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Maintaining Heterogenous Electricity Infrastructure

A Multiple Case-Study of Swedish DSO Perceptions and the Adoption of Risk-Based Maintenance

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Abstract

Today's societal development imposes several challenges for distribution system operators (DSOs) due to increasing electrification, implementation of modern technologies and aging infrastructure. Simultaneously, operators are expected to provide a continuous and stable supply of electricity to end-users at every given moment. In order to face these challenges and ensure the electricity supply upon which society depends, data-driven and risk-based maintenance approaches have recently gained traction.

This study's purpose is to investigate the potential for maintenance management support tools in heterogeneous infrastructural systems. More specifically, the study attempts to assess the suitability of data-driven and risk-based approaches for Swedish DSOs and how specific asset characteristics together with operator experience influence maintenance needs. This is done by analyzing switchgear assets in a multi-case study of 7 DSOs and by using Great Britain's framework, the Common Network Asset Indices Methodology (CNAIM), as a reference point.

The empirical findings identified tacit knowledge as one main driver for maintenance decision-making. Although the analyzed DSOs have implemented risk-based factors in their maintenance decision-making, this is done without a formal risk-based framework. Rather, network operators rely on tacit knowledge acquired through informal channels. The results indicate that age by itself is an insufficient variable for maintenance since more factors, such as operational conditions, local environments and asset technology also play a vital role in determining an asset's health. The results also show that organizational factors served as obstacles for the implementation of more technologically advanced maintenance supporting tools. Data-scarcity and quality as well as fragmented information systems or financial resources were identified as the most prominent obstacles, although their severity depends on DSO size.

On one hand, risk-based methodologies such as CNAIM are theoretically applicable for DSOs in Sweden since risk-based logic is already established in maintenance today. On the other hand, a successful implementation of such a risk-based framework requires taking organizational heterogeneity into consideration as different DSOs face different limitations.

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Populärvetenskaplig sammanfattning

Svenska elnätet står inför ett flertal utmaningar till följd av samhällets elektrifiering, åldrande infrastruktur och implementerandet av modern teknik. Dessa utmaningar ställer allt starkare krav på elförsörjningen, bland annat förmågan att leverera kontinuerlig elektricitet till svenska industrier och samhällen. Säkerställandet av elförsörjningen kräver ett förbättrat underhållsarbete via välgrundade beslut kring exempelvis hur, när och om olika elektriska komponenter ska ersättas eller underhållas.

Syftet med detta arbete är att undersöka hur förutsättningarna ser ut för mer data- och riskbaserade underhållsmetoder hos svenska elnätsbolag. Detta har preciserats genom att undersöka specifikt hur sju svenska elnätsbolag arbetar med underhållsarbete i relation till ställverk på spänningsnivån 10 kV. Materialet som ligger till grund för arbetet är baserat på intervjuer med dessa elnätsbolag som är av olika storlek, står inför diverse utmaningar inom deras organisation och som befinner sig på geografiskt olika platser.

Å ena sidan visar resultatet att underhållsbeslut primärt grundar sig i erfarenhet och individbaserad kunskap hos personalen på de olika elnätsbolagen. Å andra sidan framgår det tydligt att elnätsbolagen redan analyserar ett flertal av de faktorer som ligger till grund för riskbaserade underhållsmetoder. Med det sagt utgår underhållsarbete och beslutstagande i den bemärkelsen utifrån faktorer såsom komponenternas skick, sannolikheten till dess haveri, lokala miljöförhållanden och konsekvenserna av ett eventuellt haveri. Faktorerna analyseras däremot via informella kanaler och är i högsta grad beroende av de individer som fattar besluten.

Vidare återfanns ett växande intresse för mer datadrivna och riskbaserade metoder med ändamålet att förbättra underhållsarbetet och beslutstagandet i relation till ställverken hos de olika elnätsbolagen. Däremot uttrycker flertal av elnätsbolagen även hinder och svårigheter med implementeringen av sådana system såsom bristande datakvalité, fragmenterade stöd- och informationssystem samt begränsade organisatoriska resurser. Dessutom upptäcktes att storleken på elnätsbolagen har en stor inverkan på vilket av dessa hinder som är mest framträdande.

Slutsatsen indikerar att riskbaserade metoder har potential att stötta svenska elnätsbolag med deras underhållsarbete och beslutsfattande. Däremot behöver implementerandet av sådana systematiska metoder anpassas utifrån organisationens förutsättningar. Parallellt med detta finns en vilja från elnätsbolagen att utvecklas åt ett mer data- och riskbaserat håll men att detta arbete då bör ske hand i hand med mänsklig erfarenhet och expertis för att möta de utmaningar som elnätet står för idag.

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Konstantinos Kehagias & Viktor Larsson,
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Glossary and Abbreviations

ABB - A leading technological company that works with electrification and automation.

AIS and GIS - Air and Gas insulated switchgears.

Condition-Based Maintenance (CBM) - A maintenance strategy in which equipment is monitored and maintained based on its inspected or measured condition.

Condition Based Risk Management (CBRM) - An asset management methodology that uses condition data and risk assessment to prioritize maintenance and support management decisions.

Common Network Asset Indices Methodology (CNAIM) - A risk-based asset management methodology derived from CBRM that helps network operators assess asset risk, based on factors such as asset health, failure probability and consequences of failure.

Consequence of Failure (CoF) - A quantification of the potential operational, financial, environmental and safety related impacts associated with asset failure.

Distribution System Operator (DSO) - A stakeholder responsible for delivering power from the transmission grid to end users.

ESEM - Eskilstuna Energi and Miljö.

NALF and NAL - Switch disconnector types.

NGC, NGB and NEBB - Switchgear-type.

Probability of Failure (PoF) - The likelihood of failure for an asset in a given time frame.

Risk-Based Maintenance (RBM) - A maintenance strategy that prioritizes maintenance activities based on the likelihood, or risk of failure and the consequence of failure.

SECI (Socialization, Externalization, Combination, Internalization) - A model describing how tacit and explicit knowledge are created, shared, and transformed within organizations.

Switchgear - Electrical equipment which is used to protect, control and isolate parts of an electricity network.

SF6 - Sulfur Hexafluoride gas used in some switchgears as insulation.

Time-Based Maintenance (TBM) - A maintenance strategy where inspections, service and replacements are carried out on a fixed time interval.

1. Introduction

Electricity distribution networks are facing increasing pressure due to the electrification of society, its aging infrastructure as well as integration of new technologies such as electric vehicles and varied renewable generation (Ejuh Che *et al*., 2025; Li and Jenn, 2024; RISE, n.d.). Developments and changes such as these increase the complexity in both planning and operation of electricity networks, which is highlighted in regulatory and academic literature (Ofgem, 2021; Ruester et al., 2014; Sundsgaard et al., 2023). Santos and Massol (2022) argue that electricity networks are in need of continuous adaptations concerning rapidly changing energy systems to remain relevant, specifically in the context of low carbon and renewable power system transformation. In a report published by the International Energy Agency (2025), modern living conditions are argued to have drastically increased the demand for electricity. It is strongly implied that electricity presents a foundational infrastructure which daily life and economies depend on. This is exemplified, mainly by the fact that everything from transportation and water supplies to basic household appliances, industrial processes and AI related services are incredibly energy demanding systems. The increasing dependence on electricity across several sectors reinforces its role as critical infrastructure (IEA, 2025). Historical trends presented by the World Bank (n.d.) also illustrate that global electricity demand has increased significantly in recent decades, indicating an increased reliance on electrical energy. Hence, reliable electricity distribution is likely to remain a critical prerequisite for future economic activity, societal functionality and energy system transformation.

As electricity becomes essential in a variety of societal functions, interruptions in its supply may hinder crucial services and impact supply continuity negatively (IEA, 2025). In addition, existing electricity networks were mainly designed for more predictable and centralised systems which makes it increasingly challenging to accommodate new demands such as intermittent power generation, changing load patterns and higher utilisation levels (Santos and Massol, 2022). As a consequence of increased complexity, some regulators require distribution system operators (DSOs) to maintain high levels of reliability while simultaneously limiting costs for customers (Seppälä and Järventausta, 2024). Pressures such as these, which increase complexity and operational risks of today's energy systems, have resulted in growing emphasis on systematic, risk-based approaches to asset management (Sundsgaard et al., 2023). As a consequence, grid complexity, aging infrastructure and increasing dependence on electricity make modern electricity networks more difficult to manage. This results in an increased need for approaches that support more predictive, informed asset management and decision-making.

1.1 Purpose and Research Questions

The purpose of the study is to investigate the potential and suitability for maintenance management support tools in heterogeneous infrastructural systems.

RQ1: How can asset population characteristics, such as age and environmental conditions, together with operator experiences and perspectives support understanding of maintenance needs in heterogeneous electricity systems?

RQ2: How do Swedish DSOs perceptions and approaches to predictive maintenance indicate the suitability of data-driven and risk-based approaches?

1.2 Scope

This study is limited to Swedish DSOs operating at the medium voltage level (10-20 kV), with a focus on switchgear on a 10 kV level. The study is qualitative in nature as it aims to capture and understand the perception of risk-based and data-driven maintenance tools from a DSO's perspective. Although multiple DSOs were included in the study to gather multiple perspectives and the opportunity for comparison, it does not entail a statistical generalisation to the Swedish distribution system as a whole since a mere 7 DSOs out of circa 170 were analyzed. Broader infrastructure levels, such as regional and transmission networks fall outside of the study's boundary.

2. Introduction to Maintenance Decision-Making in Heterogeneous Infrastructural Systems

This chapter provides the necessary background for the study by introducing the electricity distribution network in Sweden and the role of key infrastructure components within the network itself. Thereafter, asset management and risk-based approaches in electricity distribution are presented, including the development and application of different established methodologies. Finally, practical challenges related to maintenance and asset management within electricity networks are discussed.

2.1 Electrical grids

The electrical grid is an integrated system which delivers electrical power from power generation to the consumer e.g. houses, industries and other consumers in the grid (Donev et al. 2024). According to Catanach and Ketchledge (2024) the primary purpose of the electrical grid is to deliver a reliable and efficient supply of electric energy within a country. In order to support a network which meets these demands, multiple elements have to co-exist and be integrated in an adequate way. At its core, the energy which is distributed in the grid is in the form of electricity, which is often distributed over thousands of kilometers to the end-user. In order to understand the principle of the grid, fundamental aspects of electricity are of importance to comprehend. Ali Keyhani (2016) categorizes three key elements which make up the electrical grid as power generation, transmission and distribution.

The generation is the process of transforming energy from primary sources such as wind, solar, hydro and nuclear into electric power, most commonly done by driving a turbine connected to a generator (Catanach and Ketchledge, 2024). In Sweden, the electric power generation vector is largely based on hydropower and nuclear power, together accounting for approximately 70% of total production with the overall mix being 98.8% fossil free (Swedish Energy Agency, 2025).

2.1.1 Transmission and distribution

The generated power from power stations has to be transported for distribution to various sectors or systems such as industries, residential areas and transportation systems. Electricity transportation occurs via what is referred to as transmission cables. Svenska Kraftnät serves as the only operator allowed to carry out transmission on the highest voltage level between 220 and 400 kV, in what is referred to as the transmission network (Svenska Kraftnät, 2024). Transmission lines in the grid are often designed to carry high-voltage power in order to minimize power loss in long distance transportation (Catanach and Ketchledge, 2024). In Sweden, the grid can be categorized into different groups depending on voltage level ranging from high to low voltages. The voltage is transformed from the high-voltage transmission network to lower voltage levels within the distribution network, which consists of both regional networks and local networks. The regional network operates at a voltage level of 130 kV and the local network at a voltage level of 40 kV and lower.

There are approximately 170 DSOs active in Sweden, of which 129 are municipal companies. 110 out of these 170 companies have 15 000 customers or less, which creates a fragmented market compared to several other European countries (Nordling, 2016). As a reference, one of the three biggest DSOs in Sweden, Vattenfall, has 900 000 customers (Vattenfall, n.d.). Energimarknadsinspektionen (2024) notes that there is no competition between DSOs in Sweden as it is not justifiable to build multiple parallel networks in the same area. As a consequence, the government agency Energimarknadsinspektionen, has the responsibility to control DSOs so they do not charge excessive network fees. Nordling (2016) explains that there is regulation in the form of a revenue framework which in turn limits the network fee which the DSOs are allowed to charge. The revenue frameworks are meant to cover operation, maintenance and investments to the grid in order to maintain reliability of supply and long term network capacity. Swedish DSOs also have to complete risk and safety analysis and submit to Energimarknadsinspektionen, however DSOs are not bound to use a specific method or approach when doing this (Svenska Kraftnät, 2014). These regulations are established by Energimarknadsinspektionen in accordance with Swedish and EU legislation and are updated at a four year interval for every DSO active in the Swedish electrical grid (Nordling, 2016). A typical electrical grid in Sweden with power generation and distribution from the transmission lines in the grid can be seen in Figure 1 below.

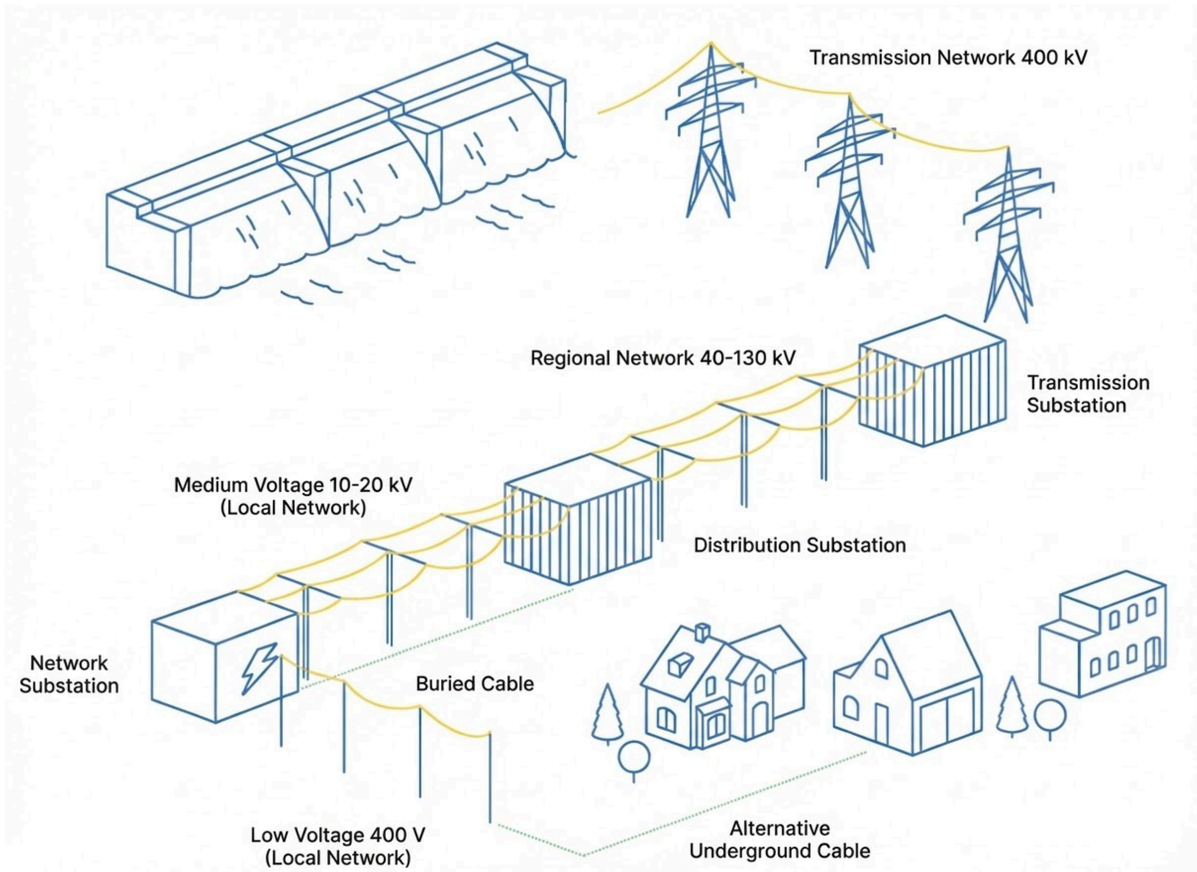

Figure 1: An example of an electrical Grid in a Swedish context (Vattenfall, 2026)

DSOs main function is to transport electricity from the transmission system to end-users, ensuring that customers can access energy on demand. It is also the distributor's role to provide the possible infrastructure enabling the transformation from higher voltages to lower ones, hence making electricity available for all consumers (Catanach and Ketchledge, 2024). Vattenfall (2026) underline that a DSO in Sweden has to design a network consisting of components such as transformers, switchgears, stations, cables and more in order to have an infrastructure which can withstand the possibility of a voltage drop from 400 kV to 230 V, which is the voltage level in Swedish wall sockets.

2.1.2 Switchgears

Switchgears play a critical role in the network infrastructure in order to ensure safe and reliable power distribution within the electrical grid. Switchgears are constructed in different ways depending on the voltage level and power system that the individual switchgear is attached to, in Sweden this ranges from 400 V to 400 kV. Switchgears are components used in electrical grids to protect and isolate different sections of an electricity network in order to maintain a reliable power supply and enable safe operating conditions for personnel. Important functions are power distribution, protection against electrical faults, insulation and safety, monitoring and control as well as voltage regulation (Vattenfall, 2024). Every type of switchgear has an insulation technique, which differs depending on the power systems conditions and requirements. The most common types of insulation techniques are air insulated switchgears (AIS) and gas insulated switchgears (GIS). GIS solutions traditionally use gas called SF_6, an extremely potent greenhouse gas, however it enables switchgears to be installed in instances where space is limited. AIS solutions on the other hand, are used when space is not a limiting factor and air can thereby be used as the insulation (Burges et al. 2020). According to Vattenfall (2024) one of the most crucial benefits which switchgears offer are the possibility to disconnect equipment in a safe way for service personnel along with protecting other types of equipment in the power station. In the event of a fault, power needs to be cut off quickly and in a controlled manner in order to prevent short circuits and overloading, which can cause fires or other damages to the electrical system.

2.2 Asset management

According to the International Organization for Standardization, ISO 55000 (2014), asset management is defined as an organization's attempt to realize value from its assets. The ISO 55000 discusses how realizing value involves balancing factors such as costs, risks, opportunities and performance benefits in relation to the organization's objectives. It is also stated that asset management enables organizations to improve their decision making and asset managing effectively throughout the assets lifecycle. Several pros are mentioned for asset management in the ISO standard, such as improved financial performance, informed decisions for asset management, managed risk and improved efficiency- and effectiveness in the organization.

Particularly, the importance of systematic asset management for organizations which rely heavily upon physical assets to achieve their objectives is underlined and discussed.

In a paper by Brown and Humphrey (2005) asset management in electrical power systems is described as a process meant to balance system performance, reliability, risk and cost in infrastructure decision-making. The two authors discuss how asset management supports decision making related to maintenance, restoration and replacement planning throughout the systems lifecycle. Sadnicki and Liu (2019) also relate to this, arguing that modern methodologies for asset risk modeling within electricity networks support investment planning, investment prioritization and asset risk assessment. Sadnicki and Liu additionally argue that asset risk modeling may support the justification of complex asset investments, improve communication between operators and aid in broadening investment planning processes. The aforementioned development towards more risk-based asset management by Sundsgaard et al. (2023) is also exemplified by Great Britain's (GB) regulator Ofgem through the development of the Common Network Asset Indices Methodology (CNAIM), which is used to assess and forecast asset risk within electricity distribution networks through evaluations of asset condition, the probability of assets failing, and the potential consequences associated with those failures (Ofgem, 2021). Together, these approaches may serve as a demonstration of asset management in electrical grids and how it has developed into a more data-driven and risk-based process for cost efficiency and reliability in electricity distribution.

2.3 Risk-Based Asset Management in Electricity Distribution Systems

The demand for more risk-based approaches within asset management in electricity distribution is corroborated by authors Catrinu and Nordgård (2011) as they argue that asset managers recognize the need for improved risk-based and data-driven methodologies under operational uncertainty. Similarly to Brown and Humphrey (2005), Catrinu and Nordgård claim that electricity distribution asset management requires balancing several criteria such as reliability, cost and safety within operationally complex environments. Sundsgaard et al. (2023) and EA technology (n.d.) delve deeper into this topic by describing Condition Based Risk Management (CBRM), a broader approach where maintenance and replacement decisions are based on an asset's condition and risk exposure rather than relying solely on its age. Additionally, it is noted that organizations such as the Australian Energy Regulator and the International Electrotechnical Commission both have recognized the importance of Component Risk Models within electricity network regulation (Sundsgaard et al., 2023), where risk-based asset management is an inherent component. The Australian Energy Regulator (Jemena, 2025) has also published formal guidelines related to CBRM for an Australian DSO, showcasing the international application of these principles within electricity infrastructure networks. India serves as an additional example where CBRM implementations have taken place in an electricity distribution context which further illustrates the global adoption that is taking place (Sadnicki and Liu, 2019).

Within GB's electricity sector, these broader principles associated with CBRM and probabilistic asset modeling have been formalized through the development and implementation of CNAIM. CNAIM was developed jointly by GB's six DSOs and Ofgem (Sadnicki and Liu, 2019). The development was amongst other things, a result of regulatory requirements which ultimately contributed to standardized approaches of risk assessment across GB's DSOs (Ofgem, 2021). Sadnicki and Liu describe GB's DSOs as being leading in condition-based asset modeling, highlighting the comparatively advanced development of risk-based asset management practices within GB's electricity distribution sector. The authors further describe how utilities within GB employed several probabilistic and condition based modeling techniques prior to CNAIM, including decision trees, linear and exponential regression, Weibull curves, stock-and-flow models, and agent-based simulations (Sadnicki and Liu, 2019). Emerging from these broader CBRM principles and earlier probabilistic modeling approaches, CNAIM was subsequently introduced as a common framework for the assessment, forecasting, and regulatory reporting of asset risk across GB's electricity distribution sector (Sadnicki and Liu, 2019).

2.4 Risk-based approaches and CNAIM

The growing importance of condition based maintenance approaches has been associated with increasing system complexity, higher reliability requirements and rising maintenance costs from other practices (Jardine et al., 2006). Khan and Haddara (2003) further describe how developments in modern maintenance strategies have been motivated by increases in the number, size, complexity and variety of physical assets together with growing awareness of the impact of maintenance on safety, environmental performance and profitability. Earlier maintenance approaches largely relied on corrective maintenance or time based maintenance (TBM) performed at predetermined intervals regardless of actual equipment condition (Jardine et al., 2006). However, Jardine et al. (2006) argue that as systems became more complex and reliability requirements increased, traditional TBM became increasingly costly and could result in unnecessary maintenance actions despite equipment remaining in acceptable condition. Wang (2002) further highlights that deterioration and failure behavior in complex systems cannot always be adequately represented through simple periodic maintenance policies alone. This has resulted in increased implementation of condition based maintenance (CBM), where maintenance actions are based on monitored equipment condition rather than fixed maintenance intervals (Jardine et al., 2006). Khan and Haddara discuss that risk-based maintenance (RBM) approaches have recently emerged, using both the probability and consequences of failure in order to support maintenance prioritization and resource allocation (Khan and Haddara, 2003).

Building upon these developments, CNAIM incorporates condition based principles through the inclusion of an asset's health and condition information within the risk assessment process (Ofgem, 2021). Risk in asset management is commonly represented through assessments of the Probability of Failure (PoF) and the Consequence of Failure (CoF), where the likelihood of failure is evaluated together with the potential operational, financial, environmental and safety related impacts associated with the event (Khan and Haddara, 2003; Ofgem, 2021). Within CNAIM, asset risk is assessed through a combination of asset health, probability of failure and consequence of failure calculations, where condition, environmental and operational factors are incorporated into the assessment process (Ofgem, 2021; Jennrich and Lund, 2021). The resulting risk assessments can further be used to support maintenance prioritization by evaluating the likelihood and consequences of asset failure, where risk is often presented in monetised terms (Ofgem, 2021; Sadnicki and Liu, 2019). This representation enables a comparison between assets and asset classes by supporting risk-based investment prioritization within a regulatory context. CNAIM further incorporates several operational, environmental and asset specific modifiers within the PoF and CoF assessment process (Ofgem, 2021).

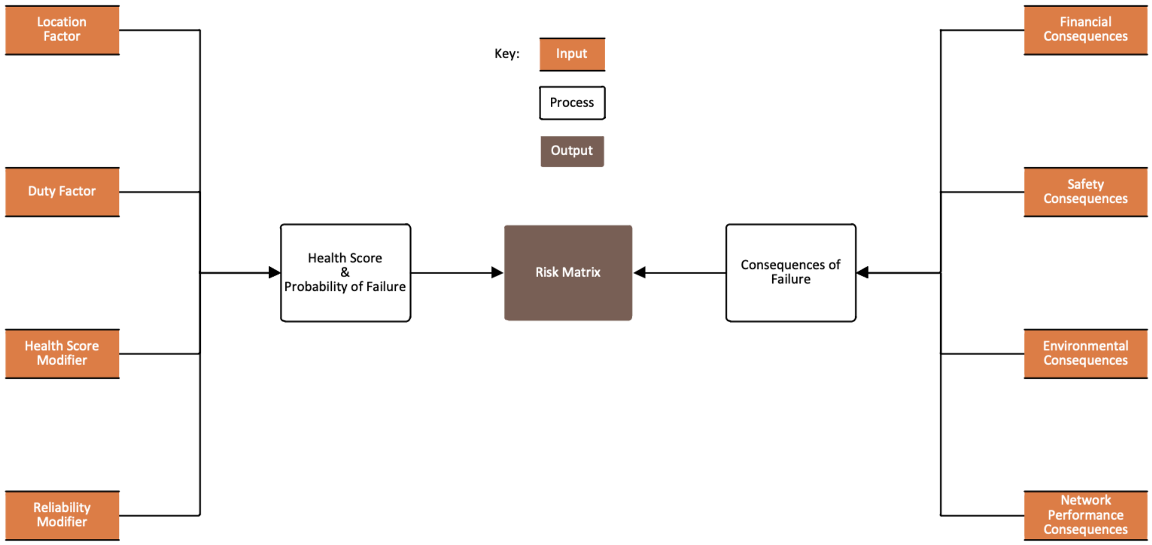

Figure 2: An overview of CNAIM's process (Ofgem, 2021)

2.5 Practical challenges in risk-based asset management

As electricity distribution systems continue to evolve due to increased electrification, renewable integration and broader energy system transformation, the need for more adaptive approaches in grid management has subsequently increased (Santos and Massol, 2022). Catrinu and Nordgård (2011) further discuss how electricity infrastructure organizations increasingly face challenges related to aging infrastructure, asset populations, limited resources and growing system complexity, making maintenance prioritization and investment allocation more difficult. In more fragmented distribution system contexts such as Sweden's electricity sector with approximately 170 DSOs (Energimarknadsinspektionen, n.d.), the coordination and standardisation of risk-based asset management approaches may therefore prove increasingly complex.

Wang (2002) additionally argues that deterioration and failure behavior in complex systems cannot always be adequately represented through simplified periodic or time based approaches alone, particularly due to the stochastic nature of failure behavior. In heterogeneous infrastructure systems operating under varying environmental and operational conditions, this may further limit the effectiveness of maintenance strategies based primarily on fixed maintenance intervals. However, while more condition-based approaches may help address some of these limitations, Jardine et al. (2006) describe how CBM methodologies rely heavily on condition monitoring, diagnostics and data acquisition systems in order to support maintenance decision making. The applicability of such approaches may therefore become increasingly dependent on the availability, consistency and comparability of asset data across organizations.

Ofgem (2021) further describes how methodologies such as CNAIM incorporate multiple condition, environmental and operational parameters within the risk assessment process, requiring extensive asset-specific information and model assumptions. However, CNAIM was developed jointly between Great Britain's DSOs and Ofgem within a shared regulatory framework, supporting more standardised reporting structures and asset evaluation processes (Ofgem, 2021). In more fragmented organizational settings, it may therefore become more difficult to implement and apply similar methodologies consistently, potentially increasing the need for coordination, comparable asset information and adaptation to local network conditions. Furthermore, previous research within electrical utility organizations highlights that important operational knowledge is often experience-based and difficult to fully formalize or codify (Perjanik, 2016). In situations characterised by limited or inconsistent asset condition or failure data, this may increase the reliance on expert judgement and tacit operational knowledge in supporting maintenance and asset management decisions, potentially increasing organizational dependence on experienced operational personnel.

3. Theoretical framework

This chapter introduces the study's theoretical framework. It presents theoretical perspectives relevant to maintenance decision making, risk-based approaches and the broader organizational and infrastructural context in which these practices operate. Thereafter, theories related to maintenance strategies, risk and localization are presented. Finally, perspectives on knowledge formation and the role of experience within organizations are presented. All together, these theories provide a foundation for understanding maintenance practices and serve as a reference point when interpreting the study's empirical findings.

3.1 Large Technical Systems

A majority of societal activities depend on large-scale infrastructure such as energy, transportation, distribution and communication systems. Research on Large Technical Systems (LTS) started to take place in the 1980s and originates from Thomas P. Hughes (1983) work around large infrastructure and production systems. Sovacool et al. (2018) emphasizes four attributes for a LTS regarding its categorization: they are sociotechnical, large, coordinated and varied. In later studies, discussions have evolved around system change, how mature systems can go through phases after they have been established and how they adapt, struggle and transform. In complex systems, like electrical distribution, transformation and structural challenges are important to take into consideration, as these systems are influenced by innovation as well as stagnation and decline (Magnusson and Grundel, 2023).

The central focus of LTS theory is the system itself and often with influence from other construct movements such as societal or regulatory, tied with technological change. LTS theory highlights that technology can have a deterministic effect and shape patterns of policy, strategy and action. Systems undergo overlapping phases and are not always linear as invention and technological progress need time to develop into established momentum and style (Sovacool et al., 2018). The introduction of system changing aspects often involve many stakeholders as negotiations regarding importance and implementation take place. Conflict of usage between stakeholders is common as every individual organization views the system changing aspects differently depending on the effects on their organization and adaptability (Van der Vleuten, 2009). The expansion and development of infrastructural systems are often not in phase with the systems meant to control and coordinate them while being driven by the economic and societal demand for expansion and improvement. Technological and organizational capabilities are also deemed necessary for this continued development according to Lehtonen and Nye (2009). These are challenges that mature and established systems face as they become more complex and intelligent. Lehtonen and Nye (2009) highlight other challenges with matured systems as well, e.g. path dependence and inertia as mature infrastructure systems are often built around existing arrangements and institutional rules. Obstacles are often not the technical components themselves rather organizational-, mindset-, skill- and philosophical structures.

3.2 Corrective Maintenance and Preventive Maintenance

Traditionally, maintenance theory distinguishes between two larger classes, corrective and preventive maintenance (Wang, 2002; Hameed et al., 2010). Jardine et al. (2006) discuss this classification in further depth and describe time based preventive maintenance as scheduled interventions based on age or specific operating time rather than by observed asset degradation. Thereby, time based preventive maintenance is determined in advance, based on expected lifetime characteristics, in contrast to condition based maintenance which uses condition data.

The underlying logic behind TBM is that it assumes age is a sufficient indicator for determining when failures occur or become more likely. What is considered as sufficient and not is context-based and although TBM can be considered sufficient, CBM may more accurately capture asset degradation and failure behavior, based on Wang (2002). This is largely due to the fact that many technical systems exhibit stochastic failure behavior which is not fully captured in purely TBM, where statistically derived lifetimes are considered fixed. The preventative approaches, TBM and CBM, greatly contrast with corrective maintenance which as the name implies, is performed reactively. In this approach, maintenance actions are only taken after a component has failed, meaning that failed components are repaired or replaced once failure has already occurred (Hameed et al., 2010). This may increase the need for spare parts availability and unplanned repair interventions, especially in systems where the consequences of component failures are grave.

3.3 Condition and risk-based Maintenance

In several frameworks, such as CBRM and CNAIM, TBM and CBM principles are combined with risk-calculations into what is considered risk-based asset management methodologies (Ofgem, 2021; Jemena, 2025).

Andersen and Nielsen (2024) highlight that CBM can lead to significant cost efficiencies under realistic operating conditions, particularly in systems characterized by stochastic dependence between components and high failure costs. However, they also emphasize that CBM is not necessarily superior to time based maintenance. Instead, its relative advantage depends on several interacting factors, such as the number of components in the system, the degree of economic and stochastic dependence, replacement costs and the variability in component lifetimes. Overall, CBM methods require more data than TBM and are therefore more complex and resource-demanding.

Jardine et al. (2006) describe how the development of CBM emerged as a response to the limitations of other maintenance policies. The authors argue that CBM is a parameter-based approach for maintenance decision making, thereby reducing reliance on strictly TBM. All together, while CBM improves the estimation of failure likelihood through the use of real time condition data, it does not inherently provide a systematic framework for prioritizing maintenance actions across assets with differing consequences of failure.

In contrast to previous approaches, risk-based maintenance (RBM) supports maintenance decision making by integrating both the probability of failure and the associated consequences, enabling prioritization based on overall risk (Khan and Haddara, 2003). Therefore, RBM is particularly suited for prioritizing maintenance activities at a system level. CBM primarily supports decisions regarding when maintenance should be performed based on asset condition, whilst RBM aids in maintenance prioritization across assets with quantified risk as a reference point (Khan and Haddara, 2003; Jardine et al., 2006).

3.4 Risk Theory and Engineering Simplification

Kaplan and Garrick (1981) define risk as a set of triplets consisting of scenarios, their associated probabilities, and consequences. Within engineering risk assessment and risk-based maintenance approaches, this conceptual interpretation of risk is commonly operationalised through quantitative formulations based on the PoF and CoF (Vladeanu and Mathews, 2019). Within CNAIM, risk is primarily expressed as the product of PoF and CoF (Ofgem 2021).

$$RISK = PoF \times CoF \qquad (1)$$

Additionally, Khan and Haddara (2003) describe engineering risk assessment approaches in which consequences may include financial losses, human health impacts, environmental damage, and operational impacts. The authors further explain how quantitative risk values can be utilized to support inspection prioritization and maintenance activities. Once more, similar probability and consequence based approaches are also incorporated within the methodologies CBRM and CNAIM (Ofgem, 2021; Jemena, 2025).

3.5 Contextualisation of Risk Models

Risk-based assessment and management methodologies are applied across several industrial and technical domains in society. Berg (2010) discusses applications within areas such as industrial plants, nuclear power, aerospace projects and financial systems which illustrates the broad applicability of such approaches. Simultaneously, both Berg (2010) and Chemweno et al. (2018) emphasize that risk assessment methods, risk criteria and assessment approaches depend on the operational and application context in which they are used. Chemweno et al. (2018) specifically note that risks are domain specific and that the application of risk assessment methods varies depending on the application context. Berg (2010) similarly highlights the importance of establishing the operational and environmental context and argues that risk criteria should be in line with the type of risks which are being analyzed. All together, these perspectives indicate that while risk-based methodologies may appear transferable across different systems their implementation may also require adaptation to fit system-specific technical, operational and environmental conditions. In the CNAIM methodology specifically, localization appears to have been treated as a necessary part of the implementation process from the beginning. Jennrich and Lund (2021) discuss that DSOs outside of GB need to adapt the methodology to local network configurations and operating conditions since such conditions are embedded in the model through parameters related to PoF and CoF. Similarly, Sundsgaard et al. (2023) identify limitations in how CNAIM represents risks associated with digitalized distribution systems and propose adaptations to the methodology to better reflect such conditions. In short, the methodology and RBM theories in general appear to support contextualization when implementing risk-based approaches.

3.6 Methodological Challenges in DSO Benchmarking

As risk models require local adaptation for precision, comparing results directly between different operators becomes a significant challenge. Jamasb and Pollitt (2000) argue that benchmarking is a central component of incentive regulation, yet they caution that results remain sensitive to methodological choices, variable selection, and environmental factors. Consequently, benchmarking using risk-based or other indicators does not ensure direct comparability between DSOs as heterogeneity in operational conditions can affect model outcomes (Jamasb and Pollitt, 2000).

Similarly, Rita et al. (2023) highlight that benchmarking DSOs requires consideration of differing operational conditions and harmonized datasets in order to support meaningful comparison across organizations. These perspectives indicate that structured benchmarking and risk-based approaches may support DSO comparison and efficiency assessment if local operating conditions, data consistency, and methodological assumptions are taken into consideration. Subsequently, when these factors are addressed accordingly, benchmarking can serve as an important mechanism for supporting assessment efficiency and increased transparency in DSO comparison. This allows operators to identify relative performance differences, support overall network efficiency and help with decision making (Jamasb and Pollitt, 2000; Rita et al., 2023).

3.7 Tacit Knowledge and Organizational Knowledge Creation

Tacit knowledge represents a form of knowledge that individuals possess but may be unable to fully articulate explicitly. Referring to Polanyi's work, Nonaka (1994) describes tacit knowledge through the idea that individuals may know more than they are able to express explicitly. According to Polanyi (1966), individuals may successfully perform actions or make judgments without being able to explain the detailed processes underlying them. Nonaka illustrates this by comparing it to riding a bicycle or swimming, situations where individuals are capable of maintaining balance or staying afloat without consciously understanding or verbally explaining the mechanisms involved (Polanyi, 1966), similarly to a black-box. Nonaka (1994) also argues that tacit knowledge possesses a personal quality that makes it difficult to formalize and communicate. Tacit knowledge therefore reflects practical and experience-based understanding that can be difficult to specify or express explicitly (Polanyi, 1966; Nonaka, 1994).

Further, the author distinguishes between tacit and explicit knowledge, where explicit knowledge refers to knowledge that can be transferred through formal, systematic language and that is codified or documented. Organizational knowledge creation is, according to Nonaka (1994), driven by continuous interaction between tacit and explicit knowledge through what is referred to as the Socialization, Externalization, Combination and Internalization (SECI) process (Figure 3). Socialization refers to the transference of tacit knowledge through shared experiences, observation or practice, where individuals gain knowledge through personal interaction rather than explicit documentation. Externalization describes the process through which tacit knowledge becomes articulated into explicit forms which enables experience-based understanding to become communicated and shared with others. Combination refers to the process through which different forms of explicit knowledge become organized, mixed and systemized into new explicit knowledge. Ultimately, Internalization is the process through which explicit knowledge gradually becomes incorporated into tacit knowledge through learning and practical application (Nonaka, 1994).

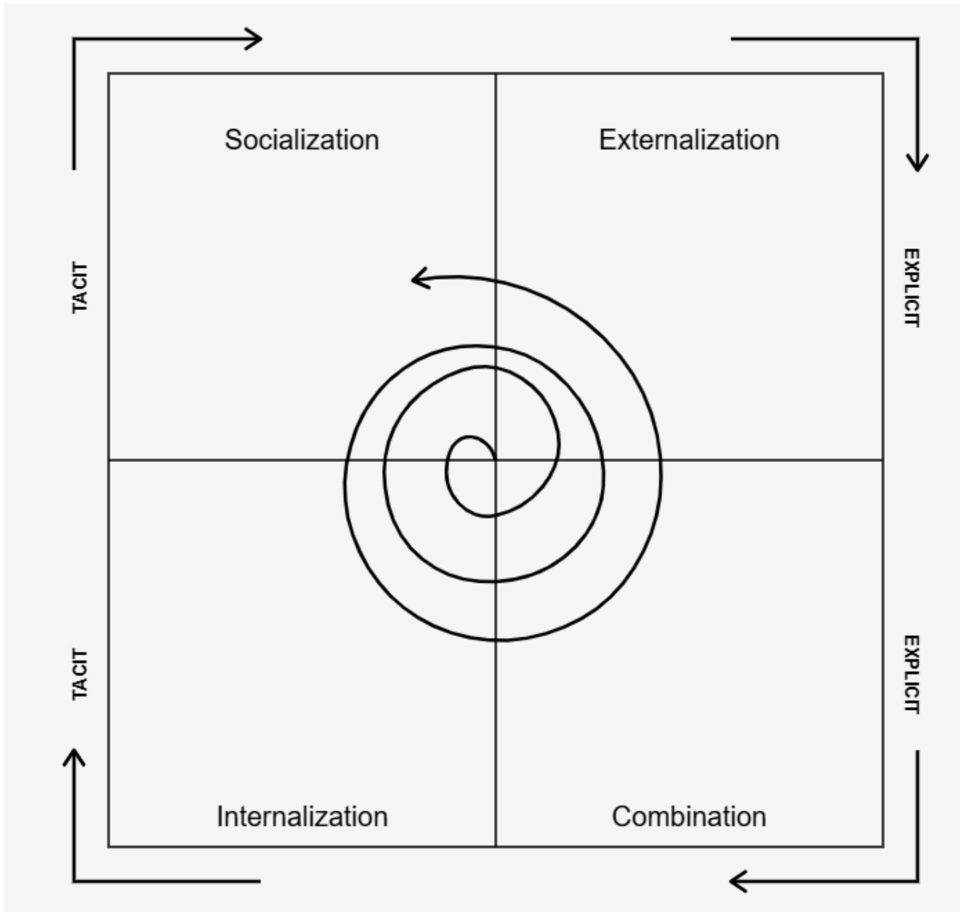

Figure 3: Knowledge transfer within the SECI process, inspired by Nonaka's interpretation

Beyond representing practical and experience-based understanding, tacit knowledge may also constitute an important organizational resource. Nonaka and Takeuchi (1995) argue that making personal knowledge available to others is a central activity within knowledge-creating organizations, where individual experience and expertise become transformed into knowledge valuable to the organization as a whole. Through the continuous interaction between tacit and explicit knowledge, described through the SECI model, individual experience and "know-how" may become shared and integrated across the organization. Because tacit knowledge often consists of practical "know-how" and experience that may be difficult to formalize or communicate explicitly, organizations may rely on individuals' experience to support organizational learning and innovation processes (Nonaka and Takeuchi, 1995).

Nonaka (1994) argues that while knowledge is created at the individual level, organizational knowledge creation depends on individual perspectives becoming articulated and amplified through social interaction. As Nonaka (1994) notes, such perspectives otherwise remain personal unless they become shared with others within the organization. Through the SECI process, tacit and explicit knowledge continuously interact across individual, group and organizational levels. In this process, knowledge becomes created, shared and amplified, enabling experience-based understanding to extend beyond the individual level rather than remaining solely embedded within specific individuals. However, as individuals may know more than they can express, the externalization process and translation of knowledge may not fully represent the tacit knowledge of individuals.

In a similar context, Alavi and Leidner (2001) identify making knowledge held by individuals available and meaningful to others as a core challenge within knowledge management and highlight the importance of making that knowledge accessible within organizations. Further, the authors note that knowledge-based resources may contribute with innovative advantage due to their socially complex nature and difficulty of imitation. At the same time, they discuss how organizations may experience setbacks when important personnel leave, as knowledge associated with individuals may become difficult to retain or transfer. Alavi and Leidner (2001) additionally state that organizations may forget acquired knowledge over time and describe organizational memory as extending beyond specific individuals to include written documentation, electronic databases, documented procedures and codified knowledge embedded within networks. All together, these examples showcase that knowledge residing with individuals may represent an important organizational resource while highlighting the significance of processes which enable tacit knowledge to become communicated, articulated and retained across the organization.

4. Methodology

This chapter presents the methodology applied in the study. It begins by outlining the research strategy and philosophy followed by the research design. Thereafter the data collection and the analytical procedure will be presented. The section concludes with ethical considerations and a discussion of methodological limitations.

4.1 Research strategy and philosophy

The way maintenance is understood, prioritized and practiced within the Swedish electricity distribution system is not a phenomenon that can be captured by numbers or in a single sentence alone. How DSO operators chose to reason about asset condition, risk and the importance of data-driven approaches is shaped by multiple years of accumulated organizational experience and culture, personal judgement but also the specific characterizations of their respective networks. This reality shaped the methodological choices for this study.

Fundamentally, this study is concerned with understanding how individuals in a large technical system evaluate and formulate decisions with regards to their work and the challenges associated with that system. Epistemology, the philosophy of how knowledge can be acquired (Saunders et al., 2023), is therefore a central aspect. Specifically, whether knowledge about maintenance practices and strategies is best generated through measurement, collecting quantitative data or through meaning and understanding of how people interpret, experience and reason. The study adopts an interpretivist epistemology approach, which highlights that knowledge about human behaviors and practices as well as strategies are best understood by engaging with the individuals working within the system, instead of measured predefined variables (Bryman, 2016). In addition to this epistemological approach is a constructive view of reality. Ontology concerns the assumptions that researchers make regarding the nature of reality and consequently influences how the studied phenomenon is experienced and understood (Saunders et al., 2023). The study adopts a constructivist ontological position with the phenomena of maintenance needs, risk perception and attitudes towards data-driven approaches as they are not fixed or universally defined in the system but rather shaped by each DSO's operational history, network composition and accumulated experience and attitude of its workforce. Each DSO therefore represents its own reality and recognizing along with treating these differences is a necessity given the heterogeneous nature of the Swedish electricity distribution system.

These considerations led to the adoption of a qualitative research strategy in order to gather the perspectives and differences of the stakeholders. Qualitative research, as Bryman (2016) describes it, prioritizes the understanding, meaning and experiences over the quantification of variables. According to Yin (2018) it is particularly well suited to studies where the aim is to explore how and why compared to how much, and where the research phenomenon is closely connected to real world settings such as DSOs in the electrical distribution system. Bazen et al. (2021) argues that the one of the greatest strengths of which qualitative research offers is the possibility to understand the stakeholders from their perspective. This is particularly important in complex systems where multiple parameters affect each other and on different scales. The research questions are thereby designed in such a way to explore how knowledge, experiences, perceptions and organizational reasoning shape maintenance practices and views on predictive maintenance among Swedish DSOs. Addressing such questions requires an understanding how these perspectives are interpreted and applied in practice, something that numerical analysis alone can not capture.

In cases where descriptive data attributes were available, Figures (4 through 7) were created and incorporated to provide additional DSO context for the reader. Schreiber (2008) highlights that descriptive statistics in qualitative research, allows for a richer picture. However, this descriptive material does not alter the methodological path. The study is qualitative in its orientation, design and analytical approach, the descriptive data serves as complement and illustration meant to provide additional context.

4.2 Research design

To address the research questions, the study adopted a multiple case study design, an approach where several cases are studied in order to compare, explore patterns and to facilitate a broader understanding of the phenomenon which is studied (Mills et al., 2010). Robert Yin's (2018) definition of a case study is an empirical gathering which investigates the phenomenon in depth and in a real world setting, a definition that fits the study well.

The choice of a multiple case study instead of a single case study reflects the nature of the research questions. Research question 1 concerns heterogeneous electricity distribution systems, implying that there is a variation across DSOs and that understanding these differences is essential. The second research question requires multiple DSOs in order to draw some type of analysis about similarities and differences regarding the suitability of predictive data-driven systems in a Swedish electricity distribution context. Treating each participating DSO as an individual case therefore opens up the possibility for a systematic comparison between entities.

Yin (2018) argues for a distinct difference between two logics when selecting cases in a multiple case study, one is literal replication, where cases are expected to produce similar results to each other. The other logic is theoretical replication, where selected cases are expected to produce contrasting results. This study follows the second logic as Swedish DSOs vary considerably in terms of network capacity, geographical conditions, asset age and organizational resources. These key differences are expected to give varying perceptions and approaches to predictive maintenance and is precisely the variation which the study sought to capture and understand.

The participating DSOs were selected based on their willingness and possibility to engage with the study and their ability to contribute to the research questions through interviews. Initial contact was made with a broad pool of Swedish DSOs, of whom a subset agreed to participate. The selection of participants was initially based on relevance and possibility of accessibility. Geographical variation among the participating DSOs was intentionally sought, as this was expected to reveal differences in operations conditions and network characteristics.

4.3 Data collection

The primary source of empirical data in this study was conducted through semi-structured interviews with representatives from Swedish DSOs. This section describes the process of identifying and the process of contacting potential participants, followed by the interview approach.

4.3.1 Participating stakeholders

In order to gather the empirical material needed to address both research questions, a selection of suitable participants from Swedish DSOs was required. Initial contact was established through email, in which multiple representatives at different DSOs all across Sweden were approached and invited to an introductory meeting. The initial contact with DSOs was directed towards ones varying in terms of size and geographical location with the intention of gathering a wider range of operational conditions and network sizes. A number of DSOs declined to participate due to time constraints or insufficient workforces, though many expressed genuine interest in the subject matter.

The DSOs which accepted an initial meeting were given the opportunity to discuss their network, experiences, current maintenance practices, operating system and challenges they have faced in the past or are facing at the moment regarding their switchgear population. These conversations with each DSO were important in terms of establishing the studies scope but also in terms of establishing a mutual understanding between the researchers and the participating organizations. Following the initial meetings, a subset of DSOs agreed to participate in the study and provide at least one interview, alongside follow-up questions with a knowledgeable representative. The participating DSOs varied in terms of size, geographical location and organizational structure, which was the intention given the study's interest in capturing multiple perspectives and perceptions in the heterogeneity of the Swedish electricity distribution system.

During the initial meeting, a subset of the participating DSOs had the possibility to provide descriptive data regarding 10 kV switchgear assets. The attribute that was possible to extract from every DSO was age. Attributes other than age varied considerably across organizations, reflecting differences in record keeping practices and data- accessibility and availability. As mentioned beforehand, where available, the descriptive data is used in this study to provide contextual background on an individual DSO and their asset population, rather than acting as analytical material used for answering the research questions.

4.3.2 Semi-structured interviews

The reason for using semi-structured interviews as the primary method of data collection was motivated by the nature of the research questions which requires access to knowledge, reasoning and perception from a DSO perspective. As Bryman (2016) argues, interviews are particularly well suited to research that aims to understand how individuals and organizations interpret as well as their experiences within a specific context. This is relevant in complex sociotechnical systems like the electric distribution system, where knowledge is often tacit and embedded in professional practices and culture, rather than formally documented. Bazen et al. (2021) argues that the inclusion of stakeholders within the system allows one to gain understanding of important nuances and details in underlying dynamics, which is not visible from an outside perspective. That argument is particularly fitting to systems where multiple parameters interact in ways that are not apparent to those outside the system.

Semi-structured interviews were chosen over structured interviews along with unstructured interviews for several reasons. A fully structured format would have increased the risk of missing nuanced and context-dependent insights which the research questions aim to capture. On the other hand, a completely unstructured approach would have made systematic cross comparison difficult regarding the DSOs perceptions and approaches. The semi-structured format offers a balance between formality and flexibility, ensuring that key themes are brought up but the DSOs have the freedom to express their perceptions and experiences (Bryman, 2016; Kakilla, 2011). This flexibility was considered important given the DSOs variability in terms of operational practices, data capabilities and organizational approach to maintenance.

An interview guide was developed prior to the interviews, consisting of a set of questions which were centered around the core themes of the study. These themes included the DSOs perception of maintenance strategies, long term vision, the role of asset attributes, indicators of condition and failure risk, factors affecting degradation and perceived relevance, risk and feasibility of risk-based approaches to asset management. These themes were designed to address how operator experience and asset characteristics shape maintenance reasoning, as well as to address DSOs perception and what differentiates from one another in terms of approach to data-driven methods.

Rather than following a strict sequence, the interview guide served as a framework to ensure thematic coverage across all interviews, while the order and amount of questions were allowed to vary depending on how each conversation developed. The interviews were deliberately opened with questions that encouraged the respondents to talk freely about their experience and perception of challenges, expectations and visions about their grid. For instance reflecting over a specific incident which surprised them or challenges of components that they are currently concerned about. This is an approach used to unlock tacit knowledge naturally before continuing with a more structured setting, ensuring that the interviews are more grounded in the experience and perception of the respondent rather than shaped by the researchers assumptions (Kakilla, 2021). The interviews were conducted with operations engineers, operation managers, grid managers and asset managers, reflecting the intention to capture the perspectives of those who are in contact with grid operations daily as well as those with a broader strategic responsibility. Table 1 presents the interviews conducted with representatives from the participating DSOs.

Table 1: Compilation of the interviews conducted with 7 respondents from 7 respective DSOs

Respondent	DSO	Role	Date	Duration
Respondent 1	Trelleborgs Energi	Operations Manager	2026-05-06	50 min
Respondent 2	Filipstad Energinät	Grid Manager	2026-05-08	80 min
Respondent 3	ESEM	Operations Planner	2026-05-11	60 min
Respondent 4	Mälarenergi	Operations Engineer	2026-05-12	50 min
Respondent 5	Göteborg Energi	Asset Expert	2026-05-18	55 min
Respondent 6	Sundsvall Elnät	Maintenance Engineer	2026-05-20	55 min
Respondent 7	Höganäs Energi	Operations and Maintenance Manager	2026-05-21	55 min

4.4 Empirical analysis

The analysis of the empirical material was guided by what Bryman (2016) refers to as an abductive reasoning approach, an interactive movement between the theoretical frameworks and the empirical material gathered throughout the interviews. The analytical process is thereby a continuous dialogue between what the literature discusses and what the interviews reveal, allowing the phenomenon to develop gradually throughout the process.

The primary analytical method applied to the qualitative data was thematic analysis, which offers a structured yet flexible method to identify, analyze and interpret patterns of meaning (Ahmed et al., 2025). The interview transcripts were first read all the way through so that the researchers could familiarize themselves with the content and get a good understanding of the material. Thereafter, an identification of the text with key themes took place, relevant sections were highlighted in regards to the research questions.

Given the multiple case study design, the thematic analysis could be conducted at two levels, individually and collectively. This allowed the study to identify similarities between the DSOs but also differences in attitudes, perceptions and organizational strategies and conditions. The analysis was conducted jointly by both researchers, an approach that strengthened the credibility of the findings according to Bryman (2016) as interpretations and emerging themes can be discussed and compared throughout the process. The process decreases the risk that the analysis is shaped by individual assumptions and ensures that it instead is grounded in the empirical data (Bryman, 2016).

4.5 Ethical consideration

The study involved engagement with employees within the Swedish electricity distribution network, and a number of considerations were taken into account throughout the research process. Following Bryman's (2016) four principles: information, consent, confidentiality and no harm to participants, an ethical approach was taken into each interview. Prior to each interview, the respondents were given the opportunity to be anonymous if they would prefer that. They were also informed about the study's purpose and were offered the possibility to withdraw from the interview and not participate in the study at any given time (Bryman, 2016). The respondents gave consent in terms of recording the interviews for transcription and analysis, something which they were explicitly asked before the interview began. If the respondent were to change their mind regarding something they had said or would like to retract any specific statement they had made, they were free to do so at any given point during the interview or afterwards.

4.6 Limitations

This study has multiple limitations and challenges which need to be addressed as they affect the research process and outcome. These limitations are divided into two categories depending on if they influence the design of the study or if they are methodological weaknesses in accordance with the chosen methodological strategy.

4.6.1 Study limitations

The participating DSOs were selected based on the availability and willingness to participate in the study, meaning that the participating DSOs were self-sampled. This outcome introduces the possibility that DSOs which declined participation may hold different opinions and perceptions than the participating ones, therefore caution should be taken into consideration when making broad conclusions across the Swedish distribution network. The limited availability of descriptive data from the DSOs represents another drawback, as only a subset of the participating DSOs were able to provide descriptive data on their 10 kV switchgear units.

4.6.2 Methodological limitations

The number of participating DSOs are appropriate for a multiple case study, however the findings can not be seen as statistically representative of the Swedish distribution system. As Yin (2018) emphasizes, the goal of a multiple case study is analytical rather than a representable statistical generalization of a system. The value of the study therefore lies in the depth of the insights and the analytical findings, rather than a large sample.

5. Findings

The following sections present the empirical findings from the participating DSOs which were derived from the semi-structured interviews. Each interview was conducted with a DSO representative, selected based on their operational experience and insight to maintenance and decision making. The DSOs vary considerably in terms of size, geographical location and organizational structure, which reflects the heterogeneous system of the Swedish distribution network. The findings are presented per DSO, capturing each respondent's perception, experience and reasoning regarding maintenance and data-driven and risk-based approaches.

Table 2: Participating DSOs, number of customers and their assumed size

DSO	Numbers of customers	Assumed DSO size
Trelleborgs Energi	18 000	Small
Filipstad Energinät	3 200	Small
ESEM	65 000	Medium
Mälarenergi	100 000	Large
Göteborg Energi	270 000	Large
Sundsvall Elnät	28 000	Medium
Höganäs Energi	16 000	Small

5.1 Trelleborgs Energi

Respondent 1 has worked at Trelleborgs Energi since 1998 and has served as head of operations for the past 12 years with an educational background in electricity distribution. Trelleborgs Energi has 18 000 customers, is located in proximity to water and the Swedish coastline, which means some assets require more attention because of diverse environments.

> “We have some stations in the harbour and they are affected by residue from the traffic, traffic exhaust and salt from the sea… in principle you need care of them every year” - Respondent 1

Rural stations however, face challenges with spider webs, moisture and dust which over time can create electrical faults. Although dust and humidity are factors that are also found regardless of location and are damaging to the asset over time. Cleaning surfaces of a component is thereby a recurring maintenance task across the network. Respondent 1 highlights that technology type is a strong determinant of maintenance need. For example, Trelleborg noticed problems with NGC models after 20 to 30 years of service in comparison to NAL and NALF models from a comparable production era, which respondent 1 argues is due to design quality and technology type.

Maintenance in the network is planned annually, with intervals differentiating depending on the equipment's environmental exposure and infrastructural criticality (e.g hospitals). A digital inspection system allows field technicians to record observations or defects and register that in the system. This generates action lists that enables the maintenance team to continually prioritise which assets require attention. The inspection driven approach means some assets are revisited annually while others have multiple years between visits, mainly decided by environmental challenges. Replacement of an asset is often planned in advance, however, in instances where the asset model type has proved to be dangerous to service personnel, that type is reactively replaced as soon as possible. Respondent 1 describes it as unacceptable to expose personnel to predictable risks and it is viewed as the most decisive factor in asset replacement or decision-making. He also identifies personnel resources as the most crucial aspect of maintenance planning and competence as the most significant long term challenge. Regarding data-driven systems he is cautiously optimistic, as he describes those systems as a support mechanism for less experienced staff and identifying problems with newer types of assets where industry experience is limited.

Figure 4 below, represents the age distribution of switchgear assets at Trelleborgs Energi. The installed assets were grouped into 4-year cycles and presented as a percentage of the total switchgear population at 10 kV. The figure was created using DSO-personal age descriptive data.

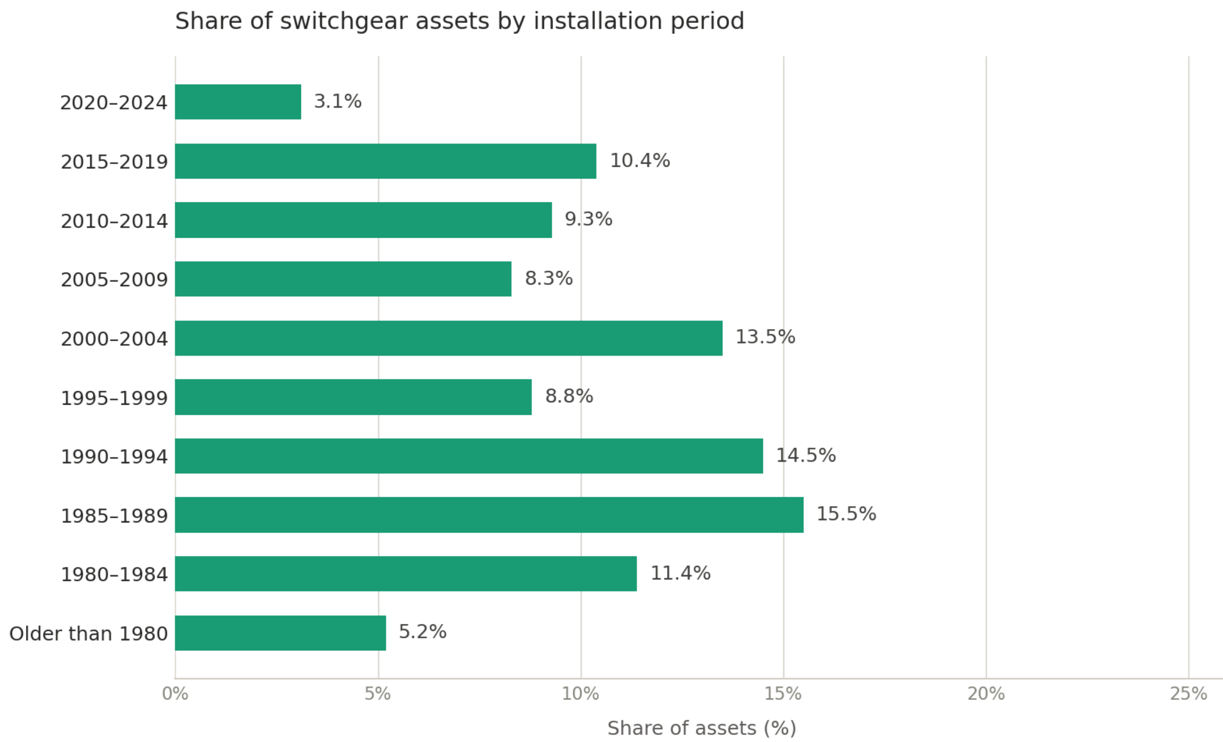

Figure 4: Distribution of installed 10 kV switchgear units by installation period

5.2 Filipstad Energinät

Respondent 2 serves as the responsible manager for Filipstad Energinät, serving approximately 3200 customers. He has a background as an electrical and telecommunications engineer and has held his current role for five years, following ten years in a similar position at a neighboring DSO. Respondent 2 emphasizes that the organization is too small to maintain in-house specialists for all types of assets in the grid and relies on external contractors for more technical tasks. He has also observed that older equipment tends to be more robust than newer installed equipment, which he attributes to manufacturing strategies that are cost-driven as well as manufacturing designs which are inferior today compared to older designs. Respondent 2 also identifies infrequent operating conditions as damaging since components of a switchgear unit can be a pathway to degradation. Circuit breakers in a switchgear unit that rarely switch the moving parts can become stiff and fail to function properly when needed, whereas an identical type of component in an active environment continues working properly as they operate regularly.

In some instances, maintenance prioritization within the organization occurs through internal discussion and with regard to technicians, regulatory obligations and customer cruciality, i.e. a significant institution such as a hospital might be prioritized ahead. Risk reasoning within the organization is mainly based on experience with influences from the amount of spare parts available, knowledge from colleagues in the industry and national industry organizations. Digital data infrastructure, specifically regarding maintenance, is limited at Filipstad Energinät, however respondent 2's ambition is to implement a system which can store and handle digital inspection and photographs.

"*The digitalization is not something that will benefit us now… rather it is for historic references and future knowledge*" - Respondent 2

The reasoning behind this is to enable historical referencing and asset condition updates over time. Respondent 2 emphasizes that digitalized systems like these are hard to implement as Filipstad is too small of an organization for the necessary financial investment, the system would only make sense economically for this type of organization, if multiple organizations came together and shared the cost. With this backdrop, he regards individual dependent knowledge as a significant organizational risk and sees digitalization as a mitigation strategy, while at the same time he recognizes that some practical experience is difficult to formalize and document.

5.3 Eskilstuna Energi och Miljö

Respondent 3 has worked with electrical distribution systems at Eskilstuna Energi och Miljö's (ESEM's) operations department since 1990, where she is responsible for maintenance planning and coordination and serves 65 000 customers. Respondent 3 brings up certain switchgear models which ESEM have had problems with, these switchgear units are of type NEBB and NGB which have historically caused operational issues. These older, open-framed switchgear types serve greater risk for maintenance personnel during a fault, which was the driving factor for replacement rather than outdated technology per se. She also mentioned that newer switchgear types have recently been the source for faults, which she attributes to insufficient quality control during manufacturing and a reduction in construction quality. Respondent 3 emphasizes that environmental context is important to take into consideration as assets near roads, industrial operations or agricultural areas require more frequent maintenance since dust and organic material accumulates into web-like material and eventually becomes so large that they may cause conditions prone to short circuits. ESEMs network also include some stations that are placed on soft ground made of lake-bottom sediment, in one instance a switchgear asset, located close to a lake, sank and caused a short circuit. The fact that stations sink by a bit is not uncommon in ESEMs network, however Respondent 3 points out that they are aware of this and they do not experience problems on a regular basis, hence maintenance is minimal in this aspect. ESEM has shifted their philosophy of maintenance in recent years by adopting a condition-driven aspect in addition to fixed time intervals, as the condition of an asset can adjust the interval of maintenance. Respondent 3 mentions that assets deteriorate through inactivity and ESEM therefore "exercise" or try out components during inspections.

"*A problem is that a component can be in the same position, and when they actually need to be maneuvered, they can't. Therefore we exercise components from time to time*" - Respondent 3

ESEM transitioned to a digital inspection documentation eight years ago which enables pattern recognition across the network. Risk and vulnerability analysis are also made to identify customer impact from asset failure, which is then a driving factor regarding investment decisions. She also mentions that the transition to predictive approaches have encountered obstacles in terms of organizational constraints, such as personnel and organizational resources, rather than the lack of technological tools. Respondent 3 however describes the ideal predictive maintenance system as one which is capable of specifying when a fault is likely to occur at an individual asset, although she recognises this is aspirational at the moment due to organizational and technical preconditions. From the beginning of 2026, six colleagues of Respondent 3 have retired and she describes this loss of knowledge embedded in these individuals are difficult to replace. She acknowledges that this might be a growing and acute risk to ESEM as multiple colleagues are headed for retirement in the near future.

Figure 5 represents the age distribution of switchgear assets at Eskilstuna Energi and Miljö. The installed assets were grouped into 4-year cycles and presented as a percentage of the total switchgear population. The figure was created using DSO-personal age descriptive data.

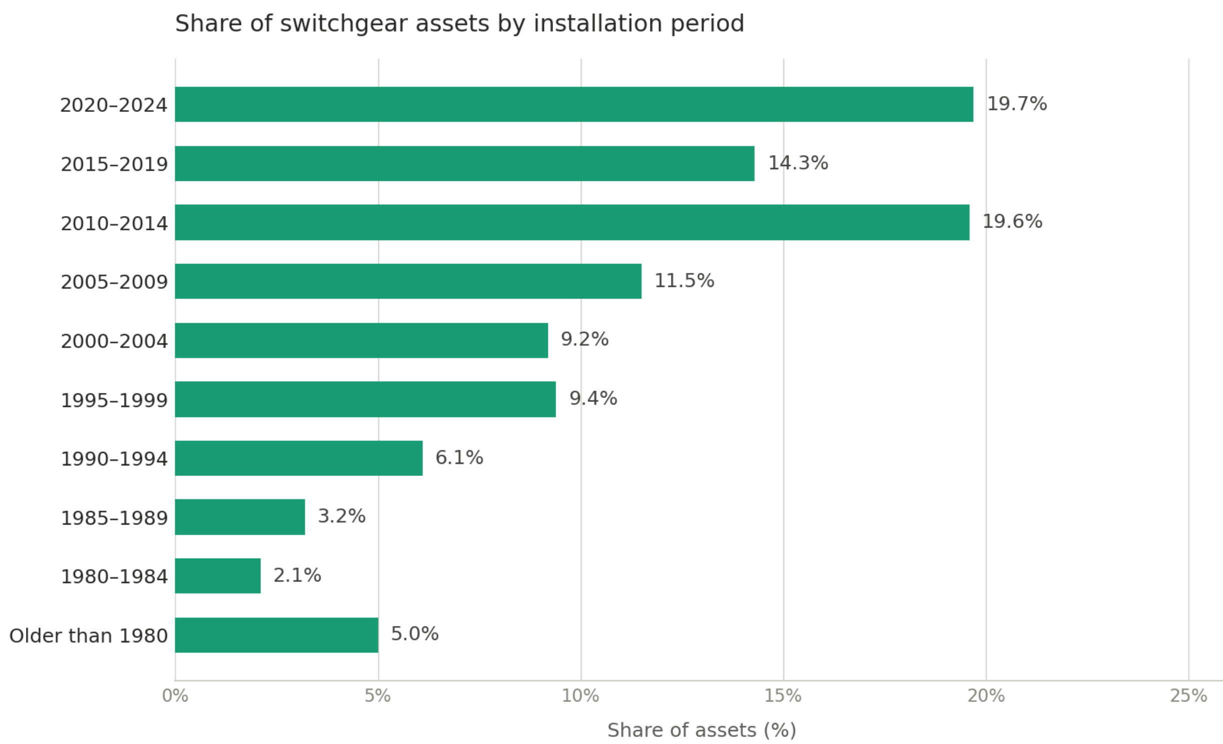

Figure 5: Distribution of installed 10 kV switchgear units by installation period

5.4 Mälarenergi

Respondent 4 works as an operational engineer at Mälarenergi, which serves just over 100 000 customers. He has a technical background in manufacturing at ABB before starting his tenure at Mälarenergi, bringing also a manufacturer's perspective to equipment behavior. Respondent 4 states that asset age is the most central aspect regarding challenges to the assets population that Mälarenergi operates. Further, He mentions that in recent years they have experienced problems with NGC switchgear models. Respondent 4 also emphasizes that a majority of problems are caused by long periods of time where components are static, as lubricants and mechanical components stiffen over time. Older equipment design and quality are also superior compared to contemporary equivalents according to Respondent 4. According to Respondent 4, he is opposing the common concept of maintenance free contemporary equipment, as it is rarely maintenance free in practice. Another aspect which Respondent 4 points out is that assets that are installed in poor environments show greater visible deterioration than equivalents of comparable age that are installed in well insulated surroundings. Respondent 4 recalls a station placed in the vicinity of an industrial facility where the asset showed visible accelerated conditioning breakdown due to the dust and by-products emitted from the surrounding industrial operation. Although only the exterior was harmed, if the asset is not maintained more frequently, the interior will eventually be affected negatively as well. Respondent 4 noted that this occurred at this previous job which was at another location than where Mälarenergi operates.

Maintenance is primarily carried out over a 5 year cycle by Mälarenergi's own personnel with regards to switchgears. These intervals can be adjusted if the technician notices something during an inspection or a manufacturer gives notice of troubled components. Replacement prioritization follows a list which takes personnel safety as its most important factor. Mälarenergi also uses data-driven tools so technicians can access assets' individual service history, introducing a dimension of historical conditioning data. Respondent 4 emphasizes that the larger data-driven landscape at Mälarenergi is fragmented and relevant data for assets are across multiple systems and documents. The organization is actively exploring for a solution of a data lake which can consolidate this information and frame it in a way which is necessary for precondition and reducing the reliance on age and individual judgement. A quote from Respondent 4 is:

"*I would like to consolidate all information into a single system… with risk classifications and color coding it would be much easier prioritize the right maintenance efforts*" - Respondent 4

Respondent 4 highlights that the relationship between data-driven approaches and expert knowledge are complements to each other rather than substitutes. Individual knowledge plays a central role at Mälarenergi and although the organization has been partially successful, judgement about which assets needs more frequent attention as well as adjusting intervals rely heavily on accumulated knowledge of experienced individuals. Respondent 4 acknowledges that this gap in "know-how" knowledge will become visible in the near future. In order to tackle this challenge, Respondent 4 is positive about the idea of sharing data between DSOs as they do not compete with each other and collective data could benefit the sector, particularly in preserving expertise which is largely organizationally bound. If an experienced operator at one DSO gains insight about a component or issue, that knowledge should not be lost when they retire and another DSO should not have to relive that same issue. He mentioned that a shared national inventory for spare parts could be a great first step to this collaboration which would reduce delivery time risk across the sector while helping out in crisis situations.

5.5 Göteborg Energi

The respondent from Göteborg Energi has worked in the organization for more than 20 years and has a degree in power electrical engineering. The respondent also holds a position which requires strong knowledge of operations, maintenance and asset management within the organization which has over 270 000 customers. Based on the respondents expertise, age and operational issues are the two primary factors regarding replacement decisions of switchgear units. Additionally, newer generations of switchgear assets are more precisely designed than older generations due to modern tools and the need for more precise capabilities, meaning they are dimensioned more accurately based on their purpose. Maintenance at Göteborg Energi is mainly based on fixed four year intervals that are derived from sectoral recommendations, however these are continuously adjusted based on field observations. Environmental context and placement of assets is not considered a large issue at Göteborg Energi as virtually all switchgear units are installed in a well insulated indoor environment, providing protection against environmental factors such as saltwater. The respondent mentions how consequence of asset failure is an explicit prioritization factor in the organization, as high consuming customers, primarily industrial customers, are prioritized. The respondent emphasizes that this is a regulatory requirement as they are mandated to restore power restoration faster for high power demanding customers (e.g industries).

Regarding the digital infrastructure, Göteborg Energi has challenges with data quality, which is described by the respondent as being the primary weakness with keeping competent personnel as the second. Test protocols and component attributes are well managed, but field observations and maintenance records are poorly captured. On occasion, field personnel enter data into a digital tool but entries can be uninformative and some technicians insist on using pen and paper instead of digital tools.

"*The biggest challenge is not technical, rather it is about changing ways of working… there is a challenge to get them* (field technicians) *to understand why writing down details matter*" - Respondent 5

The respondent attributes this to cultural rather than technical barriers as field technicians have not effectively been shown why structured data entry matters for strategic and maintenance work. A condition assessment scale exists internally in the organization but lacks clear instructions on the scoring instructions, enabling personal interpretations and thereafter inconsistent entries. An ideal support system according to the respondent would collect data from observations while analyzing costs and failure causes at a component level as it would enable pattern recognition across manufacturers and models. The respondent expressed slight hesitation regarding data sharing between DSOs as the respondent has personal previous experience from similar data-sharing projects between multiple DSOs, where the project stalled because no party would fund the required system. Large DSOs such as Vattenfall, Ellevio and E.ON also possess the majority of asset data needed for more precise analysis but have the least incentive to share it, creating a structural asymmetry as the central barrier. The respondent opposes regulatory mandates as a solution as it would be too burdensome for smaller DSOs, arguing that simplicity of participation (e.g. simplifying data-sharing) is a more effective strategy.

5.6 Sundsvall Elnät

Respondent 6 is a maintenance engineer at Sundsvall Elnät, where he has worked for four years and holds a degree in electrical engineering. Sundsvall Elnät serves 28 000 customers within a primarily compact urban network. Problems regarding switchgear assets are mostly regarding mechanical faults with components such as stiffness and disconnectors not closing correctly. These issues are not considered immediate but create limitations in operability and can cause personnel safety and pose a failure risk over time. Respondent 6 also points out that stations that are situated close to quarries are exposed to heavy dust accumulation, which can lead to problems if they are not cleaned regularly. Another aspect is also moisture which Respondent 6 expects to become more pronounced over time as transformer loading decreases and insufficient heat generation creates conditions for condensation, especially in colder more moisture prone regions such as Sundsvall.

The organization's maintenance strategy is built around a fifteen year revision cycle covering all network stations. Revisions include cleaning, lubrication, functional checks and contact surface treatment. Inspections are made in order to decide prioritization order regarding replacing units, typically within a three to five year action plan. Respondent 6 emphasizes that personnel safety is the most important aspect, weighed clearly ahead of functional reliability. In the event of critical safety concerns, it is dealt with as quickly as possible and directly handled by the operations manager. External factors such as municipal roads and other utility projects can also cause early replacement of units as it reduces overall project costs compared to conducting a replacement-specific project. Respondent 6 also identifies three problems with the data infrastructure such as poor data quality in the current maintenance system, inspection data being stored at a station level instead of a component level making component analysis difficult and the total data volume being too small for a statistical conclusion at an organizational scale. Inspections are currently conducted to identify and report acute failures or reparation needs instead of generating analytical data, an aspect Respondent 6 highlights as extremely important if the organization wants to evolve and implement data, risk and condition driven approaches. However, a new operational system is being implemented in collaboration with other DSOs, with the possibility of potentially enabling real time monitoring of components but the consequences and the extent of this collaboration is yet unclear according to Respondent 6.

Respondent 6 is positive towards data-driven approaches but highlights that structural barriers hinders Sundsvall Elnät at the moment. The organization lacks sufficient data so inter-DSO data sharing is a prerequisite if the organization is to adopt more technologically advanced approaches. Respondent 6 references CNAIM as an example of what type of technology he would like to move towards but highlights that the organization needs more data points to implement such methods accurately. He argues that increasingly specified inspection protocols and standards of what is necessary to inspect as well as how to weigh those results is important.

In order to move towards more risk-based approaches, Respondent 6 explains that data sharing across DSOs are necessary for their organization, and in order to do so every DSO has to have a data pool which is similar. Sundsvall Elnät is part of a cooperative regional association which exchanges knowledge and experience, but does not share systematic data in large extents. Further, he sees potential of moving towards a data-driven format in the future, although he considers a broader national cooperation being necessary rather than just a regional one which they are a part of now.

Figure 6 represents the age distribution of switchgear assets at Eskilstuna Energi and Miljö. The installed assets were grouped into 4-year cycles and presented as a percentage of the total switchgear population. The figure was created using DSO-personal age descriptive data.

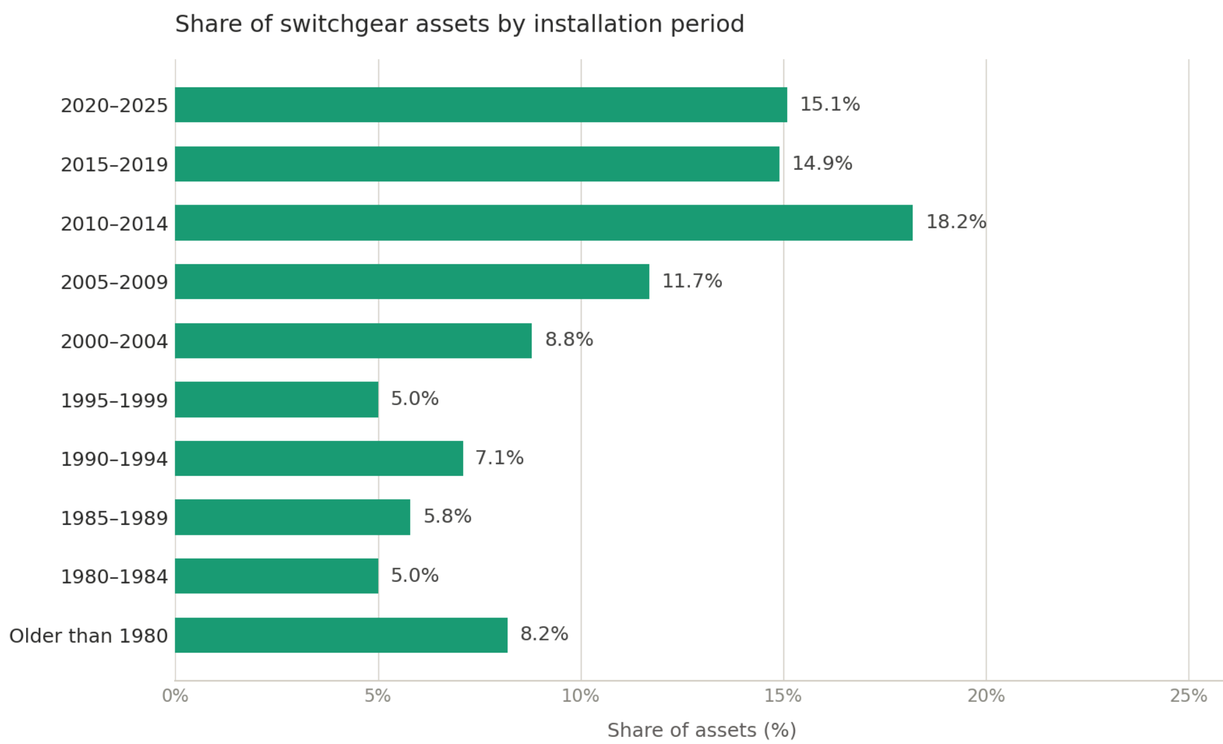

Figure 6: Distribution of installed 10 kV switchgear units by installation period

5.7 Höganäs Energi

Respondent 7 is responsible for operations and maintenance at Höganäs Energi, where he has worked for 38 years and held this current position for 16 years. The organization serves around 16 000 people and has customers across both urban areas as well as rural settings. All switchgear assets at 10 kV are housed in indoor installations, limiting environmental exposure. Rural stations can accumulate dust, dirt and form spider-like formations occasionally, but are cleaned on a regular yearly basis before issues arise. The most common problems involve insulation faults, burn marks and mechanical issues with components which require regular "exercise". Respondent 7 also emphasizes a major difference regarding construction techniques and specific types. The oldest assets are largely problem free and robust, while other types such as NGC and NGB types are actively replaced due to construction weakness. Höganäs Energi plans to replace all NGC and NGB units during 2026 and 2027. This decision was taken within the organization and based on experience and knowledge rather than external guidance, though later it was confirmed by other DSOs that they also experienced problems with those switchgear types. Replacement strategy in the organization is primarily driven by personnel safety concerns, with budget and regulatory requirements serving as additional factors which are taken into consideration.

Maintenance at Höganäs operates on two levels, annual visual inspections and a detailed revision every 6-8 years, during which the components are "exercised", lubricated and functionally tested. The interval is determined by equipment type and mechanism rather than age alone, however age and condition also modify how often an asset is reviewed. Prioritization of assets are made through discussions among colleagues following inspections and what was noticed in parallel to regulatory requirements. There are no data-driven support tools which measure condition or risk, assessments are purely based on experience and collective judgement. Respondent 7 explains that the consequence of failure and probability of failure are considered when assessing prioritization decisions. He also discusses how they internally weigh the impact of an assets failure and the disruption this causes in the electrical grid. Respondent 7 acknowledges that advanced risk tools would be beneficial for many organizations, however as Höganäs possess a great deal of experience and knowledge in the organization, combined with a relatively small network, the need for data-driven risk tools is not as obvious as in large organizations with higher personnel turnover according to Respondent 7.

Höganäs has limited monitoring systems for switchgear assets at a 10 kV level, Respondent 7 argues that in person inspection for older components is the most capable form of method as smell, sound and tactical assessment is most necessary. Newer compact assets are better suited to automated monitoring as direct physical inspection is not possible to the same extent given the mechanical composition of newer assets. Respondent 7 also regards the sector's move towards more data-driven maintenance as inevitable, although smaller DSOs with high experience levels will install these approaches slower than larger ones. Respondent 7 identifies at the same time the organization's largest future challenge, competence and knowledge immersed at an individual level. Höganäs Energi is developing structured protocols and methodological descriptions to capture and retain knowledge, but Respondent 7 is clear that documentation can not substitute practical field experience:

"*But out in the field you need to be there to see, to feel, to pull on things… which is not something data-driven can replace*" - Respondent 7

Regarding digitalization he identifies both opportunities and risks, a comprehensive system that can preserve documentation and the collection of experience would help organizational memory over time. However, he also expressed how system knowledge can become concentrated, rather than it being distributed across the organization. Respondent 7 describes it as essential to coordinate efforts with system operators and on-field operators so that knowledge spreads evenly across the organization and between different types of employees.

Figure 7 represents the age distribution of switchgear assets at Eskilstuna Energi and Miljö. The installed assets were grouped into 4-year cycles and presented as a percentage of the total switchgear population. The figure was created using DSO-personal age descriptive data.

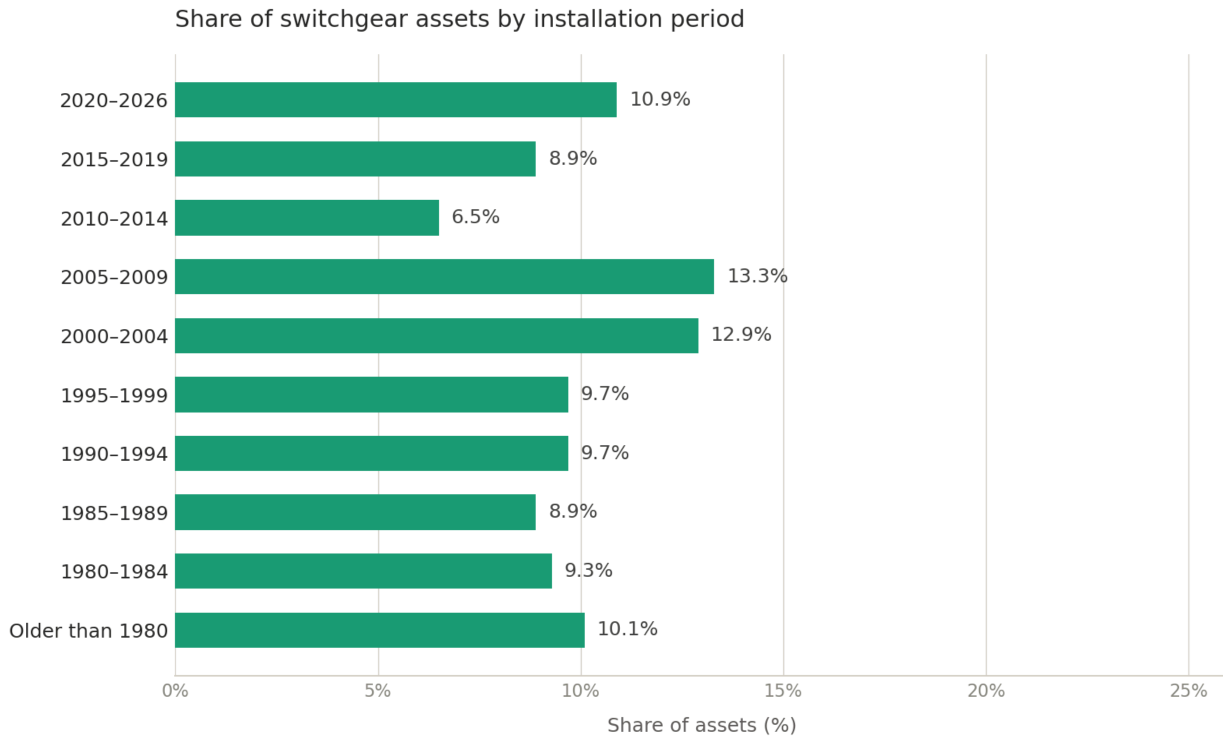

Figure 7: Distribution of installed 10 kV switchgear units by installation period

5.8 Cross case findings

Several themes were raised independently across the participating DSOs. The physical environment was described as a relevant contributor to maintenance for 6 out of 7 DSOs where dust, humidity, spider webs and proximity to roads, industrial facilities and quarries were prominent, something that resulted in additional maintenance. The exception being Göteborg Energi as the DSO has all of its switchgear assets installed in well-insulated indoor environments. Respondent 2, 3 and 4 specifically note that inactivity damages components that are rarely operated which leads to stiffness and eventually failure. ESEM addresses this by deliberately "exercising" components during inspections.

Risk reasoning grounded in PoF and CoF is present across all seven DSOs, most commonly by weighing it informally when prioritizing maintenance and decision-making. One example is Göteborg Energi who conducts risk-reasoning by prioritizing high demand industrial customers based on CoF. Personnel safety is described as a primary factor across most DSOs in regard to risk management and CoF. The loss of experienced personnel is identified and raised as a risk for the DSOs, with ESEM and Höganäs explicitly identifying it as their most acute long-term organizational challenge. All seven DSOs share the perception that the sector is moving towards more data-driven and risk-based maintenance while relating to it positively. Several respondents noted that a considerable share of knowledge sharing occurs informally between colleagues, raising the concern that critical information is sometimes lost or goes unnoticed. Respondent 7 regards the development towards data-driven approaches as inevitable, although he argues it will happen slower for smaller DSOs who are reliant on individual experience. Sundsvall sees future potential in more data-driven formats and ESEM describes an ideal data-driven system as a desirable aspiration. Respondents consistently emphasize that this development will happen gradually and that it will inherit a more complementary role to practical experience. They also underline that such an approach and development will be expressed differently depending on each organization's perspective and precondition.

The organizations differ in their data infrastructure and their keenness on data sharing. The smaller organizations. For Filipstad and Höganäs who have limited data volume and personnel resources, digitalizing maintenance data is an obstacle that will require time and dedicated resources. At Filipstad it is described that it could be feasible but is dependent on cost sharing. Respondent 4 from Mälarenergi raises data sharing across DSOs and a shared national spare parts inventory as an ambition and desire. Sundsvall identifies inter-DSO data sharing as a precondition for progress in terms of risk-based approaches, but argues also for a national cooperation of data sharing. The interviewee from Göteborg Energi expresses slight concern towards data sharing based on prior experience from a project which stalled regarding data sharing, arguing that the central barrier to this is structural asymmetry in which the largest DSOs hold a clear majority of data but have the least incentive to share it.

Table 3: Compilation of recurring themes during the interviews with corresponding observations and occurrence in the empirical material

Theme	Summary observations	Occurrence
Current Maintenance Practices	Maintenance is described as time-based, with condition-based inspections influencing how maintenance operations are performed	7 out of 7 DSOs
Risk Perceptions and Decision-Making	Risk consideration is incorporated in maintenance operations	7 out of 7 DSOs
Data Quality and Decision Support	Data quality and fragmentation were described as limitations for adopting data-driven approaches	5 out of 7 DSOs (Except Trelleborg and ESEM)
Asset Age and Degradation Perspectives	DSOs consider asset age a main indicator of degradation, although age alone is an insufficient tool for evaluating asset condition	7 out of 7 DSOs
Perceived causes of asset failure	Mechanical or technological faults were described as the most occurring causes for asset failure or maintenance needs	7 out of 7 DSOs
Environmental Influences and Local Conditions	Local factors (e.g humidity, salt and proximity to heavy industries) were described as relevant contributors to maintenance needs and asset degradation	6 out of 7 DSOs (Except Göteborg Energi)
Operator Experience and Individual Knowledge	Experience-based knowledge was described as central in maintenance-related decision-making, creating organizational challenges	7 out of 7 DSOs
Perspectives on Predictive and Risk-Based Approaches	Interest in and risk-based and digitalized approaches was expressed, although challenges were highlighted	7 out of 7 DSOs

6. Analysis and Conclusions

The following chapter discusses the empirical findings in relation to the theoretical framework and the study's context. By relating the findings to the theoretical concepts, the chapter is meant to interpret and reflect upon the findings while providing the reader with broader perspectives, commonalities and distinctions between Swedish DSOs.

6.1 Experience-based reasoning

A pattern that is recurring between all participating DSOs is that maintenance prioritization is driven by experience-based judgement rather than a formal risk quantification. Decisions regarding which assets are most critical to inspect, when it is time to intervene and how to allocate resources when limitations occur are strongly based on tacit knowledge which has been accumulated by individuals through years of experience, often by the process of "learn by doing". Although a technological risk assessment tool or methodology is absent in most cases, risk reasoning is not, as it is embedded in individuals. However, the lack of stricter regulatory requirements and methodologies regarding how risk-based approaches are conducted for maintenance and decision-making amplify the reliance on tacit knowledge and DSO-specific working methods. Individual-based risk reasoning therefore results in risk reasoning being expressed differently by DSOs in practice, with the outcome being a large variation in the level of data and digitalization used in risk approaches in regard to maintenance and decision-making. This underlying logic mirrors the conceptual core of RBM which is argued by Khan and Haddara (2003) while also taking PoF and CoF into consideration. This is clearly understood in the conversation with respondent 7 at Höganäs Energi, who explicitly states that PoF and CoF are informally considered when decisions are made regarding maintenance. A similar type of logic is described by Respondent 2 at Filipstad Energinät where maintenance prioritization is determined by internal discussions among colleagues which are shaped by the assessment of technical observations, regulations and the criticality of the consumer (e.g hospitals).

This pattern across DSOs is consistent with what Nonaka (1994) describes as tacit knowledge, practical, experience-based understanding that individuals or groups possess. The most common type of knowledge transfer is socialization, which can be observed across the participating DSOs as the transmission of tacit knowledge occurs through shared experience, observation and interaction rather than clearly defined documentation. Prioritization decisions are discussed among colleagues, which is largely based on inspections where field technicians give their assessment of which assets require attention. In addition to this, informal industry networks exist which allows organizations to compare observations and enables knowledge circulation. Using the concepts of Nonaka (1994), this knowledge transfer occurs through socialization rather than externalization.

The reliance on knowledge through socialization is a challenge that all participating DSOs identify as the most significant long term challenge in their organization, not only in relation to maintenance and decision-making but in general. These observations are consistent with Alavi and Leidner's (2001) argument that organizations may suffer meaningful setbacks as knowledge transfer is hard to retain when personnel leave, yet is vital for the organization. One example is Höganäs Energi who have begun developing more structured protocols and methodological descriptions to try retaining operational knowledge within their organization. This reflects a deliberate effort to try and initiate the process of articulating tacit knowledge into explicit and communicable forms, known as the process of externalization.

Collectively, these findings point to a core tension that is noticeable and can be identified in the analysis. The tacit knowledge across the participating DSOs represents a maintenance challenge as well as an organizational resource. This challenge is the strongest argument for moving towards more data-driven risk approaches as it could help externalize and preserve experience embedded in the organization. On one hand, externalizing knowledge appears to be something all DSOs consider beneficial. On the other hand, respondent 7 is more withdrawn and problematizes the process, similarly to Nonaka (1994), while arguing that data-driven and risk-based approaches should be used as aid as tacit knowledge is not always transferable. This illustrates that DSOs in Sweden do not necessarily choose or need to choose between contrasting approaches, but that sometimes a combination of the two is preferred and viewed as beneficial.

6.2 Asset heterogeneity and limits of age-based maintenance

TBM structured around the age of an asset is still the most dominant operational strategy across the participating DSOs. The empirical material however emphasizes that several factors actually determine when equipment deteriorates or fails. Age is described as a contributing factor across DSOs, although serving as an insufficient basis for maintenance prioritization by itself. Age is an indicator of risk rather than a direct measure of it, as it correlates to failure. Insulation type, asset model and environmental exposure are some examples of why assets can deteriorate independently of age. The DSOs asset population also varies in terms of installation period, which can be visualized in Figure 4, 5, 6 and 7 but as mentioned, the empirical material does not suggest a proportional relationship between age and asset failures or maintenance. The described heterogeneity in these networks is not accidental, rather it reflects that DSOs historically have made their purchasing decisions independent of each other. The result is a considerably varied distribution of installed assets which TBM intervals do not fully take into consideration. This is in line with how DSOs function today, as many have moved away from strict TBM and instead incorporate condition-based inspections to further complement and strengthen maintenance practices. Across the participating DSOs there is an interest for more risk-based approaches as they see the sector become more digitalized and condition driven.

Respondents across the seven DSOs identify manufacturer type and asset technology as a strong contributor in regard to maintenance and decision-making. Respondent 1 from Trelleborg Energi attributes the problems of NGC switchgear models, in comparison to NAL and NALF assets made in the same era, to design quality rather than age. Interviewees from Mälarenergi and Höganäs reach the same conclusion independently from their own operational experience, hence Höganäs has decided to replace all NGC and NGB assets until 2027. In addition, critical knowledge regarding assets is often circulated through conferences, personal contacts or intermediary organizations rather than registered in public systems or databases, as described by several DSOs. Simultaneously, many respondents expressed that much of the knowledge exchange which occurs in informal situations results in critical information going unnoticed. One possibility for tackling the issue of informal knowledge exchange is to introduce mechanisms which facilitate formal information sharing instead, either on an organizational or regulatory level. Swedish DSOs are already obliged to submit a substantial amount of information to regulatory bodies such as Energimarknadsinspektionen. Including further reporting which includes relevant asset information could potentially reduce the risk of critical information going unnoticed and increase transparency, further aiding in DSOs maintenance and decision-making.

Several respondents independently describe how inactivity, environmental exposure and operational intensity affect the assets degradation in ways that time based intervals can not capture. Circuit breakers that rarely switch can stiffen and fail to function when needed, a pattern mentioned by Filipstad, Mälarenergi and ESEM. Environmental context introduces variation, as the interviewee from Mälarenergi recalls a station placed in the vicinity of a heavy industry, which deteriorated faster due to dust and industrial byproducts. The respondent from Trelleborg on the other hand identified saltwater and harbour traffic exhaust as significant factors showcasing that these environmental stressors depend on the DSOs geographical location. This is consistent with Wang's (2002) argumentation that deterioration in complex systems is partly stochastic and shaped by a combination of operating conditions, environment, age and usage, making TBM insufficient on its own. The broader point is that DSOs already reason along these dimensions in their practice, adjusting their maintenance prioritization based on factors they know influence their assets, without a formalized data-driven model to support that reasoning.

The empirical findings suggest that the distinction between DSOs current maintenance practices and data-driven, risk-based methodologies is not in their analytical logic, rather in its formalization. The participating DSOs take many of the parameters incorporated in RBM methods such as CNAIM into consideration when conducting maintenance and decision-making, e.g. asset condition, environmental exposure, failure consequences and model type. The core difference therefore resides in how methodologies such as CNAIM offer a transferable and systematic approach compared to relying excessively on individual experience. In short, risk-based foundations are present at these organizations, they are simply not implemented methodologically.

6.3 Data preconditions and barriers to risk-based approaches

The previous two sections cover the conceptual logic of RBM and the presence that it has in DSO practice as well as the asset population operated by Swedish DSOs are heterogeneous enough so a formalized methodology would be analytically valuable. This section however analyzes whether organizational and data preconditions are available and if the possibility for such approaches actually exists at DSOs. The evidence suggests that this is not the case for every DSO which participated in the study. The reasons for this are rooted in the structural features in the Swedish distribution context and something that most DSOs can not overcome individually.

The most fundamental aspects for any RBM model are reliable, condition-based asset data, environment and operational parameters. A methodology such as CNAIM for example, requires a structured set of observed and measured inputs e.g location factors and reliability modifiers to calculate its PoF value, which requires a systematic data collection across a DSOs asset population (Ofgem, 2021). The respondent from Göteborg Energi describes the data quality as their primary weakness regarding the organization's current approach. While inspection protocols are relatively advanced, field observations and documentation about maintenance are poorly captured as there is discrepancy between what the operational personnel wish to have and what the field technicians report. As some field technicians continue to report observations on paper, which in some instances are not logged into the existing digital system, there is a continuous gap between how work is conducted and how it is documented. The respondent refers to this as a cultural barrier and not because of a lack of digital tools as field technicians are not aware of the importance of structured data entries in order for strategic and planning work. This is an important distinction as the obstacles are organizational and behavior related, rather than the lack of digital tools, therefore limiting the evolution into a more data-driven and risk-based system. The data that Göteborg Energi manages to document is also often fragmented, further hindering their ability to conduct work in a more data-driven manner.

Respondent 4 at Mälarenergi also describes a similar problem, as their data is fragmented and scattered across multiple systems and documents as well. The absence of a single and aggregated system makes it difficult for them to consolidate data in an informative way. Because of this restraint, a wish is to create a data lake which consolidates the data, has a perception of risk classifications and color coded visuals which can help the organization move toward a system that is less dependent on individual judgement. However, Respondent 4 describes that a data-driven system cannot replace expert knowledge, rather be complementary and potentially mitigate the organizational “know-how” that can be lost when a colleagues retire or transfer to other organizations. This description is further shared by all DSOs, who see RBM as a tool which can facilitate rather than replace operational work.

Sundsvall Elnät presents a similar trend regarding their organization and what can be deduced is that DSOs which are large enough and therefore have begun collecting more data often identify issues with the quality, systematization and volume of their data sets. The DSOs journey towards RBM highlights that inter-DSO data sharing becomes increasingly important for many organizations rather than a desirable ambition. Respondent 6 from Sundsvall explicitly references CNAIM as an example of a RBM methodology that he would like to work towards, but argues that the organization currently lacks the data volume, quality and systematization to utilize the model properly. Current maintenance work is, according to all DSOs, more focused on reporting failures for regulatory requirements rather than for the sake of generating analytical data. This is due to the fact there has not been a need of generating analytical data needed for more predictive and data-driven approaches. Hence inspection and maintenance activity itself needs to be reframed in order to gather the necessary information for a predictive and systematic data-framework like CBRM or CNAIM.

Another aspect which influences this is the size of the DSO. Respondent 7 at Höganäs Energi argues that advanced risk tools are more necessary for larger organizations with higher personnel turnover and larger networks. For networks of similar size and experience level as Höganäs, respondent 7 argues that the value of an advanced data-driven and risk-based system is less compelling. Respondent 2 at Filipstad reaches the same type of conclusion, with the addition that their organization is too small to justify financial investment into a system that would only be feasible if multiple DSOs shared the financial burden and thereafter the benefits. These arguments are not because smaller organizations lack ambition or proper incentive but rather a rational assessment of organizational context and the fact that different organizations operate under circumstances where RBM might be deemed unworthy to implement. This pattern is deduced when identifying how different DSOs relate to the adoption of risk-based frameworks and by analyzing how they work with data. Smaller DSOs appear to conduct and collect less data, mainly because they do not have use of it, unlike larger DSOs. A system consisting of 500 assets is unlikely to require the same level of digitalized reviewing and decision support as a system comprising 5 000 assets, mainly since maintaining an acceptable understanding of the entire asset population becomes increasingly difficult at larger scale. As organizations and their asset population grow, so do the negative effects of knowledge erosion which ultimately result in a stronger need for data-driven approaches in order to prevent said effects. With that being said, these DSOs are not strictly against the implementation of such frameworks or working methods. On the contrary, several DSOs express interest and pros with digitalization and view more data driven approaches as beneficial. This raises the question of how such frameworks should be implemented realistically in order to fit each DSO, something that ultimately has to be decided based on the respective DSO and the challenges which it faces.

The previous discussion focused on organizational prerequisites but respondents also emphasized sectoral challenges. The respondent from Göteborg Energi highlights the asymmetry which many respondents describe as one of the most prominent challenges towards implementing RBM approaches. The larger DSOs such as E.ON, Ellevio and Vattenfall hold most of the asset data needed for more precise analysis and RBM adoption, but they also likely possess the least incentive to share it. These DSOs have enough internal data to implement such approaches and sharing it mainly results in increased workload and costs without clear benefit. The DSOs that are most in need of a shared data pool can therefore not create it independently as they lack the resources to do so. This type of disproportion is not something new as the respondent from Göteborg Energi references a previous project she took part in regarding data-sharing between DSOs that eventually stalled because no party would fund the required system infrastructure. Without clear incentives, participating in a large collaborative initiative with smaller DSOs is likely not considered worthwhile by larger DSOs.

The interviewee from Göteborg Energi opposes a regulatory mandate as a solution for this, arguing that it would put even more pressure and a disproportionate burden on smaller DSOs with limited resources. Respondent 6 from Sundsvall would instead like to see a broader national cooperation rather than just regional coordination which is common for a few DSOs at the moment. The respondent is uncertain how regulation would affect the sector in a positive way despite such efforts having worked in GB. Jamasb and Pollitt (2000) argues that an effective benchmarking and comparison between DSOs requires harmonized datasets and a structured reporting structure. This was feasible in GB due to the small number of existing stakeholders in their electrical distribution network. In Sweden there are approximately 170 DSOs at vastly different scales, different structures as well as data practices, making it an entirely different starting point. CNAIM as a RBM methodology was developed within a setting where the parameters and vision of the framework could be coordinated among few stakeholders. Similar conditions do not exist across all DSOs in Sweden, some are closer to being able to implement similar principles and some are hindered technically or organizationally. Tackling this issue therefore likely requires different approaches than the ones previously used in GB.

6.4 An assessment of RBM suitability in a Swedish context

The logic of RBM is already established and present at DSOs, mainly as tacit knowledge and formalizing this logic would be beneficial in order to manage a heterogeneous asset population. However, not all organizations currently have the possibility to fully formalize this approach. This final section therefore synthesises the previous discussion and addresses the overall question of whether data-driven and risk-based approaches, such as CNAIM, are suitable for Swedish DSOs and what a realistic path toward greater suitability would be.

Firstly, CNAIM appears aligned with most challenges which Swedish electricity infrastructure are facing today, while the methodology also is designed to address the issues lifted in the empirical material. The necessary parameters which are utilized for analysis in RBM or in frameworks such as CNAIM are also in line with those which DSOs identify as important in asset management and decision making. In different ways, all participating DSOs addressed these parameters as relevant for maintenance prioritization and decision-making. The analytical logic is not something that is new to Swedish DSOs, it is already present but embedded in tacit knowledge and individual experience. Implementing more data-driven and risk-based approaches to complement or partially replace this logic is therefore relevant and in line with how Swedish DSOs want to evolve.

Secondly, although the conceptual suitability of RBM is clear, that does not mean it automatically can be transferred into practical applicability. Chemweno et al. (2018) emphasizes that risk assessment is context driven and its application requires adaptation to the specific context of which it will be used in. Jennrich and Lund also (2021) support this argument when referencing RBM such as CNAIM, as it also needs to consider local network conditions. The CNAIM methodology is constructed in a setting where few DSOs are stakeholders and an organized effort of regulatory requirements and incentive was used in order to create a harmonized methodology. Sweden's fragmented networks with many small size DSOs and limited data infrastructure are not necessarily in a great position to implement the model across every DSO. RBM is easier to implement where DSOs already possess a strong foundation seen from a data perspective and DSO size. Enforcing RBM at an organization which does not possess the necessary basis is likely not supported economically. Those organizations would benefit from digitalizing and collecting data incrementally, at a slower pace, as it would facilitate the incorporation of more advanced maintenance techniques in the future, such as CNAIM.

The third aspect is that the barrier to implementing RBM is not necessarily motivation or that DSOs do not see the value of such practices. On the contrary, Swedish DSOs are positive towards risk-based systematic approaches as they could help their organization with maintenance and decision-making. Respondent 6 at Sundsvall gives a clear example of this by expressing that he would like to move towards CNAIM but they lack the data points at the moment of which the methodology requires. Respondent 3 at ESEM also highlights the same type of excitement when discussing a future risk-based system which could better identify when a fault could occur by quantifying the risk. For smaller DSOs such as Filipstad and Höganäs, the hesitation is grounded in organizational limits as data volume and quality are insufficient, personnel resources are limited and the value versus cost is often deemed too great for the organization. For larger DSOs on the other hand, such as Göteborg Energi and Mälarenergi, the main obstacles are data fragmentation and data quality which has to be addressed first. These DSOs are much better prepared to implement RBM or frameworks such as CNAIM.

The fourth and final observation is the trajectory of predictive maintenance approaches which is based on the empirical material. Instead of relying on employee expertise and fixed maintenance intervals, several DSOs are beginning to utilize condition based methods and collect data which guides the decisions. ESEM is a good example of this as they have implemented a digital inspection system which allows them to manually identify patterns throughout their complex grid. Sundsvall is another example, where a DSO has joined an inter-DSO collaboration and is exploring the possibilities of data-sharing to further strengthen their decision-making and maintenance practices. Taken together, these types of improvements suggest that DSOs are moving towards increased digitalization and data-driven approaches as a solution. Although the journey looks different for every organization, what remains the same is the fundamental challenge of managing assets in outdated infrastructures where knowledge erosion and increased system complexity are prominent.

7. Discussion

7.1 Key Findings

Electricity distribution systems are transforming, leaving DSOs to manage aging infrastructure and heterogeneous asset populations with growing complexity. Examining the practices and perceptions of 7 Swedish DSOs through semi-structured interviews, the study arrives at a clear but conditional verdict.

The study found that asset population characteristics and operator experience are complementary rather than competing inputs to understanding maintenance needs. Age by itself is considered insufficient, however combined with accumulated operator experience and inspections it generates informal risk assessments which weigh PoF and CoF implicitly within organizations. DSO reasoning shows that the analytical logic behind data-driven and risk-based frameworks, such as CNAIM, is not foreign to Swedish DSOs but is already present in how they reason and approach asset management and decision-making.

Operators view systematic approaches positively and the decisive barrier in whether to implement RBM frameworks or not is primarily organizational capacity rather than motivation. The suitability of such approaches is therefore conditional on each DSOs size and available data infrastructure. CNAIM was developed for the small and coordinated set of DSOs in Great Britain. A transfer to Sweden's fragmented context of roughly 170 DSOs does not come without challenges and requires adaptation to local conditions.

These findings carry several implications. Because experience-based reasoning resides in individuals rather than in documented systems, the loss of an experienced individual through retirement or movement between organizations becomes a systematic risk to maintenance capability. This gives DSOs a concrete reason to formalize and preserve that knowledge in order to mitigate the potential loss. The challenges lie primarily in organizational capacity rather than in DSOs motivation. Sector development therefore depends less on persuading operators of the value of risk-based methods and more on building the data infrastructure that enables them.

Because implementation must take heterogeneity across organizations into account, it cannot be done uniformly. As DSOs collectively move toward digitalization and data-driven approaches, management support tools such as CNAIM are increasingly well suited to assist with both asset management and decision making.

These findings also highlight how society maintains the infrastructure it depends on. As electrification deepens and distribution becomes more critical to daily life, economic activity, and the energy transition, the ability of DSOs to preserve knowledge and ensure conditions for systematic maintenance becomes a shared societal concern rather than just a technical one. Retaining and transferring operational experience may prove to be almost as important as investing in the assets themselves. Managing the infrastructure is increasingly a shared challenge that depends on cooperation and data sharing across operators. Ensuring that the smaller and less resourceful DSOs are not left behind is thus central to the resilience of infrastructural systems as a whole.

7.2 Future studies

The findings provide several possibilities for conducting future research on this topic. As the study includes interviews with seven out of approximately 170 DSOs in Sweden, at a specific voltage level and a specific asset type, a broader incorporation of DSO participation would further test if the conditional suitability identified in this study holds across the sector. A natural extension would be to conduct a quantitative analysis linking asset characteristics to condition or failure behavior for individual components on different voltage levels. This would widen the scope beyond medium voltage switchgear assets to several components and enable the role of asset characteristics in maintenance prioritization to be tested across a varied asset base. As a whole, this extension would likely provide a more accurate representation of maintenance needs and aid in determining the fitting countermeasures for asset failure across the Swedish electricity network.

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