

Information systems are widely used to support network operation, and are today practically mandatory. Trimble NIS is a map-based network information system that offers versatile tools for modeling and controlling the most vital processes of network operation. Trimble NIS also includes the maintenance application, that is based on the maintenance information collected and linked to the network objects. In this section, the maintenance application and its features will be reviewed from the perspective of the maintenance process.

6.1 System overview

Network planning and operations are carried out with the help of different IT solutions. Supervisory Control And Data Acquisition (SCADA) is used in remote control and measurements, event data gathering and reporting. The network model of SCADA does not contain detailed device-specific information and it does not have the tools for network analysis e.g.

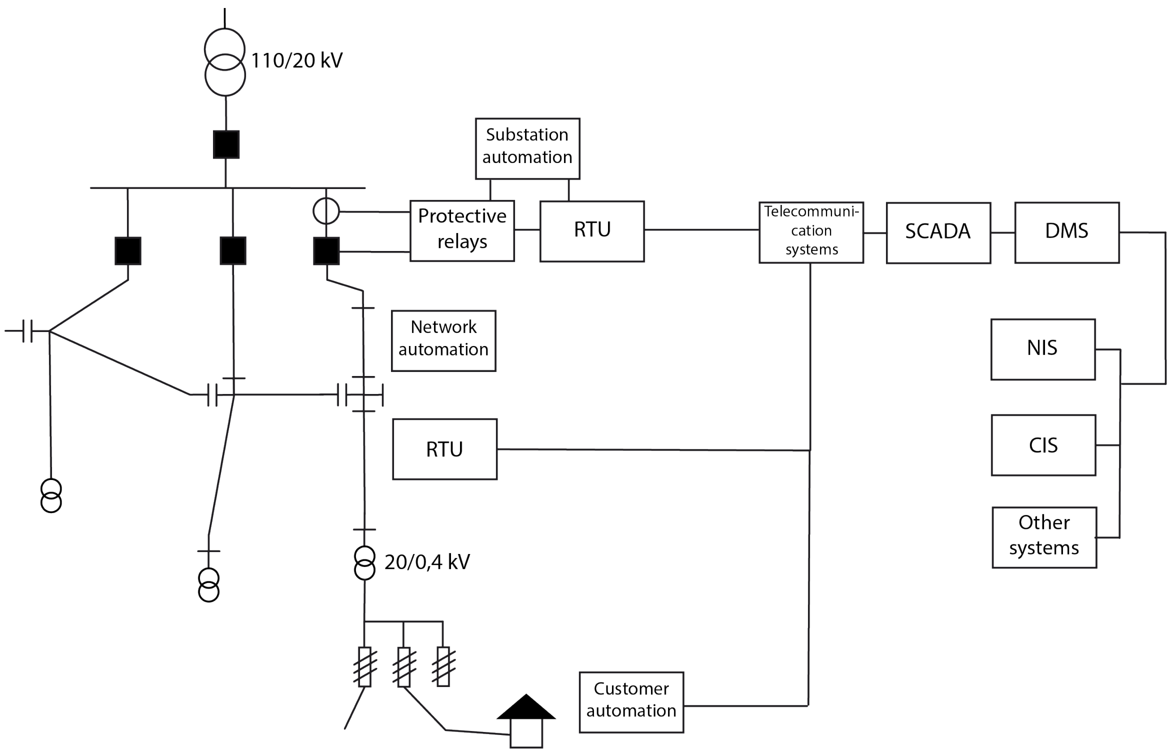

Figure 8: System architecture.

Distribution management systems, such as Trimble DMS, are used for network analysis and control together with SCADA. DMS provides more detailed information about the network than SCADA. DMS is used for network analysis, switching operations and planning, as well as outage management and fault locating.

Network information systems, such as Trimble NIS, are used for network modeling, planning, power system analysis and asset management. The system is based on the network model created from objects stored in a database. Normally, the detailed network is digitized in NIS and the same model is used in DMS. Together SCADA, DMS and NIS form a complete information system, that is used in many sectors of network operation.

6.2 Maintenance application

There are many different applications on the market for asset management and maintenance needs. Some of them provide tools for planning and managing maintenance at a very detailed level, and are used by many TSO's and energy companies. The maintenance application of Trimble NIS combines maintenance, property and location data of network objects into the same view, and is particularly well suited for the maintenance of objects in a map-based network model.

In the maintenance application, maintenance data is saved in the properties of a network object. Maintenance data includes scheduled maintenance works, sudden faults and repair works. The application can be used to plan detailed inspection, repair and service works for different parts of the network. Gathering maintenance data enables network operators to analyze the condition of the network, plan maintenance actions in advance, and effectively manage maintenance costs and resources.

Maintenance data storage and retrieval is based on predefined actions and observations and their values. Saved maintenance data can be visualized or printed as reports. The old maintenance data of network objects is saved as history data, and it is possible to review the maintenance history of the network objects. In addition, maintenance data can be used as a part of the network condition index.

The maintenance application is suitable for different maintenance strategies. Planning and scheduling periodic inspections and services is efficient, and allows a shift towards preventive maintenance. However, reactive maintenance is also supported, and variety of tools have been developed to repair faults and manage the related maintenance works. Web based field application, Utility To Go, enables network operators to assign maintenance works to field workers. The collected maintenance data is saved to Trimble NIS in real time, so separate inspection records are not needed.

6.2.1 Maintenance data

The main types of the maintenance data are observations and actions. Observations describe the condition of the object, for example condition of the pole. Actions describe maintenance tasks, such as inspection of a pole or a distribution cabinet. The hierarchy of the maintenance data is also supported. It allows the user to form hierarchical entities of observations and actions.

The structure of maintenance data supports different types of data. An observation may include data as numeric values, yes/no type data, text values and classified data. Classified values or ranges of observations can be defined as faults, potential faults, or normal values. The importance of an observation can also be defined, which provides additional information about the maintenance need of the object. Importance can be used to prioritize maintenance actions, that can be used to create and schedule maintenance works.

Maintenance actions can include observations gathered during the inspection or service. Suitable values of the observations can be classified as faults. Fault is the condition of an object that requires repair. It is possible to define repair actions for every fault value. Designated repair actions address the fault values and converts them to repaired values. The status of a maintenance action may be *completed* or *planned*. Planned actions will take place in the future. A due date and importance may also be set for the planned actions.

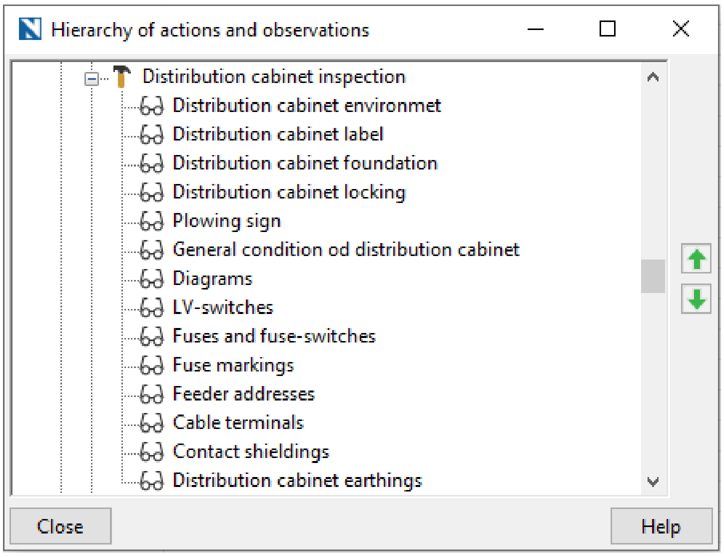

Figure 9: Inspection of a distribution cabinet.

Observations and actions may also include explanations that complement the observations or actions. Explanations cannot be used on their own, and they have no functionalities. An explanation can, for example, include a detailed service manual. In addition, it is possible to collect attribute information such as the installation year or nominal voltage during inspections and services. Attribute information is stored in the properties of a network object.

6.2.2 Maintenance themes

A maintenance theme defines what actions can be performed, to what types of objects and how often. Generally, a theme consists of the following:

- Actions: What inspections or services are performed.

- Object classes: To what kind of network objects the actions are performed to.
- Repetition: How often the actions are performed (optional).

An example theme for a distribution substation inspection is presented in figure 10. It includes all the actions performed during the inspection. The actions contain observations on the condition of the substation, transformer and other features affecting its operation.

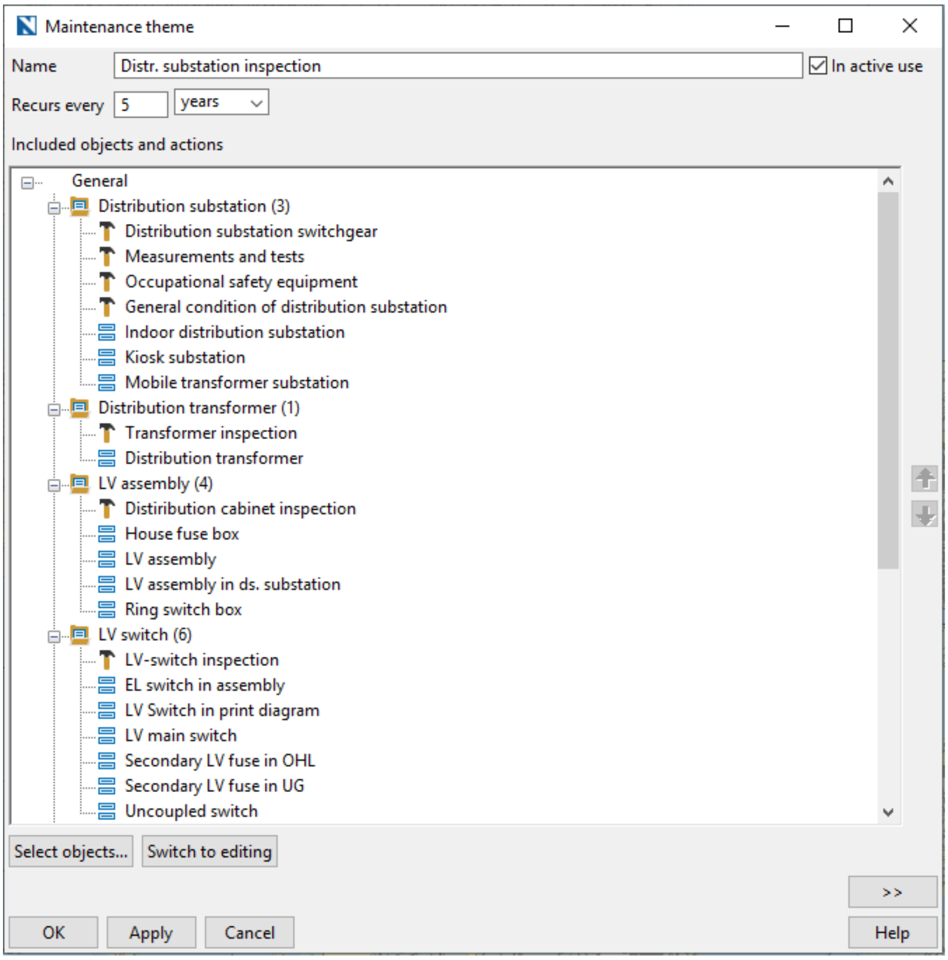

Figure 10: Maintenance theme window.

Yearly planning of maintenance is based on the maintenance themes. In yearly planning, maintenance actions are planned according to a maintenance theme on a general level for an upcoming year. The available budget can be taken into account in the planning. The actions get their costs according to the price list used. The planning is always done to the active planning year. The yearly planning can also be done as a part of the long-term planning process when using the Network Investment Management (NIM) application. The program automatically proposes actions based on the theme for the entire network area. Actions can be move to a suitable year as preferred. The program creates the planned maintenance actions in the active plan according to the proposed actions for the year in question.

6.2.3 Maintenance works

Maintenance works are used to group actions into smaller units. They include both the actions and the network objects to which the actions have been added. The use of maintenance works is optional; maintenance actions can also be performed separately. However, a work must be used if it is desired to assign maintenance actions to a specific person or a group. A maintenance work usually consists of actions that require similar hardware, material or know-how. The creation of a maintenance work is possible from selected objects, planned actions, or faults. It is also possible to create maintenance works from the scratch.

From the process point of view, maintenance works can be created and utilized in many ways. For example, creating maintenance work from selected objects can be useful in situations, where urgent maintenance actions are needed for a few network objects. Another example could be selecting all the distribution cabinets of a certain maintenance area, creating planned inspections, and including them in a work.

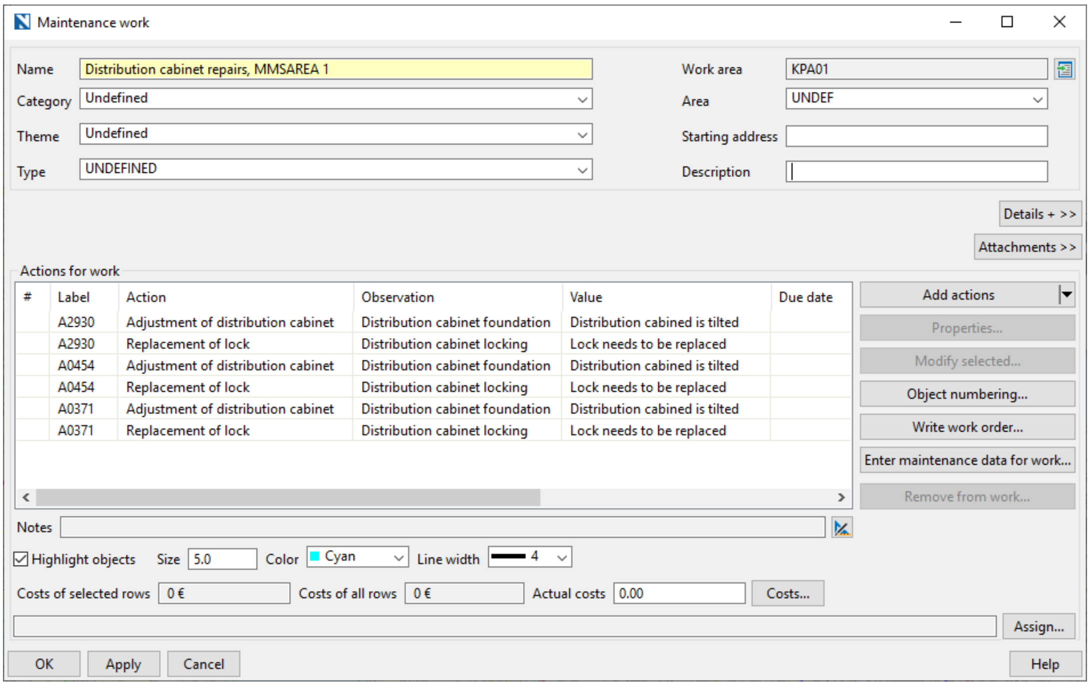

Figure 11: Maintenance work generated from fault classifications.

Creating works from faults is a very convenient feature. The functionality of the maintenance application makes it possible to search for observations classified as faults or potential faults. The search can be filtered, for example, by type, theme, and location. The application generates a list of faults according to the search criteria and highlights them on the map, so they can be easily viewed for further actions. For example, a network company may have a practice, that at the end of the year all non-repaired potential faults will be searched for and jointly repaired. This way, the objects that have a potential fault rating will be repaired within one year of receiving the classification.

Work orders provide maintenance personnel with information on the maintenance works to be done. The work order contains the maintenance work, which in turn contains information on the network objects to be checked and what needs to be inspected or repaired. These can be actions and observations, explanations, object properties or free attributes.

The work order is either sent to a mobile device or printed out on paper or file as a form to be filled out in the field. It is also possible for the maintenance personnel to print a map showing the sites to be inspected, and also the best route to travel between them. When a maintenance work is assigned to a workgroup, the status of the work changes from *planned* to *in progress*, and when the work is marked done, the status of the work changes to *completed*.

Utility To Go can be used to replace the traditional work orders and inspection forms. The maintenance works are assigned to UTG users in Trimble NIS.

6.2.4 Utility to Go

Utility To Go (UTG) is a mobile application developed by Trimble, that enables viewing the network and its operational status in the field. Utility To Go is implemented using web technology, so it can be used on any mobile device with a modern browser.

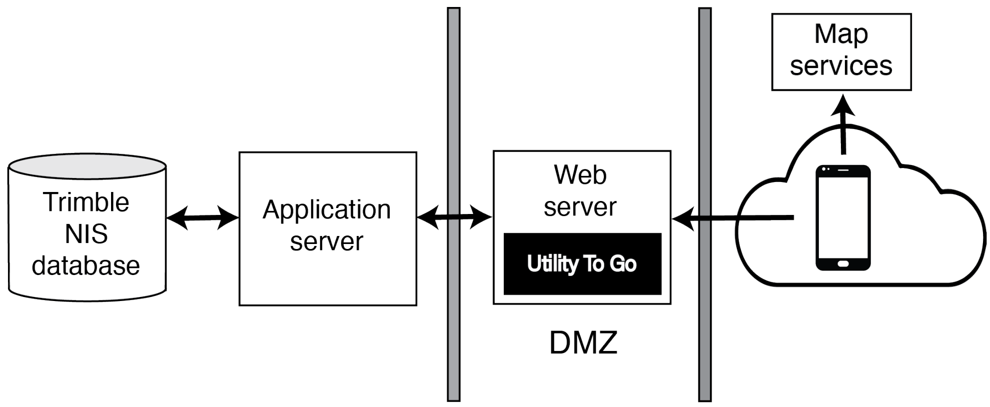

Figure 12: Utility To Go in system architecture.

A network operator will create usernames for the inspectors in the UTG application. Contractors' access to the system is limited as necessary. For example, the contractor may only be allowed access to network objects contained in the work assigned to him/her. In addition to assigned works, inspectors may perform general maintenance actions in the area. These may include, for example, repair actions that are not part of any specific maintenance work and are not urgent.

When an inspector chooses to perform an action, such as a distribution cabinet inspection, a checklist for the observations is opened. The inspector marks the condition of the objects according to the observations. Once the maintenance work has been completed, updating the browser will remove the maintenance work from the work list and update the maintenance data to Trimble NIS. UTG requires a network connection, but it can also be used offline. If the maintenance work is completed offline, it will be updated on the system when the device is back online.

6.2.5 Maintenance cost management

Maintenance costs can be managed by predefined costs. A cost caused by an action can be defined directly for the action, or by connecting the action to a price list. The cost is defined in the properties of an action as a price per object or meter. Price lists are useful, for example, when there are itemized costs for the maintenance actions, or when there is a separate, external price list to be used. It is also possible to define contractor-specific sub price lists. This enables calculating and comparing the maintenance costs of different contractors.

The program automatically calculates the estimated costs for faults. The estimated cost is calculated on the basis of the price for the default repair action. If an object has several faults, the program sums up the costs for repairing each fault separately, even if there was a single action that would repair all the faults at once.

Assigned costs can be used, for example, for next year's budgeting, maintenance work planning and yearly planning. Once the costs of the actions have been determined, the program calculates the cost of the scheduled maintenance work. This way the planner can decide whether to carry out the planned maintenance work, or whether another solution would be more profitable, such as replacing an overhead line with cables.

7 Requirements

The practical part of this thesis consists of the development and productization of the maintenance framework. The framework was developed in a pilot project involving two network companies representing the target segment of the maintenance framework. In this section, a general overview of the development project, pilot customers and the requirements analysis will be given.

7.1 Project plan

Overview of the pilot project is given below. The project plan can be divided into four parts:

- Preparations
  - Background and objectives
  - Internal project meetings
  - Schedule
  - Guidance and monitoring
- Organization of the project
  - Acquiring pilot customers, launch meetings
  - The roles and responsibilities of the stakeholders
  - Communication, other practical aspects
  - Needs assessment
- Developing the maintenance framework
  - Acquisition of information, requirements specifications
  - Maintenance programs for MV and LV networks
  - Delivery of the initial version
  - Testing, user feedback
  - User acceptance testing
- Productization of the maintenance framework
  - Installation package, SQL-scripts
  - User manual and user training
  - Product description
  - Marketing, additional sales

7.2 Pilot customers

Target segment of the maintenance framework includes small distribution network companies that don't have the maintenance application license, or customers who haven't been able to fully deploy the maintenance application. Pilot customers were decided on in an internal meeting. The idea was to sort out all the potential customers, and to propose them to participate in the maintenance framework development and testing.

A sales letter outlining the project and the role of the pilot customers was sent to the selected customers. Two companies, Kemin Energia ja Vesi Oy and Raahen Energia Oy, accepted to participate in the project. Launch meetings were held with the pilot customers to sort out their needs and to exchange ideas and thoughts about the project. Also the practical aspects, such as the schedule and communication, were decided on. Communication during the project was done via email, telephone conversations and remote meetings.

Role of the pilot customers was to participate in the development and testing of the maintenance framework. Information and feedback was collected at different stages of the project. It was especially important to receive professional insight considering the validity and functionality of the maintenance framework.

7.2.1 Kemin Energia ja Vesi Oy

Kemin Energia ja Vesi Oy is a company owned by the city of Kemi, which provides its customers with electricity, district heating and water supply services. Kemin Energia Oy started operations at the beginning of 2000. In 2001, Kemin Energia Oy transferred their electricity sales customer relationship to a regional electricity sales company, Oulun Sähkönmyynti Oy. Kemin Energia Oy purchased the share capital of Kemin Vesi Oy from the City of Kemi, and at the beginning of 2016 the Kemin Energia Group started operations. The water company merged with its parent company Kemin Energia ja Vesi Oy on January 1, 2020 as a subsidiary merger. [46]

According to the key figures for 2018, Kemi Energia Group's total revenue is €18 million and it employs 66 energy and water professionals. The Group supplies a total of 160 million kWh to 15,000 customers. About 80% of the network length of Kemin Energia is underground cable. [47]

7.2.2 Raahen Energia Oy

Raahen Energia Oy is an energy company established in 2000. The City of Raahe owns 100% of the company. The company supplies electricity sold by Oulun Sähkönmyynti Oy, which it joined at the end of 2004. The company also provides district heating in the Raahe area. The latest district heating business transaction is the acquisition of the Pattijoki district heating plant in Raahe in early 2005. Of the heat sold by

Raahen Energia Oy, Raahen Voima Oy has delivered approximately 98% in recent years. [48]

According to the key figures for 2018, total revenue of Raahen Energia Oy is €13 million and it employs 25 energy professionals. The company supplies a total of 107 million kWh to 8500 customers. Raahen Energia Oy is a typical city network operator. The MV and LV networks have a combined underground cabling ratio of more than 94%. The remaining overhead lines are to be replaced by cables in the coming years. [47]

7.3 Requirements analysis

Since the maintenance framework must be suitable for a number of small network companies, clear specifications are needed. The specifications are largely based on legislation and recommendations, and the personal needs and practices of the customers. Specifications derived from the legislation and recommendations ensure that the maintenance framework fulfills the legal requirements of a network operator. Customer needs define the usability and compliance requirements. User stories, needs assessment and prototyping are used to derive relevant information in order to form the final product specifications.

Needs assessment and needs analysis are basic tools to determine customer requirements. Needs assessment identifies needs of the customer, whereas needs analysis is used to derive information from the results of the needs assessment [49]. In this project, the needs assessment was conducted through customer interviews and a separate survey. In the launch meetings, the current situation of the customers was sorted out. The customers were encouraged to share their needs, ideas and expectations about the project.

Kemin Energia needed revision in their maintenance program. They already had the maintenance application license, but hadn't been able to fully utilize its functionalities. So far, they had used separate maintenance inspection forms, and the maintenance data was entered into NIS manually. The existing maintenance actions and observations needed clarification.

Raahen Energia didn't have the maintenance application license beforehand, but were very interested in the maintenance framework. Main expectations considered easy deployment of the maintenance application and revision of the existing maintenance practices. There was also a demand for user training.

Other thoughts that came up in the launch meetings were maintenance cost management, inspection and service intervals, utilization of the existing maintenance data, substation inspections and the maintenance of components other than network objects, such as reserve power machines. Based on the initial meetings, a needs assessment form was compiled and sent to the pilot customers. The idea was to get a general overview of the existing maintenance practices of the customer, and to determine which parts needed revision. The form addressed the following topics:

- Network structure, component numbers
- Service and inspection intervals of network components
- Maintenance programs and development plans
- Revision of the existing maintenance actions/observations
- Maintenance budgeting and resources

As a summary of the needs assessment, the main needs considered the revision of the maintenance programs, clear definition of maintenance data, easy deployment, and utilization of the application features in the maintenance process.

Evaluating the customer needs can be done in multiple ways [50]. In this project, prototyping and guidelines were used to form requirement specifications from the collected information. Application features and constraints were evaluated, so that a prototype version of the maintenance framework could be formed and tested.

7.4 Requirement specifications

Summary of the requirement specifications is presented in table 4. These specifications act as a general guideline in the development of the maintenance framework and the finalized product specifications.

Requirement	**Description**
Usability	Easy deployment and usage. Predefined features support maintenance process.
Compliance	Suitable for a large number of customers from the target segment. Supports different maintenance strategies and inspection/service intervals.
Legal requirements	Fulfills the legal requirements considering network maintenance.
Documentation	Includes relevant documentation, such as user manuals.
Scalability	Must work for different sized networks.
Modifiability	Must support modifications made by the customer.
Performance	Predefined features will not cause degradation of performance in normal use.

Table 4: Requirement specifications of the maintenance framework.

8 Product specifications

Currently, deployment of the maintenance application needs a lot of configurations. All the existing maintenance actions, such as inspections and services, must be manually defined in the system. The existing maintenance actions might also need some modifications in order to be implemented in the maintenance application. This has been done by the software consultants or by the customer. However, as the definitions are customer specific and are based on the existing maintenance practices of the customer, the quality of the maintenance data is not ensured. Moreover, it is laborious to make the definitions manually. Some of the customers haven't been able to fully utilize the maintenance application features, and the maintenance process might be unorganized.

The maintenance framework is a service package that includes the necessary features and configuration to enable easy deployment of the maintenance application. The package simplifies maintenance planning and management of inspections and operations, saving time and resources. The package is intended for small network companies.

8.1 Business case

Software consultants provide customers with professional services such as system configurations and deployments. The services are usually delivered as customer projects. Productization refers to the process of developing a service into a standard, fully-tested, packaged, and marketed product. The maintenance framework is a part of the productization strategy, where the professional services are bundled and sold as a product. With clearly defined contents, customers can easily evaluate the benefits of the service packages. The customers are provided with high-quality services, while the manual workload is reduced.

Main benefits of productization are increased sales and customer satisfaction. Productization has scale benefits and can help in narrowing down the usage gap of some applications. There exists a lot of sales potential among the existing customers. Service packages lower the buying threshold of the customers and will generate additional revenue along with the related licence sales. Customer satisfaction is improved is by transparency of the contents, quick delivery and orientation.

Development costs of a certain package depends on the application, but the expected return on investment is expected to be positive very quickly, provided that a certain percent of the target segment acquires the product. There are certain risks involved in the productization. The package contents may not meet customer requirements to the needed extent or won't generate enough additional sales. Therefore, the customer needs should be well examined. A productization project should be launched when a certain need is widely recognized. This requires a close cooperation of different stakeholders, such as customers and sales personnel.

The maintenance framework acts as a pilot project. The project will provide information on the development and business aspects of service productization.

8.2 User personas

Smaller network companies may not have well-established maintenance practices from the system perspective: The definition of maintenance data is incomplete or the maintenance process requires a general update. The organizational structure of smaller network companies is more easily adapted to reforms such as the maintenance framework, i.e. maintenance process is easily upgradeable, giving a looser guidelines for the framework development.

The package is for maintenance users who want to deploy the maintenance application as easily as possible. If the user did not complete all the needed configurations at the time of obtaining the maintenance application, the application may not be used properly and the maintenance process is not managed through the information system. Users like this do not actively seek to learn how to use the application, but continue to manage the maintenance process according to old practices.

In principle, the goal of the users is to manage the maintenance process as efficiently as possible. However, if the users don't have clear instructions on how to deploy and use the maintenance application, they may be lacking the needed know-how. The maintenance framework addresses these issues and provides customers with a turnkey solution.

8.3 Service package

The finalized product is a ready-to-deliver solution. The maintenance framework supports efficient use of the maintenance application. The maintenance application features are reviewed in section 6. The maintenance framework requires the maintenance application license. In addition, it is recommended to get the related Utility To Go licenses. The service package includes the following:

- Predefined observations and actions for MV and LV networks
- Maintenance themes
- Linking existing price list to the maintenance actions
- Installation package
- Other needed system configurations
- User manual
- Online trainings

9 Maintenance framework

In this section, the development of the maintenance framework will be reviewed. Predefined maintenance actions and observations, and parametrization of the condition classes are the core parts of the framework. Clearly defined condition classes and the related repair actions allow network operators to utilize the collected maintenance data as efficiently as possible. Installation package enables easy delivery, and user manual and training ensures efficient deployment.

Although the maintenance application directs network operators towards preventive maintenance, determining the optimal maintenance strategy for each network component is up to the network operator. Different methods to support the decisions include CIC-calculations, component criticality classification and life cycle management. The maintenance framework works as a recommendation and can also be used as a guideline while compiling the maintenance program sent to the Energy Authority.

9.1 Predefined features

The main focus of the maintenance framework was to create maintenance processes for MV and LV networks. Maintenance themes, actions and observation were compiled according to network recommendations and user needs. Other features of the maintenance package include linking existing price lists to the predefined maintenance actions and retaining the old maintenance data.

This section outlines the predefined features and their usage in the maintenance process. Detailed content of the predefined features won't be reviewed in this context.

9.1.1 Actions and observations

The maintenance framework includes a number of actions and observations related to overhead line inspections and transformer circuit inspections and services. The hierarchy of the actions and observations has also been defined. The number of actions and observations was moderated, while assuring that all network components would be adequately inspected and maintained.

Substation inspections include a large number of objects to be inspected. Inspection content is generally station-specific, so the maintenance framework does not contain any predefined features considering substation inspections or services. If the customer owns substations, it is a good idea to create substation-specific inspections based on the existing inspection forms.

Actions are always addressed to network objects. An object, such as distribution substation, can have multiple actions. In the maintenance framework, a single action usually addresses a single component, such as distribution transformer, or a set of components, such as distribution substation switchgear. The division of the maintenance actions depends on the network model and criticality of the network components. For example, switching devices, such as MV disconnectors have their own detailed maintenance actions, whereas the inspection of LV fuses is included in the distribution cabinet inspection. Some network objects, such as distribution substations and distribution cabinets, include many objects that are not digitized in Trimble NIS. These usually include markings and warning signs, insulators, earthings, occupational safety equipment etc., and are included in other maintenance actions. Figure 13 illustrates the division of the maintenance actions according to their criticality classes.

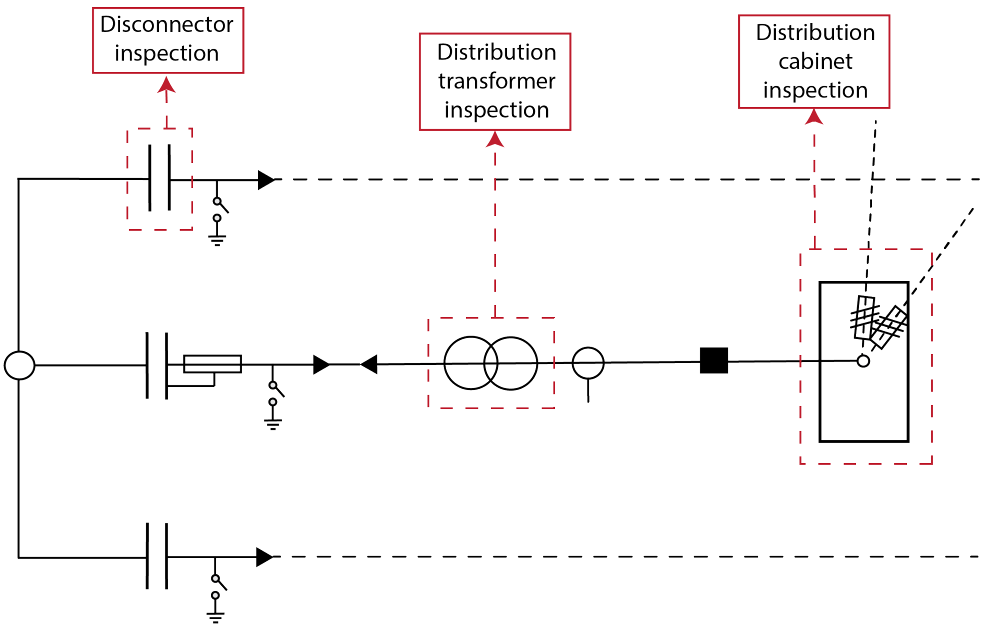

Figure 13: Maintenance actions of a distribution substation.

Definition of observations is intended to ensure the collection of high quality maintenance data. The maintenance actions generally include 5-20 observations. The predefined observations consider the condition or functionality of a single component or a part. An example action, *Disconnector inspection*, is presented in figure 14. During this maintenance action, all the important parts of the disconnector are inspected.

Predefined actions and observations support the maintenance process, and can be used with different maintenance strategies. With clearly defined inspections, services and repair actions, it is easy to manage preventive maintenance process. The actions can be used alone to create single planned actions and maintenance works, or together with maintenance themes to manage a larger amount of network objects.

Repair actions allow for reactive maintenance. When a fault occurs, a repair action can be determined for the network object. It is also possible for the field users to add and perform actions in Utility To Go. This way the whole maintenance process is controlled through the information system and the collected maintenance data can be used more effectively.

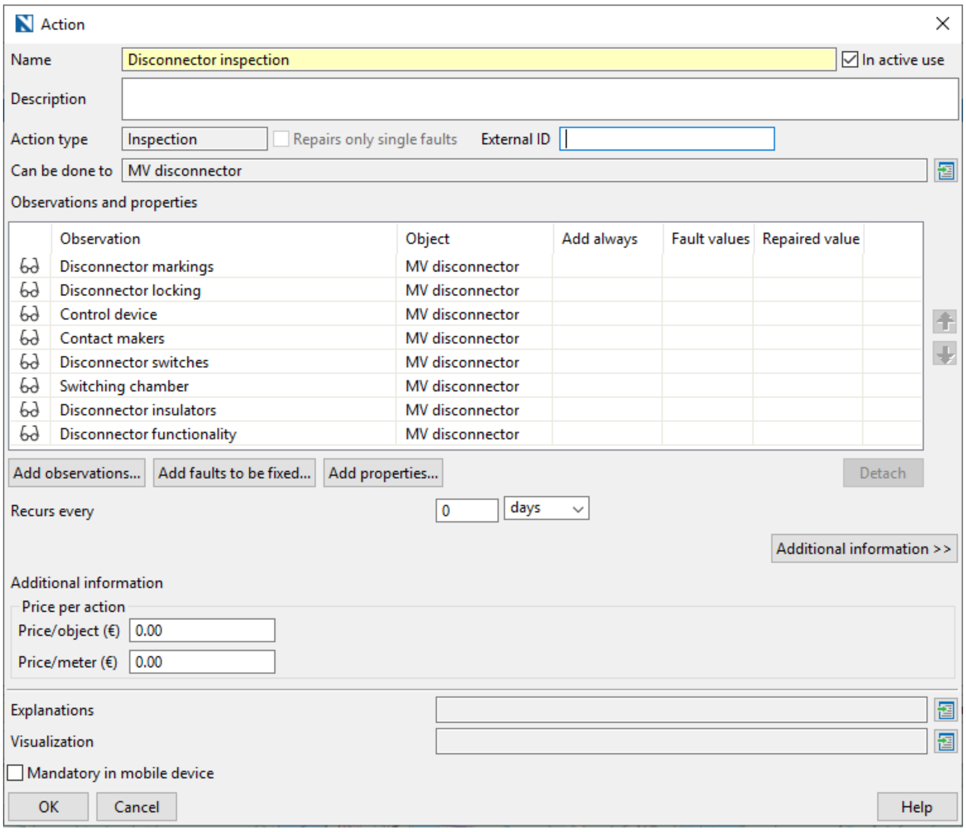

Figure 14: Disconnector inspection in Trimble NIS.

9.1.2 Predefined maintenance themes

The maintenance framework includes predefined maintenance themes. The idea was to create a few basic themes that the user can use as such or modify. The user can also create more themes if needed, using the predefined themes as a template. There is practically no limit to the number of themes, and if there is a need to create a large number of inspections at once, it is wise to create a separate theme.

Since there is a lot of variation in inspection and service intervals between network operators, no recurrence was defined. The predefined themes were designed to be as general as possible, related to routine inspections and services:

- Distribution substation inspection
- Pole transformer inspection
- Distribution cabinet inspection
- Overhead line inspection

- Distribution substation service

The structure maintenance themes is discussed in section 6.2.2. With themes, it is easy to create maintenance works for different maintenance areas, for example. When a theme is used to create a maintenance work, the program automatically generates maintenance actions for the right network components. It is possible to set a recurrence for a theme, so that the program automatically generates new actions for the network objects when the previous ones are completed. Using the recurrence is not mandatory, and in situations where there may be a lot of changes to the network, it is a good idea to use themes to create maintenance works for the planning year.

9.2 Parametrization

Major part of the maintenance framework was to develop a condition classification for the maintenance observations. There can be a lot of variation in the parametrization of the condition classes between network operators. Some may use numeric values to indicate the condition of the network objects, while some may use yes/no type data. The definitions and their implementation depends on the established maintenance practices of the network operator. Since the maintenance framework must be compatible with different customers, the definitions are based on classified values that support effective use of the maintenance application.

9.2.1 Observation classifications

Basis for the classification was clarity and compatibility. Classified values can be defined as default, potential fault and fault. Classified values also have descriptions, which can be used to provide more information on the maintenance need of a component. Each predefined observation has its individual classification. For inspections, the default condition value is generally *Okay*. Definition of potential fault and fault values depend of the inspected component. For services, test and measurements the condition values are *Completed* and *Not completed*. The main idea of this classification is to provide network operators clear information on the maintenance need of network components. The fault values also have predefined repair actions.

Some network operators may have a practice, where observations directly indicate a fault, such as *Defective insulator*, and the observation includes yes/no type data. In the maintenance framework, the maintenance need or condition of a component, such as fault, is indicated by a classified value. An example observation, *Control device*, is presented in figure 15. The default value for the observation is *Okay*. The fault value *Defects in control device* indicates the maintenance need of the MV disconnector control device.

It is possible to define potential fault value for incipient faults. Usage of the potential faults depends on the component and maintenance strategy. It is up to the inspector

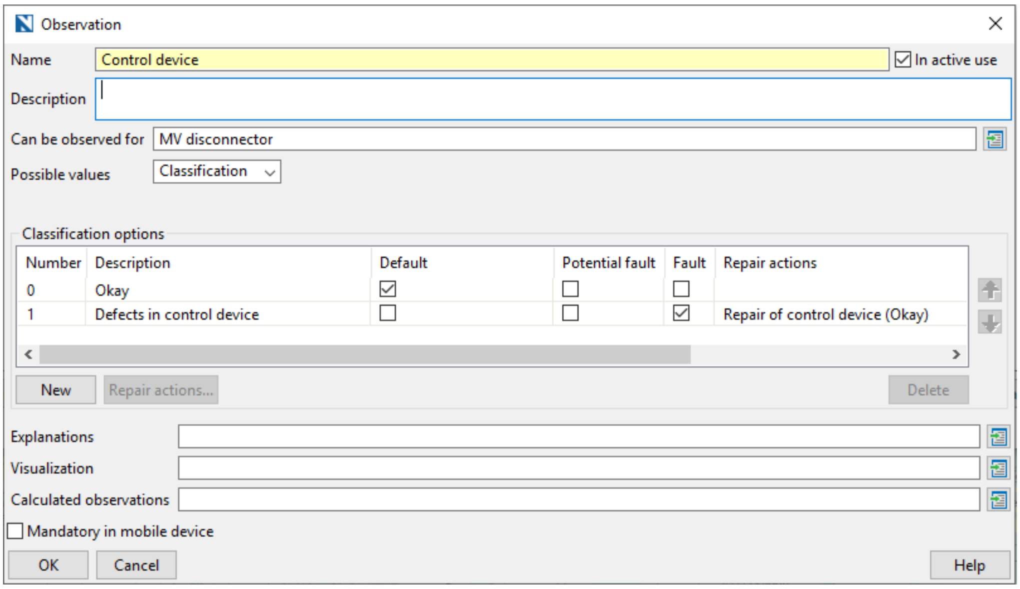

Figure 15: Observation: Disconnector control device.

to determine whether a deviation is a fault needing a repair, or a potential fault needing monitoring. Therefore, clear definitions are needed and sometimes it is better not to use the potential fault values. In the maintenance framework, the potential fault values were used sparingly. Using the importance to support the collected maintenance data is a good alternative. For example, an observation recorded as a fault can have importance *Not urgent*, which tells the maintenance planner that the repair can be postponed. Importance class definitions are also included in the maintenance framework.

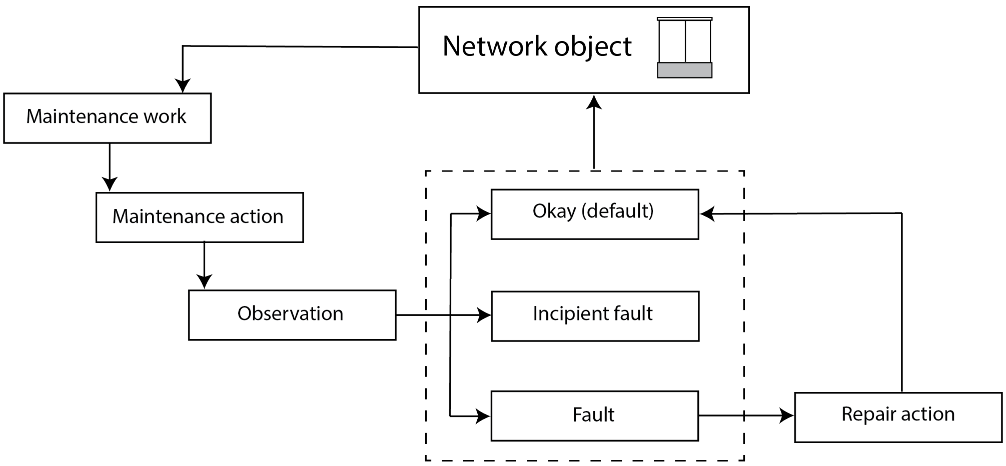

Figure 16: Maintenance process.

One aim of the classification is to reduce the amount of site visits by providing clear information about the maintenance need of a component. For example, fault value having description *Distribution cabinet tilted* provides more information than just *Fault* or a numeric value. With the predefined repair actions, planning and implementation of the repair actions is efficient. It is also possible to determine the cost for each repair action. This way the planner can decide whether to carry out the planned repairs, or whether another solution would be more profitable. Figure 16 illustrates the maintenance process.

The collected maintenance data can be used to optimize the maintenance process. Every inspection, fault and repair is saved into the maintenance history of a component. The history data can be used to determine component failure rate models and as a part of the condition index.

9.3 Installation package

Installation package was compiled to ensure easy delivery and testing of the maintenance framework. Installation package consists of SQL scripts. Initially, the maintenance programs were compiled in excel. The excel sheets were sent to the pilot customers to confirm the feasibility of the suggested maintenance actions and observations.

Compilation of the SQL scripts required studying the relational database structure of Trimble NIS. Installation scripts include the maintenance programs, as well as the configurations and initializations needed for the maintenance application deployment. If the customer has existing maintenance actions and observations in Trimble NIS, this data is also retained and set inactive.

Functionality of the installation scripts was first tested in demo environments, and then in the customer environments. After the initial delivery, some functionality problems were detected and resolved. The installation scripts were revised and tested again. At the time of writing, the installation scripts are compatible with Oracle and SQL Server databases.

9.4 Documentation and trainings

Providing documentation was one of the requirement specifications. The maintenance framework includes user manual, training materials and installation manual for internal use. The user manual contains information about the maintenance package and application functionalities. Usage examples help with the deployment and ensure, that the user gets familiar with the maintenance application. Installation manual was compiled as a guide for the software consultants.

The maintenance framework also includes user trainings. Customers can choose if they want the training, but it is available for all the customers who acquire the maintenance framework. The training is held online, and it is especially helpful for the customers, who have never used the maintenance application before. The training goes through the basics, and together with the user manual, provides users with the needed knowledge to use the maintenance application efficiently.

10 Project evaluation

From the business perspective, the main goal of the maintenance framework is to provide additional sales. Analyzing the success of the project is based on the additional sales and user feedback. User feedback also works as a guideline for further development. The pilot customers must accept that the service package is completed, so that a finalized product specification can be formed and the sales can begin.

10.1 User tests

User tests were conducted in different phases of the project. User tests were the main way to determine the functionality of the maintenance framework and installation scripts. Initial tests were conducted in demo environment. All the basic functionalities of the maintenance application were tested with the maintenance framework definitions. The maintenance framework was also installed to the Trimble NIS training environment, so additional information could be derived from user trainings. After the initial tests proved successful, the second version was compiled and delivered to the pilot customers. In first user tests, the pilot customers were asked to test the basic functionalities of the maintenance application in their production environments. User feedback was collected, and revisions were made in order to deliver the final version.

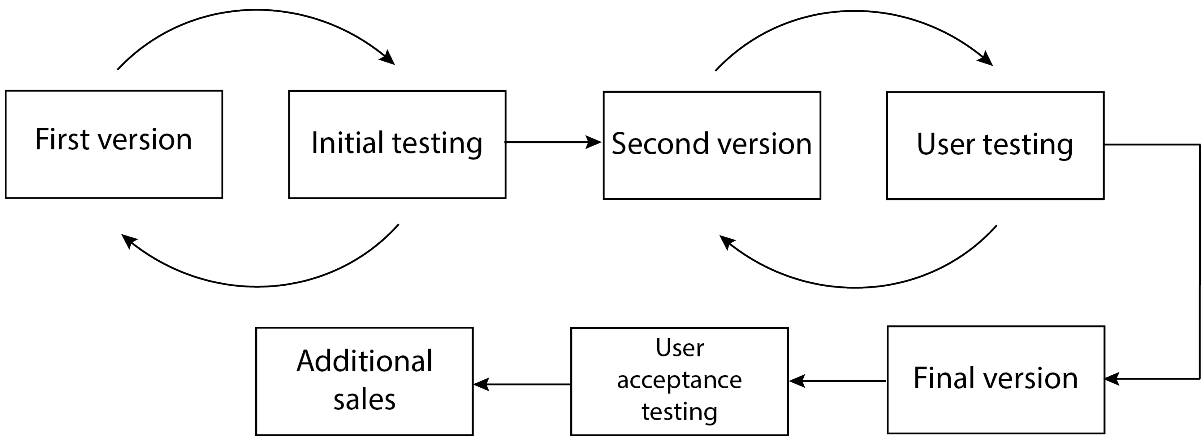

Figure 17: Testing process.

After the final version delivery, user acceptance testing (UAT) was conducted. Outcome of the UAT determines whether stakeholders accept that the work has been completed. The pilot customers were asked to create a larger amount of maintenance works, and to complete them in the field using Utility To Go. This way the whole maintenance process chain would be tested and performance in the field use could also be evaluated.

10.2 Customer feedback

Part of the user acceptance testing was a feedback survey. Customers were asked to provide written feedback, as well as to fill out the feedback form.The survey consists of an evaluation of usability and the predefined features. The survey also provides valuable information for further development. Grading scale is from 1 to 5 (1 = Needs a lot of improvements, 5 = Works great). Results of the survey are presented in table 5.

Usability	
	Grade
Ease of deployment	4
Clarity of documentation	4
General usability	4
Field use (Utility To Go)	5
Control of the maintenance process	3
Overall grade	4
Predefined features	
	Grade
Clarity of maintenance programs	3
Amount of observations	4
Classification	4
Adequacy of the inspections/services	4
Repair actions	4
Overall grade	4

Table 5: Results of the UAT feedback survey.

Feedback from the survey was generally positive. Overall grades of the usability and predefined features were 4 and 4 respectively, which can be seen as a good result. Deployment was considered easy, and could be further improved by making some customer specific modifications. The user manual was considered functional and comprehensive, but first-time users may requires some additional guidance. However, the user training complements the user manual and is useful, especially for the new users. In particular, the implementation of Utility To Go garnered positive feedback. The maintenance framework enables field users to perform maintenance actions in the field more efficiently. General usability was considered good. Control of the maintenance process, for example creating a large quantity of inspections, was considered to be more efficient.

As a whole, the predefined features were considered clear and adequate. However, getting familiar with all the features, such as themes, requires some practise. The amount of observations and actions was considered sufficient and condition classification clear and easy to implement. Repair actions were not tested in actual use, thus the grade 3.

As a summary, the maintenance framework was seen as an efficient way to deploy the maintenance application and Utility To Go, providing mandatory tools and knowhow. Also the user training received positive feedback. As a conclusion of the UAT, both of the pilot customers accepted the maintenance framework as completed.

10.3 Marketing and further development

During the project, it was important to define the out of scope features. As the aim was to develop a standard service package, anything too customer specific was excluded from the package. Certain feature requests, such as transferring maintenance works to calendar, were considered, but could not be accomplished within this project. At the moment, there exists a certain amount of customer specific definitions, but for the most parts the package can be delivered as is. Furthermore, the user manual and trainings help the customers to make the needed customer specific definitions themselves. For example, the maintenance framework does not limit the creation of new observations and actions, and it is also possible to modify the predefined ones if needed. Software consultants can also provide additional configurations as a billable service.

During Trimble's user days, the maintenance framework was introduced to Finnish network operators. The presentation attracted a lot of interest, further confirming that there is a need for a maintenance service package. At the time of writing, the maintenance framework has already accumulated additional sales. The aim is to actively market the maintenance framework to the target segment, using the results of the pilot project as an additional incentive. The market segment could possibly be expanded to medium-sized network companies, if additional sales prove successful. Further development might be needed in order to cover a larger customer base.

To get a better overview of the maintenance framework feasibility, feedback will be collected from the customers who purchase the maintenance framework. Since there might be differences in the network models between customers, it is important to gather feedback to determine the compatibility of the predefined features. For example, some network companies may not have digitized the guy wires of the poles, so the inspection of guy wires should be included in the pole inspection. Any larger feature requests might be implemented, if a clear need arises from the customer base. For now, the service package will be marketed and sold as is.

11 Conclusions

The aim of this thesis was to examine the role and cost effects of maintenance in distribution network operation, and to develop a maintenance package for the needs of small network companies based on the collected information. The development was carried out as a pilot project involving two distribution network companies. The goal of the maintenance framework is to provide Trimble NIS customers with a service package that clarifies the deployment and use of the maintenance application. The package contains the necessary features and configurations to support the maintenance process. The scope of the maintenance framework was limited to the most common components on MV and LV networks, i.e. distribution cabinets, transformers and overhead lines.

Maintenance has an important role in distribution network operation. Maintenance ensures that the reliability criteria are met and aims to maximize the service life of network components. The legislation and regulatory control place a lot of demands on network operators in terms of reliability. On the other hand, the authorities also encourage companies to invest in network security in the form of various incentives. Incentives allow network companies to achieve financial benefits by investing in network development. In many other European countries, such as Sweden and Germany, efforts have also been made to improve the reliability of network companies through legislation and regulatory control. The network companies must also compile a development plan to be submitted to the Energy Agency. The plan must include detailed measures, that will systematically and sustainably improve reliability. According to the latest development plans, the degree of underground cabling in the MV and LV network will reach 51% and 67% respectively by 2028. Therefore, the focus of maintenance in the future will shift towards underground cable network components such as distribution cabinets, cable terminals and cables, especially in LV networks. However, overhead lines will continue to exist, especially in sparsely populated areas.

The Finnish Energy compiles and publishes interruption statistics annually. Network companies have to pay compensation for interruptions experienced by customers. It is up to the network operator to decide how the standard compensation and the CIC compare to the reliability and maintenance of a particular network component. Various maintenance strategies have been studied and developed to optimize reliability and maintenance costs.

In general, network operators apply different strategies to different parts of the network. Selection of maintenance strategies can be supported by component criticality classification, CIC calculations and life cycle management. Reliability centered maintenance provides a solution that maintains a balance between preventive and responsive maintenance. A network operator defines maintenance actions, inspection and service intervals, as well as other maintenance measures in the maintenance program submitted to the Energy Agency.

Information system is needed to support effective network maintenance. Trimble NIS is a map-based network information system that can be used for network modeling, power system analysis and maintenance. The maintenance framework was developed to support the deployment and use of the Trimble NIS maintenance application. The requirement specifications of the framework were formed on the basis of legislation, reviewed theory and needs assessment. As a summary, the package must be easy to use, compliant for a large number of customers, meet the regulatory requirements, support different maintenance strategies, and be scalable and modifiable.

In the development of the maintenance framework, the aim was to find a solution suitable for as many companies as possible. Predefined features, such as themes, actions, and observations, consider the condition of the components in terms of power distribution and safety. The number of actions and observations was moderated in order not to be too extensive for the inspections and thus increasing costs. However, the inspections adequately cover all the most common network components. The condition classification was designed to be clear and to support the maintenance process. Efforts were made to determine the most common fault values for the observations. In addition, corrective actions were defined for all fault values of the observations, making it easy to analyze and repair the faults. To facilitate delivery, an installation package consisting of SQL scripts was developed, which was also used to test the framework in different environments. In addition, user manual and online training were prepared to support the deployment of the maintenance application.

Overall, the project can be considered a success. The project resulted in a service package that has already generated additional sales, and has further sales potential even among the foreign customers. User feedback from pilot customers was positive, and user acceptance testing was approved by both pilot customers. Possible further development measures are the expansion of the customer segment to medium-sized network companies. This requires a broader needs assessment, as medium-sized companies are likely to have more established maintenance practices than smaller companies. On the other hand, with the current configurations the maintenance framework provides at least the tools needed for deployment for medium-sized companies. The framework also allows modifications made by the user, so there is no real obstacles in delivering the package to different sized companies. Initially, the maintenance framework will be marketed to the original segment, i.e. small network companies. Additional sales and user feedback will determine whether the further development is worthwhile.

This thesis has provided valuable information on the productization of services, as well as on network maintenance processes in distribution network companies. This thesis can be used as an internal material that provides information on network maintenance. This makes it possible to offer better services for the customers. In addition, the results of the project can potentially be used as a framework for the implementation of similar projects.

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