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Sustainability-based multi-criteria decision analysis (MCDA) for industrial asset assessment: A case study on midlife alternatives for high voltage circuit breakers

By

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Abstract

Maintenance management has over the years evolved from a narrow perspective to a wider and strategic dimension called Physical Asset Management (PAM). PAM in a modern context includes elements of strategy, economy, risk management, environment, which earlier existed separately in organizations. UN business & sustainable development commission estimate 12 trillion USD of opportunities in achieving sustainable development goals (SDGs). Businesses eye the opportunity not only to support the vision of sustainability but also to achieve a competitive advantage.

During maintenance decisions many customers have traditionally looked at direct costs, however, focus on increasing failure rates, sustainability and life cycle thinking is trending. These criteria are not well included in repair-replacement decisions in the electric power industry; therefore, the purpose of the thesis is to assess how sustainability criteria can be included in industrial asset management decisions which are validated through a case study on high-voltage circuit breakers.

A multi-criteria decision analysis (MCDA) is adopted to assess how sustainable criteria based on the triple bottom line (TBL): Social, Environmental, Economic criteria can be included in a decision model.

The results show that a decision model based on MCDA in some extent is able to include sustainable criteria, however it can still be valuable to discuss the validity and reliability of the indicators that has been collected.
The study also show that social and environmental criteria have a significant impact on the final decision compared with a decision based solely on economic criteria, thus supporting the hypotheses that sustainable criteria make a revision (repair) more viable than a replacement.

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First, I would like to praise Hitachi ABB Power Grids, represented by industrial supervisor Daniel Trinborg for their cooperation with my master thesis, but also for being positive, available, and prioritizing their valuable time to support me in this work. Also, a warm thanks to Per Amundsen (Hitachi ABB Power Grids) and Morten Gøytil (Lede) for their active support, and to all others that have participated in this project.

A special thanks to Professor Idriss El-Thalji for his most patient and kind guidance through this journey, including a little bit of philosophic thinking; thank you.

I am most thankful for the two enriching years I have had at the University of Stavanger.

During this relatively short time, I see now, and will later probably understand even better, that what I have learned from the university subjects and their contents is more than I earlier had believed. I look bright at the future hoping for glancing moments where still the little knowledge that I have acquired so far will lead to positive moments of progress and success.

Last but not least, I would like to thank my fellow student colleagues of Industrial Economics. Your intelligence, diligence and friendliness have impressed me and has surely made me stronger. I am sure you will all proceed with being successful professionals as you always have been. Good luck – high five!

Martin Furuseth

Aastad, Jessheim 13.06.2021

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1. Introduction

1.1.Background and problem presentation

Maintenance management has over the years evolved from a classic narrow perspective of corrective maintenance, before introducing preventive replacement and condition monitoring, and later including the wider and strategic dimensions of maintenance called Physical Asset Management (PAM) [1]. PAM has historically primarily focused on reliability and maintainability, however, in a modern context, there are elements of strategy, economics, risk management, environment, which earlier existed in separate departments within an organization [2].

Jardine & Tsang claim that PAM has become an important support function in businesses with significant investments in physical asset, and has identified four developments that provide new challenges in PAM [1]:

1) Operation strategies e.g., lean; eliminating waste and buffers.
2) Societal expectations on protecting people and the environment, reducing accidents and hazards.
3) Technological changes allow condition-based maintenance (CBM) which may improve cost-effectiveness and require new capabilities and knowledge.
4) Increasing emphasis on sustainability implies that operational excellence is no longer sufficient to stay competitive and that businesses should adopt a holistic approach by not addressing PAM in isolation.

The standard for asset management ISO 55000-series argues that effective deployment of PAM and long-term sustainability performance, which supports Jardine's holistic approach. The positive influence of PAM on sustainability performance with regards to the "Tripe Bottom Line" (TBL) was empirically assessed in 2018 [3] and encourage further research from this point of view.

Stakeholders' requirements e.g. sustainability, mentioned as the 4th development in PAM by Jardine & Tsang may be challenging to meet without integrating the requirements with business objectives and a proven asset performance measurement (APM), emphasized by Parida [4]. Thus indicators are essential for measuring performance [5], which can be useful in informed decision making. Epstein implies that further implementation of low-level strategies can be challenging when there is a lack of quantified causal linkages [6], which can be interpreted as a lack of suitable measuring indicators. Thus, this issue shall be explored and addressed further.

From a historical point of view, the awareness of sustainability has rapidly increased during the last couple of centuries, however, this is a conception that has been developed over time, with roots back to ancient times [7]. With the technological development and the western industrial revolution, both consumptions of non-renewable resources and population growth excelled drastically [7]. After the great depression and WW2, the western economy developed rapidly, and technological developments and consumption were the leading developments. Environmental and ecological thinking was first linked with human activity and widespread as late as the 1960s and organizational and governmental awareness arise during the next decades [8]. Since then, the awareness of sustainability issues has gradually increased and reached the common man.

In 1987 the Brundtland Report acknowledged the contradicting interests between the paradigm of technological and economic growth and high consumptions on one side and sustainability on the other [7]. The report defined the concept of sustainable development "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [9] which can be seen as an appeasement conception between growth and conservation.

Respected institutions and organizations e.g., the United Nations (UN) Division for Sustainable Development Goals (SDG), have over the last years made us aware of the importance of sustainability and the necessity to change some of our current business practices. Their goal is to encourage and support businesses in the work towards achieving the 17 SDG goals that are important for sustainable development [10]. Another known concept first used as a term in 1994 by John Elkington, the "Triple Bottom Line" (TBL) [11] encouraging a shift in financial narrative from a one-dimensional economic concern to a three-dimensional concern: the economic, social, and environmental, also known as the three P's: people, planet, profit.

According to the “Better Business, Better World” report of the UN Business & Sustainable Development Commission, achieving the SDGs creates US$12 trillion in opportunities, and potentially 2-3 times more [12]. As stated by Porter competitive advantage are based on cost leadership, differentiation and focus [13]. That is why many businesses eye this as an opportunity not only to support the vision of sustainable development but also to achieve a competitive advantage.

In the electric power industry, among others, a way of integrating sustainability into their daily business is highly sought after, however, in the reality, the concept may feel immature and intangible, despite that many companies have started to include a sustainability framework into their accounting reports and high-level strategies (e.g., Global Reporting Initiative (GRI), UN SDG’s, Task Force on Climate-related Financial Disclosures (TCFD)). This project is motivated by the above mentioned theoretical and industry-related context and has found a natural cooperation with Hitachi ABB Power Grids throughout the study.

1.2.Research objectives and relevance

The electric power industry accommodates a significant number of physical assets as well as being part of critical infrastructure. As their physical assets are ageing, maintenance is essential to reduce the risk of failures and hazards. Customers have traditionally looked at direct costs, however, the focus on the maintenance costs and hazard rate that are likely to increase with age are trending, thus a revision (major overhaul) or a complete replacement is recommended by the manufacturer after a certain number of years, depending on its usage and stress [14]. Information on the sustainability of the decision is also important for Hitachi ABB Power Grids and several of its customers [15].

To make an informed decision the decision-maker may seek decision support by the following advice from the manufacturer or follow a maintenance methodology of their own, e.g., run-to-failure, time-based maintenance (TBM) or reliability-centered maintenance (RCM), which are well explained in literature [1, 16]. However, maintenance is heavily focused on conventional Key Performance Indicators (KPIs) such as Overall Equipment Effectiveness (OEE) and RAMS (Reliability, availability, maintainability, safety), while the sustainability indicators are not included [17]. With an emphasis on the developments and stakeholder requirements to sustainability, informed sustainable decision making seem like an important topic for any business. Hence, there is a need to study and assess how sustainable decisions can be made in PAM.

To further support the holistic approach Komonen suggests that PAM should be part of strategic management, as AM strategy reflects the vision, values, and mission of the company as well as the business objectives defined by stakeholders[18]. Komonen further emphasizes that from a strategic perspective, organizations need to develop sources of competitive advantage throughout the development and management of the organization’s key assets.” [18]. Therefore, the integration of stakeholder requirements is important to understand, and efforts should be made to collect and identify their needs, requirements, and criteria during this study.

Litterature clearly state that informed decisions within asset management are about balancing performance, quality, cost, and risk over the whole life cycle [19, 20], and different stakeholders may have conflicting priorities. Problems with conflicting objectives can be solved by using a multi-criteria decision analysis (MCDA) as a tool that can evaluate the set of alternatives based on the set of conflicting criteria in a transparent way [21]. Therefore, an MCDA will be adopted in the study.

The manufacturer, supplier, and service company “Hitachi ABB Power Grids is a well-known and significant international actor in the electric power industry. The company earlier known as the power grid division of ABB became a joint venture between Hitachi and ABB in 2020. Hitachi ABB Power Grids is the primary company behind the problem presentation and is determined to embrace sustainable development with their commitment to UN SDG’s and GRI reporting and will be following the project closely. As a professional business company, they are likely to be curious and motivated by any information that can help them provide their stakeholders and customers with value-adding products and services. Hitachi ABB Power Grids seeks to develop long-term relationships with customers and to provide “best in class” systems that support sustainable development [22].

One of Hitachi ABB Power Grids's customers, acting as the asset owner is "Skagerak Nett", which recently changed the name to "Lede". Lede is the owner and operator of transmission lines and substations in the county Municipality of Vestfold and Telemark in Norway and a customer of Hitachi ABB. Lede does also seek ways of improving sustainable performance and does also report according to GRI. Lede and Hitachi ABB Power Grids have recently been discussing their ageing high-voltage (HV) circuit breaker (CB) equipment, which is why Hitachi ABB Power Grids has suggested their HV CB as a potential case subject that may be used as an example in a study on a sustainable decision-making model.

A midlife revision of high HV CBs is an interesting case to be studied with the aim to support decision-making to answer whether revision or replacement is the most beneficial decision when including sustainability criteria/measures. In classical maintenance management this problem is named capital equipment replacement decision by Jardine and Tsang [1].

Therefore, the purpose of this thesis is to develop an MCDA-model that considers sustainability criteria to support decisions concerning PAM.

1.3. Research question

R1 "*How can sustainable criteria be included in industrial asset management decisions*?"

R2 "*How can Hitachi ABB Power Grids and Lede enhance sustainability in repair-replacement decisions on HV circuit breakers*?"

1.3.1 Hypotheses

H1: Including sustainability in the repair-replacement decision will make a repair (revision) the more viable alternative.

H2: Repair (revision) of an old HV CB will have a smaller environmental footprint than replacing it with a new one.

H3: Repair (revision) of an old HV CB has a lower total cost (LCC) than replacing it with a new one.

1.4.Methodology

To ensure the research is kept relevant and sticks to its intentions, the steps of the method are visualized as a flow diagram, see figure 1.

The author has in mind that the study should be specific enough to be utilized by the case companies, while also being transparent and general so that the results of the study can be useful in other case scenarios.

A humble approach is chosen, starting with a wide literature search and review that provides general knowledge and an idea of present challenges and existing research. Followed up by introduction meetings with stakeholders, mainly management staff in the respective case companies, the author gets an idea of the current narrative, visions, goals, and challenges. This will also provide the author with an extensive network that may be valuable for the project.

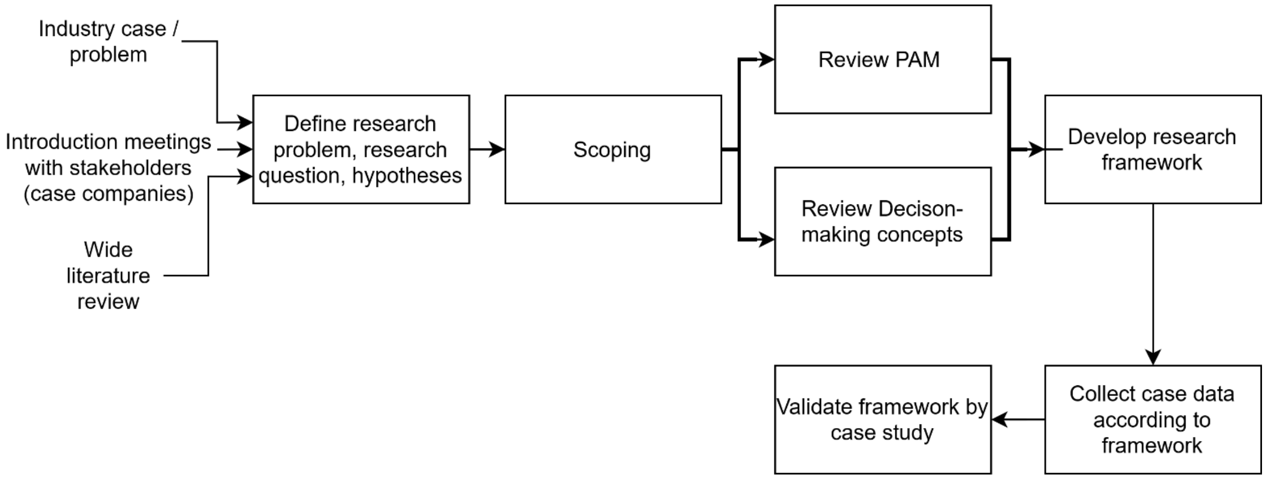

Figure 1: Method flowchart.

At first, the research question, hypotheses and research objectives are defined, followed by further scoping, and then the development of the research methodology (framework). The development of the framework starts with an extensive literature review of the sustainability, PAM concepts as well as decision-making concepts. The research framework will be developed based on the literature and will later be validated through the application of the case study.

The data collection will use both quantitative and qualitative methods. While the quantitative methods will provide an overview of the costs and environmental issues. Interviews, workshops, and a survey will provide data on non-monetary values and priorities. The cooperation with the case companies allows access to interview objects and data recordings.

The project plan can now be further structured into a work breakdown structure (WBS).

1.5. Scope of the thesis

Scoping of the thesis establishes the boundaries and narrows the focus on its intended purpose.

The approach should ideally consider several aspects of the case scenario, e.g., whether the replacement equipment will be identical or have other technological features that have an impact on the results of the decision model. It is also important that the framework of the decision model is fully developed in such a way that it may be generalized for further use. However, due to the limited number of resources, the different case scenarios are limited to:

A) A Revision.
B) A one-to-one replacement with a new and identical product.

The case scenario is further described in chapter 4.

The case scenario is also delimited to one asset owner only, namely Lede. However, including additional asset owners may be considered at a later stage after the framework is developed.

As mentioned in 1.1 PAM should be viewed holistically and in the context of the business organization to achieve high sustainable performance. However, to prevent the project focus from becoming too wide and extensive, the project will identify and assess key sustainability parameters in lifecycle management and capital equipment replacement decisions of the HV CB.

While reliability and risk management are important topics in PAM, the main focus of this thesis is to develop a decision model that can guide and inform the decision-maker and on how sustainable concepts can be incorporated in decision models.

2. Research methodology and design

2.1 Research methodology

To be able to provide an answer to the research questions and hypotheses, a research methodology is designed. Meetings with the industry laid the foundation for a problem formulation, which encouraged broad literature searches. These literature searches provided the author with knowledge about existing approaches and methods that could be relevant for the study.

According to Bratvold, decision-making methodology can be described in eight steps (see figure 2):

1) Define the decision context
2) Set the criteria
3) Identify alternatives
4) Calculate how criteria are met
5) Weigh the criteria to their relative importance
6) Calculate the overall weighted value for each alternative
7) Assess trade-offs between objectives
8) Test robustness of the decision through a sensitivity analysis

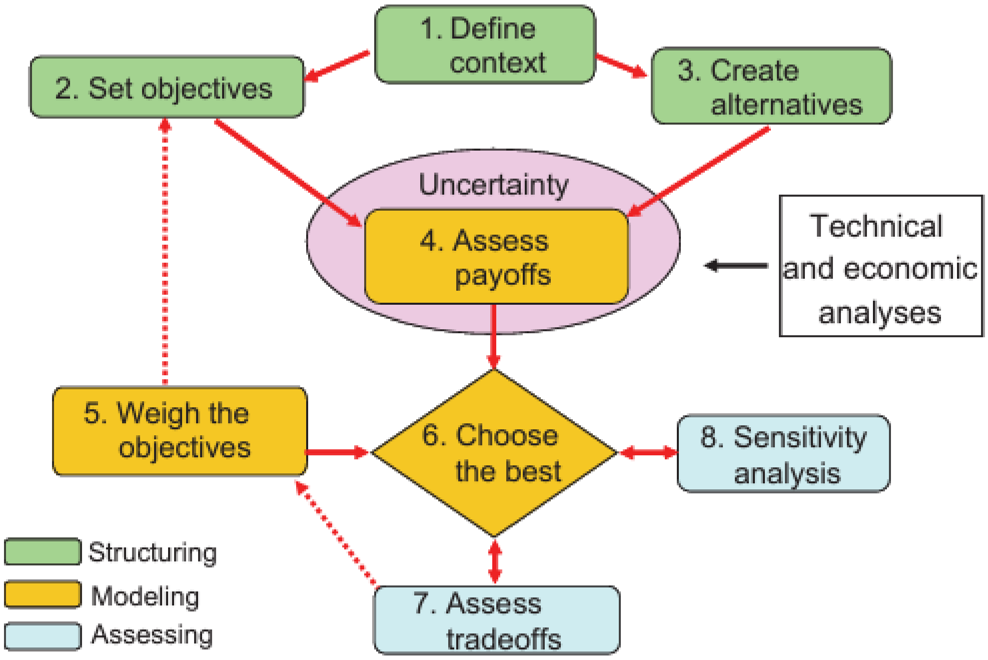

Figure 2: A decision-making methodology - From Bratvold – Making good decisions [23].

The MCDA framework in literature [23, 24] have much in common with Bratvold's decision-making methodology, besides some differences in order. The framework consists of 4+1 steps, where step 1 is kept outside of the MCDA framework, as seen in figure 3:

1) Stakeholder analysis.
2) Define indicators.
3) Assign weights to indicators.
4) Assign performance score to the alternatives.
5) Overall score – The final ranking of the alternatives.

These steps will be thoroughly explained in the following chapters.

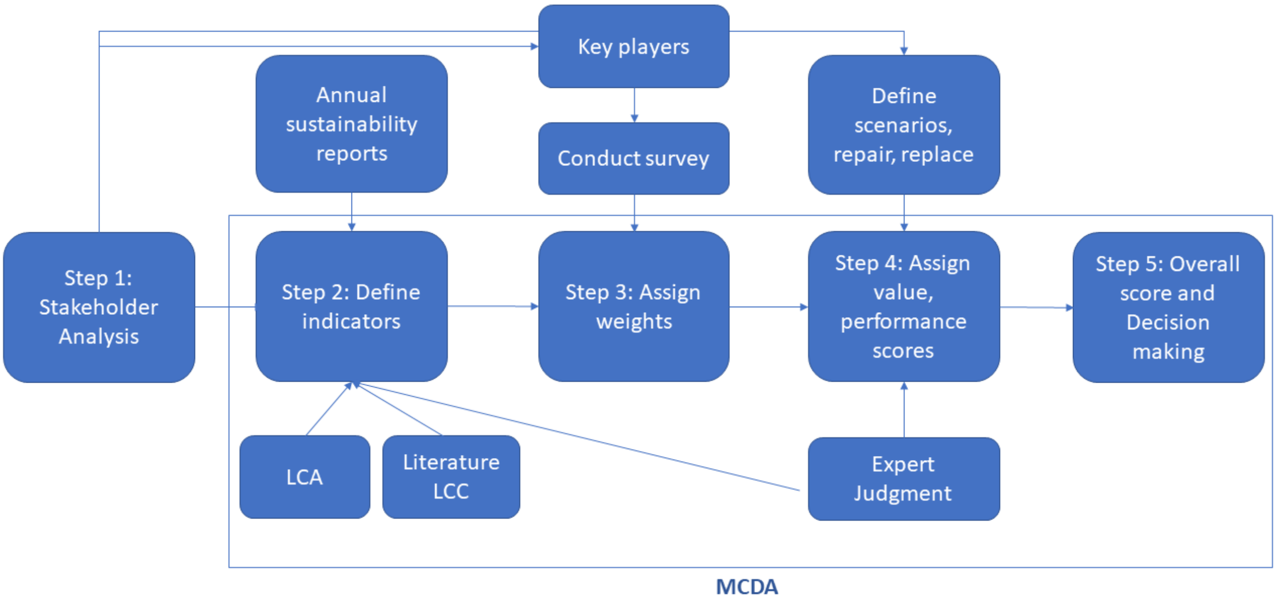

Figure 3: Research methodology – MCDA framework.

3. Theoretical background

3.1 Physical Asset Management (PAM)

As mentioned in chapter 1, maintenance management has over the years evolved from a classic narrow perspective of corrective maintenance, before introducing preventive replacement and condition monitoring, and later including the wider and strategic dimensions of maintenance called Physical Asset Management (PAM) [1]. PAM has historically primarily focused on reliability and maintainability, however, in a modern context, there are elements of strategy, economics, risk management, environment, which earlier existed in separate departments within an organization [2]. The demand for integrated thinking between the departments descends from the oil & gas crisis during the late 80s when the larger companies were forced to re-shape their business models due to a lack of integrated thinking [25]. Thus, a more holistic and life-cycle focused approach on managing infrastructure assets adapted and developed [26].

PAS 55, a standard for asset management was created in 2004, structured around the Plan-Do-Check-Act (PDCA) cycle, which is a well-known principle of continuous improvement [27]. The ISO 5500 – series which is based on the PAS 55, but is more generic and applicable to all type of assets is released in 2014 and provides a definition of asset management "the coordinated activities of an organization to realize value from physical assets" [20]. This definition is supported by Stewart stating that asset management provides for the systematic planning, acquisition, deployment, use, control, and decommissioning of physical assets while also allowing integration of policy from strategic management, middle management, and operations management into one focus, to achieve maximum value from the assets [28]. Campbell, emphasizes that good decisions in asset management are about balancing performance, quality, cost, and risk over the whole life cycle [19]. These links are illustrated in figure 4 from PAS 55.

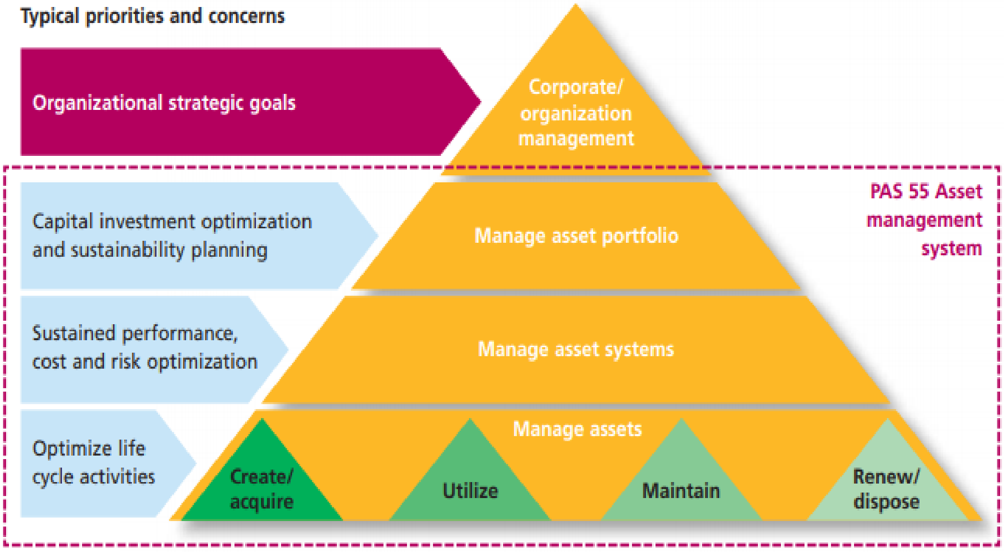

Figure 4: Hierarchy of asset management [30].

3.2 Maintenance strategy and types

A short overview of maintenance strategies and types may be relevant to provide context to maintenance management and decisions, therefore some of the most known maintenance strategies and types are mentioned in this chapter.

Jardine and Tsang mention total productive maintenance (TPM) and reliability-centered maintenance (RCM) as two central maintenance policies or processes [1]. While EN13306:2010 mentions maintenance types such as preventive maintenance, predetermined maintenance, condition-based maintenance (CBM), predictive maintenance (PdM), corrective maintenance, these can be divided into two categories: corrective maintenance and preventive maintenance (PM) [29].

3.2.1 Total productive maintenance

TPM is heavily linked with overall equipment effectiveness (OEE), lean, 5S [30]. By involving all employees to solve issues at a low level to reduce non-value adding processes and waste in the organization. As opposed to simply operating a physical asset, the operator has to perform routine inspections, services, and minor repairs with the goal of continuously improving the OEE. Deservedly, TPM is named a people-centered methodology by Jardine and Tsang [1].

3.2.2 Reliability-centered maintenance

While TPM is named people-centered, RCM has been named an asset-centered methodology [1]. RCM desires a full understanding of the system functions of each asset and assess its nature of failure. This is typically knowledge about how it fails and the consequence of failure. This includes accepting that some failures cannot be prevented by maintenance, or that the maintenance is inaccurate or have little effect on a specific failure mode. Identification of failure mode, effects, and criticality analysis (FMECA) can be used to determine what type of maintenance action and tactics are most beneficial, a maintenance task selection.

3.2.3 Corrective maintenance

Corrective maintenance is based on the classic view on maintenance because of failure and can be a deliberate part of run-to-failure strategy.

3.2.4 Preventive maintenance

Maintenance types such as scheduled, predetermined, CBM, and PdM are variants and techniques of PM.
EN 13306:2010 defines scheduled maintenance as preventive maintenance that is carried out according to a time schedule, while predetermined maintenance is carried out according to usage, e.g., number of operations.
The maintenance schedule can be based on mean-time-to-failure (MTTF), which can be calculated based on the failure statistics of the asset. An example of an MTTF distribution is the bathtub curve in figure 5, which is the failure rate as a function of time or e.g., number of operations. The upper function curve is the sum of quality failures which are more common during commissioning, wear out failures, which are more common with age, and the flat curve of stress-related failure.

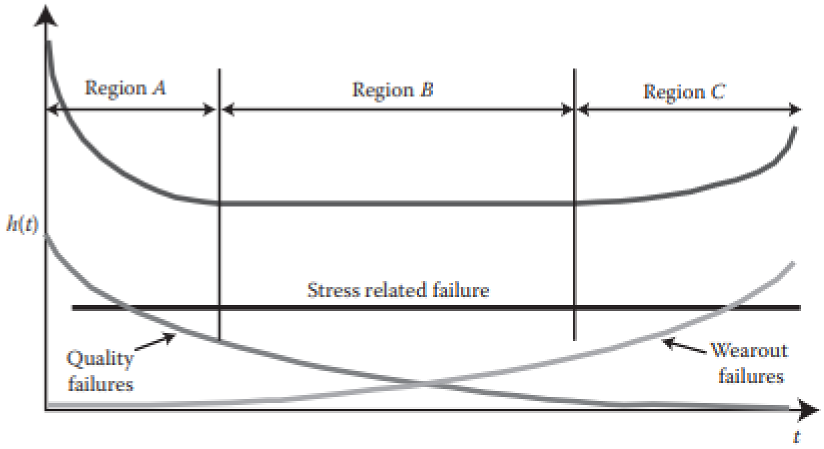

Figure 5: Bathtub curve from Jardine & Tsang [1]. Failure rate as a function of time.

CBM does also originate from preventive maintenance, allowing the use of condition monitoring technology e.g., vibration monitoring, while the system is still operating. This means that maintenance can be done just before failure, which may reduce the costs and downtime in inspections, maintenance. One of the cons of CBM is the high cost of a monitoring and analysis system.

PdM utilizes the same techniques as CBM, while also utilizing the data from the asset to predict future failure or to improve operations. The prediction or forecast can be based on both historical and real-time data where the physical characteristic of chosen parameters has been evaluated. Industry 4.0 technologies may play a central role in PdM.

3.3 Capital equipment replacement decisions

From a basic deterministic point of view, an optimal replacement age can be calculated as the time where the total equivalent annual cost (EAC) is at its minimum value. The EAC is represented as “total cost” in figure 6, and is the summary of the fixed cost, operations and maintenance cost, and ownership cost.

From a certain age, the operations and maintenance costs increase with the age. Costs moving the opposite direction is the ownership cost, which is the acquisition cost of an asset, minus its resale value, divided by the age of the replaced asset.

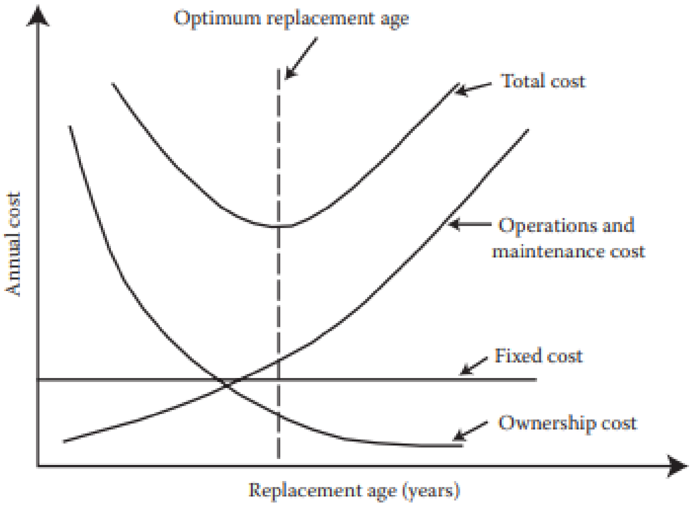

Figure 6: Classic conflict of economic life [1].

Jardine and Tsang have established models for each of the three different capital equipment replacement scenarios, which are all variants based on the model of scenario 1:

1) Constant utilization - where the equipment is evenly utilized each year.
2) Varying utilization - where the equipment has varying utilization between years.
3) Technological improvement - where the equipment is considered replaced by other technologies.

The model is constructed by calculating the life cycle cost (LCC), which shall obtain all the costs throughout the life cycle on an asset and shall be discounted to account for the time value of money. A discount factor should usually be defined in terms of the opportunity cost [31].

Niekamp [23] has identified the following stages of costs to be included: initial costs, maintenance costs, repair/replacement costs multiplied with the probability of failure, indirect failure costs and end of life costs. While Jardine looks at the annual cost method, Niekamp suggest using the present value (PV) for each year which is calculated for each of the costs and summarized to provide the net present value. The formula can be found in chapter 5.5.3.2.

3.4 Multi-criteria decision analysis

Decision-makers can face complex decisions with multiple stakeholders and criteria with contradictory goals. Multi-criteria decision analysis (MCDA) is a method that is widely used to deal with these types of problem, as it can address a different type of data and uncertainty, conflicting goals, interests and criteria [32].

The main process of an MCDA can in simple terms be seen as a decision matrix based on subjectively weighted criteria on one side, alternatives on the other, resulting in a performance matrix, illustrated in figure 7. The decision matrix has similarities with Bratvold’s explanation of a typical general spreadsheet structure for decision making [33] showed in figure 8, while figure 9 shows a more holistic view of the MCDA process based on Belton and Stewart [34] which is in consensus with Linkov and Moberg [35]. The decision-making process is supported by evaluating the alternatives against the criteria. The preferences of the decision-maker are captured through the weighting of each criterion, which will influence the final ranking of the alternatives.

$$
\begin{array}{lccccc}
 & \text{criteria} & C_1 & C_2 & \cdots & C_n \\
 & (\text{weights} & w_1 & w_2 & \cdots & w_n) \\
\text{alternatives} & \multicolumn{5}{c}{\text{-- -- -- -- -- -- -- -- --}}
\end{array}
$$

$$
X = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array}
\begin{pmatrix}
x_{11} & x_{12} & \cdots & x_{1n} \\
x_{21} & x_{22} & \cdots & x_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
x_{m1} & x_{m2} & \cdots & x_{mn}
\end{pmatrix}_{m\times n}
$$

Figure 7: A simple decision matrix [34].

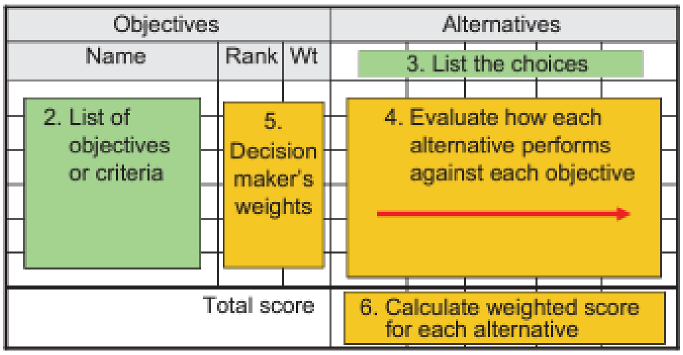

Figure 8: A typical spreadsheet for decision making [23].

Figure 9: The MCDA process based on Belton and Stewart [35], made by Catrinu [37].

Linkov and Moberg, and Niekamp present an overview of the MCDA methods by establishing three basic categories: Multi-Attribute Utility Theory (MAUT), Analytical Hierarchy Process (AHP) and outranking [23, 35].

3.4.1 MAUT

Multi-attribute utility theory and multi-attribute value theory (MAVT) can be used interchangeably, where MAVT is a simplification of the MAUT while using a value function instead of a utility function [36]. The measure units of the criteria are given a utility or value so that they can be compared against each other using the same unit of measure. A critical step of this method is defining the utility, where a utility function has 0 as the lowest value, and 1 as the highest. The weights are applied to the criteria before the final utility is calculated through additive or multiplicative techniques to provide the overall utility of each alternative [35].

3.4.2 AHP

The analytical hierarchy process was developed by Thomas Saaty during the 1980s [35]. AHP is a very different approach compared with the MAUT, as it does not use direct weights or utility functions. AHP uses a pairwise comparison between the criteria, where one criterion is weighted against another, e.g. alternative A is better than alternative B, or alternative A is slightly better than alternative C. An indication of the consistency of the results may be captured through a calculation of the consistency ratio.

3.4.3 Outranking

There exist several outranking methods, however, the idea is to compare which alternatives that outperform another considering the criteria. Outranking methods were developed due to not needing all criteria to be comparable, as opposed to utility-based methods [34]. Outranking is, therefore, less capable of exact optimization but do still provide a comparative assessment of the alternatives, where their performance against criteria is ranked independently. Without going into detail, known outranking methods are PROMETHEE and ELECTRE.

4 Data collection

The data collection chapter aims to document the type of data and sources that have been used in the study. This chapter will be structured according to the steps from the research methodology but starts with a description of the case scenario.

1 – Description of case scenario
2 – Stakeholder analysis
3 – Define indicators
4 – Assign weights
5 – Assign value, performance score

4.1 Case scenario description

To answer the research question on how key sustainable parameter can be included in a repair/replacement decision a decision model framework has been developed. This framework will be applied in chapter 5 – data collection and 6 – data analysis.

High voltage (HV) circuit breaker (CB) that has been operating for 20-30 years are usually recommended a midlife revision hereafter called revision, which can be seen as major maintenance. The recommended age for a revision is not exact and depend not only on age as a function of time but also on the amount of stress. There is a general acceptance in literature that this type of preventive maintenance can reduce the chance of wear-out failures. However, the refurbishment of the HV CB does require a higher number of labour hours compared with other maintenance services

In countries like Norway where labour hours are high seen from a global perspective the relative difference in cost between a refurbishment and a replacement of an HV CB is likely to be lower than in many other countries.
When including not only the economic but also the social and environmental dimensions of sustainability, informed decision-making becomes even more complex.

The case study will specifically assess the LTB 145D by Hitachi ABB Power Grids, see figure 10.

Figure 10: Drawing of the LTB 145D [39].

Some assumptions will be taken, to ease the study of this scenario within the given number of resources.

A1: The recommended age for revision is set to 20 years.
A2: The time horizon of the study will be limited from year 20 to year 40.
A3: A refurbishment will reset the failure rate curve (as a function of age).
A4: Replacement will be 1-to-1 in terms of technical specifications and functions of the HV CB.

A description of the two alternatives: revision and replacement will follow in the next chapters.

4.1.1 Revision

Revision is a major maintenance service that is normally done between year 20 and 30. It involves an extensive disassembly of the HV CB and replacement of certain smaller components, e.g., gaskets. The job requires approximately 30 to 40 hours from the supplier, and between 40 and 60 hours from the asset owner.

At year 40, the HV CB which has already gone through a revision is considered ready for decommissioning, meaning there is no residual value left, only costs to disassembly and recycling.

4.1.2 Replacement

A replacement implies that the 20-year-old HV CB will be disassembled, recycled, and replaced by a new HV CB assembly. The job requires approximately 40 to 60 hours from both the supplier and the asset owner separately.

The new assembly will have an accountable lifetime of 40 years, however, as this study only considers a 20-year timeline, a residual value of the new assembly should be included in the calculations.

4.2 Stakeholder analysis

A stakeholder analysis aims to document the need and requirements of the stakeholders. This information is highly relevant, as the study is already motivated by cooperation with the case companies. The stakeholder analysis may also provide information that helps clarify the industry scenario and support the identification of criteria and indicators.

Together with the industrial supervisor at Hitachi ABB Power Grids, unstructured interviews will be held with different departments in the organization. A similar type of interview is held with Hitachi ABB Power Grids' customer, Lede.

Annual reports will also be studied to identify the opinions of all stakeholders including top management. Furthermore, weekly meetings with the industrial supervisor at Hitachi ABB Power Grids will be held continuously.

The data collected will be analyzed and summarized in a template according to table 1.

Stakeholder	Needs	Requirements	Criteria

Table 1: Template Stakeholder needs and requirements.

4.3 Define indicators

Identifying indicators and criteria is a necessary step of the MCDA while also being a natural next step from the stakeholder analysis.

To define indicators in a good way, an extensive search for information was done on the Internet and through semi-structured interviews with an industry expert group, which also could provide valuable input as well as validation. The literature searches on the Internet were mainly done through Scopus – a well know database for scientific articles, and Oria – a common online library for all universities in Norway, including access to several databases.

Search groups were "Sustainable asset management", "replacement decision making", "MCDA" with various additions and replacement of words to increase the chance of finding relevant literature. To gain a wider understanding of the search groups, or on other specific technical terms, Google's search engine was used sporadically.

Several books based on essay collections from the academic and industrial cluster organizations, published by Springer [37-39] has provided the author with a broader context and understanding.

4.4 Assign weights

The identified indicators should increase the understanding of and measure the performance of each alternative, however, the indicators may differ in importance. To account for its importance the indicators will be given weights, that will impact the results of the MCDA assessment accordingly.

The importance of the indicators will be identified through a survey taken by a multidisciplinary group of stakeholders and decision-makers from the case companies, supported by an introductory presentation on the study and a later discussion.

4.5 Assign value/performance score

Both quantitative and qualitative data will be collected to assess each of the scenarios' performance on each indicator. As explained by Niekamp, a qualitative or linguistic variable may be used when no quantitative data is available, and data can even be collected in form of a confidence interval or distribution [23].

Quantitative data will be collected from the case companies through semi-structured interviews and e-mail correspondence and workshop sessions, while qualitative data will be collected from an export group during a workshop which may also be considered as a structured interview.

The performance on each indicator may not necessarily be able to differentiate between the alternatives of the case, due to missing data or equal performance between alternatives. One can argue that this process may be a part of defining indicators, however, the idea is to use high-level indicators to illustrate the potential lack of relevant data that may be collected in the future.

5 Data analysis and Results

Intro and outline

The data analysis chapter aims to organize and interpret the data that has been collected throughout the study. This chapter will be structured according to the five steps from the research methodology:

1 – Stakeholder analysis
2 – Define indicators
3 – Assign weights
4 – Assign value, performance score
5 – Overall score

5.1 Stakeholder analysis

For a better understanding of the stakeholder's needs and requirements, introduction meetings and unstructured interviews were held with Hitachi ABB Power Grids employees. The employees were mainly consisting of management staff, as well as project- and sales staff, across different divisions in the company. The same type of meeting was held with two central members of the administrative maintenance department of Lede.

A generalized summary of the meetings and interviews are documented in table 2.

Stakeholder	**Needs**	**Requirements**	**Criteria**
End-customers (consumers)	Reliable supply of electricity. Low price. Sustainable electricity production.	No losses of electricity. Minimize costs. Minimize negative impact on sustainability criteria.	Reliability. Cost-effectiveness. Sustainability.
Shareholders	High profit.	Cost-effective.	Cost-effective.
Top management	Good results through visions, goals, strategies.	Effective, efficient, and sustainable management throughout the organization (asset management).	Overall Equipment Effectiveness (OEE). Sustainability.
Employees	Stable and attractive workplace. An understanding of, and the appropriate tools to perform according to top management goals and strategies.	Forward-looking company. Information on sustainable development, decision criteria and technologies.	Sustainability. Product- and business development. Technology and asset management.
Regulatory authorities and politicians	Governance and development of the industry according to political visions.	Reduce the negative impact on sustainability criteria? Reduce loss of energy and shortages of supply? Reduce health and safety risks?	Sustainability. Overall Equipment Effectiveness (OEE). Health and Safety (H&S).
Suppliers and contractors (Hitachi ABB Power Grids and their sub-suppliers)	A good relationship with customers.	Information on customer decision criteria.	Communication with the customer.

	Competitive products with an emphasis on customer needs.	Awareness of customer visions, goals, strategies, tactics. Development of products and business solutions that meet customer criteria.	Product- and business development.

Table 2: Stakeholder needs and requirements.

Furthermore, the use of UN SDGs was remarked as an important alignment tool by the industrial supervisor in Hitachi ABB Power Grids. Not only for internal use but also to inform external stakeholders about their focus on sustainable development.

The differences between the needs, requirements and criteria of the stakeholders indicate that an assessment method that can cope with different criteria is necessary, therefore the MCDA method may seem like a good choice for the task.

5.1.1 Expert group

A small group of industry players has been gathered to provide support to the study through meetings and future workshops. The group consist of a total of three people, two from the service and sales department in Hitachi ABB Power Grids, and one from the maintenance department in Lede.

5.1.2 Key players

A group of twenty employees and experts from both Hitachi ABB Power Grids and Lede: eighteen from Hitachi ABB Power Grids and two from Lede are identified as key players from the introduction meetings.

The group is multidisciplinary, representing various job positions such as project management, sales, maintenance, and are typically employees in management positions or employees with influence on decision making.

5.2 Define indicators

To identify sustainable indicators, Elkington's TBL concept consisting of social, environmental, and economic are chosen as criteria.

As stated in the introduction chapter, the research question is how key sustainability parameters can be included in a repair-replace decision. Materiality analysis is a highly generalized approach that provides guidelines for sustainability issue prioritization that can be seen as the key initial step in practical implementation of a sustainability indicator framework [40]. This holistic view has also been remarked in literature [1, 41].

With an emphasis on following a holistic approach the 3-levelled management pyramid (figure) comes to mind, starting at the top: 1. Strategic management, 2 tactical management, 3 operational management. The indicators will therefore be selected with an emphasis on sustaining this holistic mindset, to ensure that high-level goals are included downwards in the asset management system, operations, and maintenance.

The indicators were identified during three steps:

1) The first step of identifying indicator was done by the author through literature, an existing life cycle assessment (LCA) report and annual reports.
2) The second step involved managing the collected data by categorizing and consolidate similar indicators to prevent the number of indicators to become too many and reduce the correlation among the indicators to prevent double-counting [23, 42].
3) The third step of identifying indicators was a combined workshop and validation session with an industry expert group consisting of 4 people, with both Hitachi ABB Power Grids and Lede represented.

The results are listed in table 3, followed by a description of how the indicators were identified for each of the TBL dimensions.

Source prefix (see source list)	**GRI #**	**SDG #**	**Dimension**	**Prefix**	**Indicator**
[43, 44]		12	Social	S1	Socially responsible sourcing, code of conduct, anti-corruption along the value chain
[43, 44]	102-43			S2	Interaction with customers, suppliers, investors, civil society
[43, 44]	401-1	5,8,10		S3	Tot. number and rates of new employee hire and employee turnover
[43, 44]	403-1,2,9	3,8,15		S4	Health and safety: injuries, lost days, diseases and fatalities, employees represented in H&S forum
[43, 44]	404-1,3	4,5,8,10		S5	Training and education, Regular performance- and career development review for employees
[43, 44]	405-1	5,8		S6	Diversity and equal opportunity in management and staff
[43, 44]	406-1	5,8		S7	Non-discrimination
[43, 44]	415-1, 419-1	16		S8	Public policy - Financial and in-kind political contribution, violations of societal laws
[43, 44]	413-2	1,2		S9	Negative and positive local influence, community relations and engagement
[43, 45]	303-3, 302-1	6,7,8,12,13	Environmental	E1	LCA - Resource utilization (use of renewable and non-renewable)
[43, 45]	302-1, 305-2	3,7,8,12,13,14,15		E2	LCA - Energy consumption (electrical and heat energy)
[43, 45]	306-2	3,6,12		E3	LCA - Waste (hazardous and regular)
[43-45]	305-1,305-7	3,12,13,14,15		E4	LCA - Emissions (gases) - especially SF6
[46]				E4.1	Transport during maintenance (w or w/o increased maintenance interval)
[46]				E5	Reduce footprint of nature area (less space, lighter machines, and assembly).
[44, 46]	307-1	16		E6	Violation of regulatory requirements in nature areas.
[1, 23, 47]			Economic	C1	LCC - Acquisition
[47]			Economic	C2	LCC - Commissioning, training, documenting
[1, 23, 47]				C3	LCC - Operation - energy usage and inventory. OEE - performance and quality

					not sensitive due to the binary nature of circuit breaker - either it works, or not.
				C3.1	LCC - O.1 Maintenance (hours + material)
				C3.1.1	LCC - O.1.1 Preventive
				C3.1.2	LCC - O.1.2 Corrective
[47]				C.4	LCC - Modernization - (Lifetime Extension) - e.g., increase maintenance intervals, availability of spare parts through 3D-printing.
[1, 23, 47]				C.5	LCC - EOL (End of life) - Disposal – recycling – residual value

Table 3: List of indicators categorized and consolidated.

5.2.1 Social indicators

Standard methods for assessing the social dimension are still an evolving debate [3].

Using materiality analysis in sustainability assessment is seen as a guideline and key initial steps in the implementation of an indicator framework and has become salient in sustainability assessment [40]. Therefore, publicly accessible annual reports[43, 44], GRI-reports [43, 48], materiality analysis [43] were studied to identify appropriate social indicators based on the materiality of the companies. Another benefit of using the GRI reports is the ease of alignment with the TBL-concept, and its wide acceptance as a reporting standard on sustainable indicators.

As mentioned in the stakeholder analysis, SDGs was remarked as an important alignment tool by the industrial supervisor in Hitachi ABB Power Grids. Not only for internal use but also to inform external stakeholders about their focus on sustainable development. Social indicators from the GRI reports have therefore been aligned with corresponding SDGs through GRI guidelines [49], see table 3.

5.2.2 Environmental and economic indicators

As quoted by Roda and Garetti [50] the literature is harmonious on recommending LCC as an integral part of asset management, referring to Schuman [41]. LCC together with LCA are well-accepted methods for assessing the economic and environmental dimensions of sustainability, elaborated by Niekamp [23]. The economic indicators will therefore be based on an LCC that will include the asset life cycle phases from EN16646:2014, a standard for maintenance within physical asset management (PAM), while the environmental indicators will be based on an LCA study that carried has been carried out by ABB.

5.2.2.1 Environmental indicators from LCA and workshop

The LCA study [51] and its corresponding environmental product declaration [45] of the specific HV CB, LTB 145D, measures four main indicators, which shall cover all environmental aspects throughout the entire life cycle of the HV CB:

1) Resources Utilization
2) Energy Consumption
3) Waste
4) Emissions

Additionally, input from a workshop (earlier mentioned as the third step) provided additional indicators that could be of interest:

E4.1	Transport during maintenance (a sub-indicator of emissions).
E5	Reduce footprint of nature area (require less space, lighter machines, and assembly).
E6	Violation of regulatory requirements in nature areas.

5.2.2.2 Economic indicators from LCC

The total life cycle costs are obtained by systematically following each life cycle stage as a template. The life cycle stages, which are captured from EN16646:2014 [47] are:

1) Acquisition, including design, manufacturing, installation
2) Operation
3) Maintenance
4) Modernization
5) Disposal

In the indicator-table 3, an indicator named "C2 - commissioning" is included for further consideration following Schuman's remark [41]. However, this indicator may be included with "C1 – acquisition".

5.3 Assign weights

The prioritization of indicators for assessing the sustainability of a refurbishment versus a replacement of capital equipment is a critical step of the MCDA method of this study.

A survey was formulated and presented for a multidisciplinary group of 20 key players and experts from both Hitachi ABB Power Grids and Lede: 18 from Hitachi ABB Power Grids and 2 from Lede. The participants that were participated in the survey were selected from various job positions such as project management, sales, maintenance, and typically employees in management positions or employees with influence on decision making. They were asked to answer seen from their professional point of view, and that the feedback could be used as decision support in e.g., asset and maintenance management, procurement, product development, product portfolio and business development.

5.3.1 Design of the survey

The survey was designed in Microsoft Forms, consisting of 24 questions that were distributed on four Likert scales:

1 – The perceived importance of the TBL dimensions.
2 – The perceived importance of the social indicator.
3 – The perceived importance of the environmental indicators.
4 - The perceived importance of the economic indicators.

To provide the participants with an adequate number of choices, a five-level scale was selected. A small scale of three levels was considered not being able to fully identify the participants' perceptions, while a larger ten-levelled scale could potentially suffer from parts of the scale not being applied and a higher potential of biased responses, known as central tendency bias. To prevent any bias due to "faking good" or "faking bad", known as social desirability, the results of the survey were kept anonymous.

5.3.2 Results of the survey

The survey had in total 20 respondents, 18 from Hitachi ABB Power Grids and 2 from Lede. The survey was analyzed statistically to calculate the mean, standard deviation, and weights, shown in table 4 and table 5. The mean score of the indicators is also visualized in figure 11.

Indicator	Social	Environmental	Economic	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean	3.750	4.650	3.900	4.650	4.200	3.250	4.650	3.850	3.450	4.050	3.900	4.050
Std. dev.	0.942	0.572	0.768	0.572	0.678	0.994	0.792	0.792	1.071	1.161	0.768	0.740
Relative weight	0.305	0.378	0.317	0.129	0.117	0.090	0.129	0.107	0.096	0.112	0.108	0.112

Table 4: 1 of 2. Mean, standard deviation, relative weight from the survey.

Indicator	E1	E2	E3	E4	E5	E6	C1	C2	C3	C3.1	C4	C5
Mean	4.050	3.800	4.150	4.400	4.050	4.050	3.600	3.600	4.300	3.900	4.350	3.700
Std. dev.	0.669	0.872	0.792	0.663	0.589	0.865	0.663	0.663	0.781	0.624	0.654	0.954
Relative weight	0.165	0.155	0.169	0.180	0.165	0.165	0.154	0.154	0.183	0.166	0.186	0.158

Table 5: 2 of 2. Mean, standard deviation, relative weight from the survey.

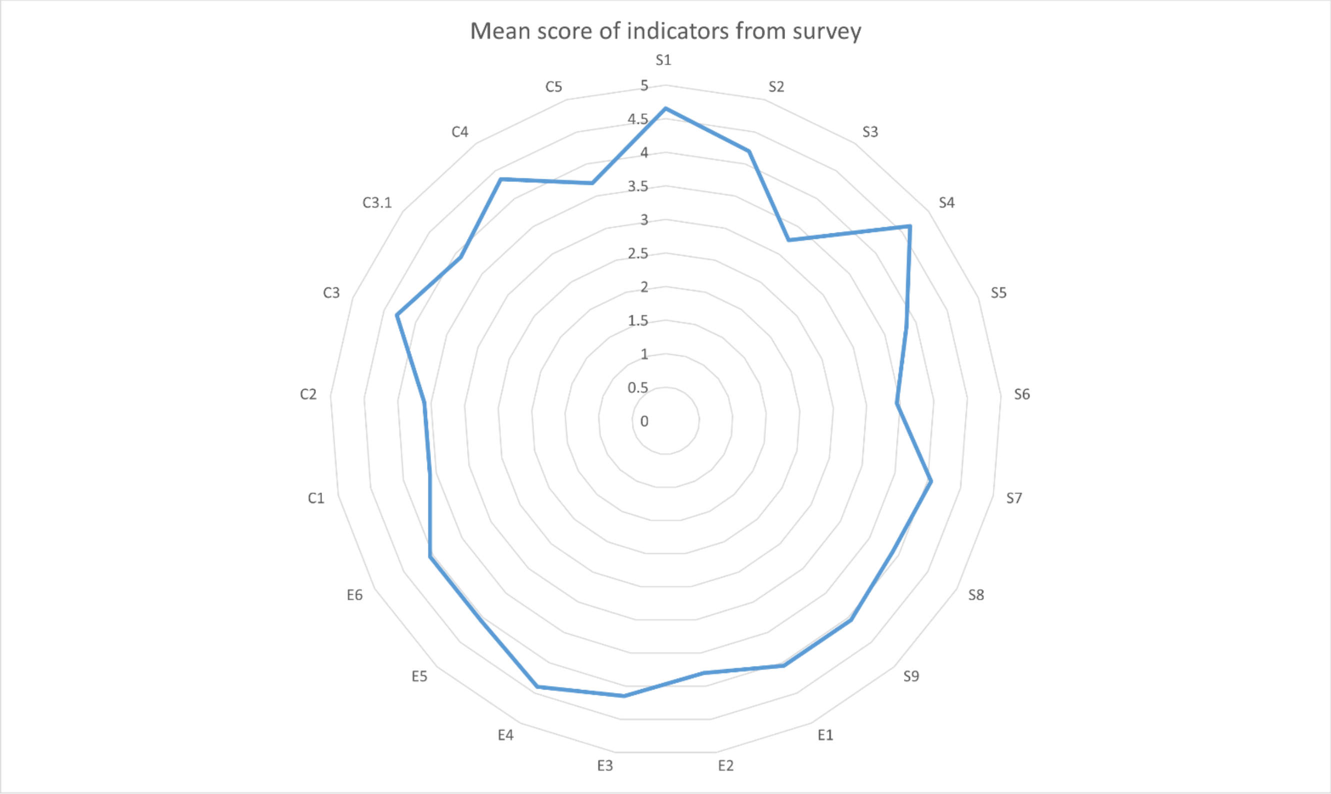

Figure 11: Mean score of indicators from the survey.

5.3.2.1 Weights

The relative weight of an indicator was calculated by dividing its mean by the sum of its group's mean. Expressed as an equation 1:

Equation 1

$$W_i = \frac{S_i}{\sum_{i-1}^{n} S_i}$$

where W_i is the relative weight of the indicator, S_i is the mean score of the indicator, and n is the number of indicators being weighted within the group.

The weights in table and table, show that the social dimension of sustainability is weighted 30.5 %, environmental 37.8 %, economic 31.7 % - indicating that the environmental dimension of sustainability is perceived as more important within the group of participants.

5.3.2.2 *Standard deviation and uncertainty*

The standard deviation measures the dispersion, which may be used as a measure of uncertainty, where a higher number tells us that the scoring provided by the participants are spread over a wider range. This means that there is a weaker consensus among the participants where the standard deviation is high.

5.4 Assign performance score

MCDA techniques can reduce the challenge of assessing different criteria and measure units against each other. To reduce its complexity the study has found it desirable to choose a simple MCDA method, the weighted sum method (WSM). WSM is a multi-attribute utility theory (MAUT) technique, which means that all alternatives are normalized to a common scale from 0 (lowest performance) to 1 (highest performance).

Performance data will be assigned from both quantitative and qualitative data. Quantitative data is used where it is available and an acceptable degree of certainty, which are typical for the indicators from the LCA or the LCC, while a qualitative assessment was done when no quantitative data was available.

How the performance score was assigned can be explained in 4 steps:

1) Assigning goals of the indicators.
2) Assessing which indicators will have equal scores for all alternatives, thereby not relevant to include in further assessments.
3) Quantitative and qualitative data is collected, assigned, and verified.
    a. Indicator assessment and calculation.
4) Normalizing the performance score

A total of two workshop sessions was held with the expert group.

The first workshop assigned the relevancy of each indicator, and a discussion on the performance scores was also started.

The second workshop discussed further and assigned the qualitative performance scores to each of the relevant indicators.

5.4.1 The goal of each indicator

It is important to clarify the direction of the performance score to prevent any miscalculations. This is especially important when the indicator goals differ in sense of which direction (max or min) has a positive impact on the performance score.

Each of the indicators is assigned a clear goal e.g., to minimize energy consumption (indicator E2), see table , column “Goal”.

Qualitative ranking scale [0, 1], where 0= not preferred, 0.5= preferred, 1= highly preferred

Prefix	**Indicator**	**Goal**	**R/R equal (not relevant? (Y/N)**
S1	Socially responsible sourcing, code of conduct, anti-corruption along the value chain	Max	N
S2	Interaction with customers, suppliers, investors, civil society	Max	Y
S3	Tot. number and rates of new employee hire and employee turnover	Max new	N
S4	Health and safety: injuries, lost days, diseases and fatalities, employees represented in H&S forum	Max reduced H&S-risk	N
S5	Training and education, Regular performance, and career development review for employees	Max	N
S6	Diversity and equal opportunity in management and staff	Max	Y
S7	Non-discrimination	Max => min. discrimination	Y
S8	Public policy - Financial and in-kind political contribution, violations of societal laws	Min	Y
S9	Negative and positive local influence, community relations and engagement	Max positive	N
E1	LCA - Resource utilization (use of renewable and non-renewable)	Min	N
E2	LCA - Energy consumption (electrical and heat energy)	Min	N
E3	LCA - Waste (hazardous and regular)	Min	N
E4	LCA - Emissions (gases) - especially SF6	Min	N
E4.1	Transport during maintenance	Min	Y
E5	Reduce footprint of nature area	Max => min. footprint	Y
E6	Violation of regulatory requirements in nature areas.	Min	Y
C1	LCC - Acquisition	Min	N
C2	LCC - Commissioning	Min	Y
C3	LCC - Operation - energy usage, inventory, OEE -availability - performance and quality not sensitive due to the binary nature of a circuit breaker - either it works, or not.	Min	Y
C3.1.1	Preventive maintenance - major overhaul. standard maintenance is omitted due to no modernization/technology change	Min	Y
C3.1.2	Corrective maintenance - operational risk (Risk of major failure (power loss, FMECA)	Min	Y
C.4	LCC - Modernization - (Lifetime Extension) - e.g., increase maintenance intervals, availability of spare parts through 3D-printing.	Min	Y
C.5	Residual value, disposal and recycling	Min	N

Table 6: Indicators, its goals, relevancy, and performance.

5.4.2 Screening of indicators

During a workshop with the expert group, the relevancy of each indicator is discussed. See table 6, column "**R/R equal (not relevant? (Y/N)"**. "Y" means that the performance of the alternatives (revision and replace) is assumed to be equal, hence not a relevant indicator for comparison for this case. Reducing the number of indicators also increases the chance of being able to monitor the indicators without getting overburdened with regards to the available resources, as pinpointed by Whitehead [40].

By assigning (Y/N) to each indicator during the beginning of the first workshop session, the following session was able to quickly shift focus to discuss the most relevant indicators which are: S1, S3, S4, S5, S9, E1, E2, E3, E4, C1, C5, which are highlighted in green in table 6.

Due to the screening and reduction of indicators after the weights from the survey was assigned in chapter 5.3, the obtained weights of the indicators were no longer valid. However, this was solved quite easily by rescaling the assigned weights within each group of indicators by following the equation from chapter 5.3.2.1.

5.4.3 Quantitative and qualitative data is collected, assigned, and verified.

After narrowing down the number of indicators in chapter 5.4.2, performance data is collected from the LCA study [45, 51] and the expert group during workshop sessions, in separate semi-structured interviews and by e-mail. The data is calculated and assigned to each indicator by the author in accordance with the scenario description of chapter 4.1. The calculation is further described in table 7.

Qualitative data that is collected during the first workshop, before being a performance score is further discussed and assigned during the second workshop.

The qualitative ranking scale is limited to three performance scores: 0 = not preferred, 0.5 = preferred, 1 = highly preferred. By limiting the number of ranking alternatives to three, the expert group may feel forced to rank the alternatives in such a way that differences between the alternatives might be enhanced and visualized.

Indicator prefix	**Indicator**	**Goal**	**Revision**	**Replace**	**Unit**	**Description**
S1	Socially responsible sourcing, code of conduct, anti-corruption along the value chain	Max	1	0.5	Ranking	A qualitative measure due to lack of data. A revision mainly requires local labour and very little material, e.g. gaskets. A replacement requires more material and production facilities that are located around the world. Hitachi ABB Power Grids' supply chain is considered risk-averse and safe, however, the chance of non-conformance is considered higher in a global supply chain versus a local supply chain. There is however uncertainty concerning this proposition.
S3	Tot. number and rates of new employee hire and employee turnover	Max new employees	0.5	0.5	Ranking	A qualitative measure due to lack of data. A revision is done in field and can be labour intensive. A replacement includes a complex and global supply chain that can create jobs along the whole value chain, however, a serial production may be able to benefit from the economics of scale. There is however uncertainty concerning this proposition.

S4	Health and safety: injuries, lost days, diseases and fatalities, employees represented in H&S forum	Max reduced H&S-risk	0.5	0	Ranking	A qualitative measure due to lack of data. In any case, the equipment that is subject to a revision or replacement is decoupled from the power station. A revision involves a relatively small supply chain, while a replacement is considered to involve a complex supply chain where H&S-risks are assumed to be more likely to happen. However, if the case scenario were to consider a replacement with new technology, which is more realistic, the performance score will probably be different. New technologies could be safety functions to prevent electric hazard, less hazardous materials such as composite instead of porcelain insulators to reduce the chance of explosion.
S5	Training and education, Regular performance and career development review for employees	Max	1	0.5	Ranking	A qualitative measure due to lack of data. To perform a revision specific expert knowledge is more vital, while the knowledge to replace is less complex and already existing as long as there are new installations.
S9	Negative and positive local influence, community relations and engagement	Max positive	0.5	1	Ranking	A qualitative measure due to lack of data. A replacement is subject to a more complex and global value chain, hence as long as the value chain is working towards max positive local influence, a replacement can have a stronger positive local influence than the smaller value chain of a revision.
E1	LCA - Resource utilization (use of renewable and non-renewable)	Min	3312	6624	GHG (kg CO2-equivalent)	A quantitative measure, collected from the ABB LCA study. Measured in accordance with Global Warming Potential (GWP) which measure unit is in kg CO2-equivalents. A revision need only to account for manufacturing and disposal once. A replacement needs to account for manufacturing and disposal twice. The use of non-renewable resources consists of two subcategories: Materials in ore Materials for energy production The use of renewable resources consists of two subcategories: Hydro energy Wood Revision = materials in ore + materials for energy production + hydro energy + wood Replacement = 2x (materials in ore + materials for energy production + hydro energy + wood)
E2	LCA - Energy consumption (electrical and heat energy)	Min	925	1850	GHG (kg CO2-equivalent)	A quantitative measure, collected from the ABB LCA study. Measured in accordance with Global Warming Potential (GWP) which measure unit is in kg CO2-equivalents. A revision need only to account for manufacturing and disposal once. A replacement needs to account for manufacturing and disposal twice. The energy consumption is measured as electrical energy and heat energy.

						Revision = electrical energy + heat energy Replacement = 2x (electrical energy + heat energy)
E3	LCA - Waste (hazardous and regular)	Min	980	1960	GHG (kg CO2-equivalent)	A quantitative measure, collected from the ABB LCA study. Measured in accordance with Global Warming Potential (GWP) which measure unit is in kg CO2-equivalents. A revision need only to account for manufacturing and disposal once. A replacement needs to account for manufacturing and disposal twice. Two types of waste are considered: Hazardous waste and regular waste (landfill). Revision = Hazardous waste + regular waste Replacement = 2x (Hazardous waste + regular waste)
E4	LCA - Emissions (gases) - especially SF6	Min	6825	13650	GHG (kg CO2-equivalent)	A quantitative measure, collected from the ABB LCA study. Measured in accordance with Global Warming Potential (GWP) which measure unit is in kg CO2-equivalents. A revision need only to account for manufacturing and disposal once. A replacement needs to account for manufacturing and disposal twice. Five categories of gases are measured in the LCA: Acidifying gases, greenhouse gases, oxygen consumption gases, ozone depletion gases, ozone formation gases. Revision = Acidifying gases + greenhouse gases + oxygen consumption gases + ozone depletion gases + ozone formation gases Replacement = 2x (Acidifying gases + greenhouse gases + oxygen consumption gases + ozone depletion gases + ozone formation gases)
C1	LCC - Acquisition	Min	200 000	400 000	NOK	A quantitative measure. Prices are normally confidential, however, for the sake of the study, a fictive cost example is provided by the expert group. The costs should provide an idea of the magnitude of the actual costs and the proportionalities between the different type of operations and alternatives. In reality, the costs may vary largely between different projects. Revision: 200 000 NOK revision Replacement: 250 000 NOK circuit breaker including transport costs to port, Norway. +150 000 NOK installation

C5	LCC - Residual value, disposal and recycling	Min	38 000	-39 706	NOK	A quantitative measure. Prices are normally confidential, however, for the sake of the study, a fictive cost example is provided by the expert group. The costs should provide an idea of the magnitude of the actual costs and the proportionalities between the different type of operations and alternatives. In reality, the costs may vary largely between different projects. Revision: 35 000 NOK removal 3000 NOK transport to recycling 0 NOK residual value = cost / lifetime x remaining years = 250 000 / 40 x 0 Replacement: 35 000 NOK removal 3000 NOK transport to recycling -125 000 NOK residual value = cost / lifetime x remaining years = 250 000/ 40 x 20 Due to discounting of the residual value, the equation is found in chapter 5.4.3.3.

Table 7: Description of indicator performance data.

5.4.3.1 Hypothesis H2 and H3

Table 7 provides the data needed to answer hypothesis H2 and H3 for this specific case scenario. Meaning further management of the data through the MCDA framework is needed to answer these hypotheses.

H2: *Repair (revision) of an HV CB will have a smaller environmental footprint than replacing it with a new one.*

By summarizing the data from the environmental indicators which are not yet weighted or normalized the total CO2 equivalent is found. The results of the environmental performance of a revision equal 12 042 kg CO2, while a replacement equals 24 084 kg CO2, hence a revision will leave a smaller environmental footprint, while a replacement will have an additional emission of 12 042 kg CO2 which equals driving 141 671 km with new fossil fuel car based on numbers from Statens Vegvesen [52].

H3: *Repair (revision) of an old HV CB has a lower total cost (LCC) than replacing it with a new one.*

The same simple method is used summarizing the performance score of the environmental indicators which are not yet weighted or normalized. The cost of a revision equals NOK 238 000 while the cost of a replacement equals NOK 360 000 if discounted to present value. Note that the cost data collected is inaccurate due to confidentiality concerns.

5.4.3.2 ABB LCA study

The ABB LCA study was collected during the data collection. As the data is useful in this part of the thesis, a summary will follow.

The LCA study was conducted in 2004 according to the recommendations and requirements of ISO 14040 series, and the LCA fulfils the requirements of a certified Environmental Product Declaration (EPD) according to ISO TR 14025.

[51]The study was evaluated according to Global Warming Potential (GWP), a method that was validated with another weighting method, Econindicator 99. [51]

The LCA has not been revalidated during this study, and its results have been used regardless. After discussion with Hitachi ABB Power Grids' factory division of lifecycle projects, the HV CB product (LTB145) has no significant changes in the material. However, the electricity mix that was used is from 1998, hence the real performance score might be different in 2021.

The environmental impact of the circuit breaker is captured into three life cycle phases: Manufacturing, use, disposal.

Most of the environmental impact comes from use – the operation phase, however, this part of the life cycle is considered equal between the alternatives and is therefore not relevant for the study. Therefore, only the manufacturing and disposal phase is included in the calculation.

A summary of the scope of the three life cycle phases in the LCA:

- Manufacturing, including:
    - Extraction and production of raw materials
    - Transportation of materials estimated 200 km with a lorry.
    - Energy consumption and emissions from the production of main parts
    - Assembly of the product

    - Not included: Manufacturing of components or prefabricated parts used in the assembling.

- Use of the product, including:
    - Transportation to customers estimated 500 km with a lorry.
    - Energy consumption for 40 years of continuous operation
- End of life, including:
    - Dismantling, where 99 % of the SF6 gas is assumed recovered.
    - Disposal
    - Recycling, aluminum 80 %, copper 95 %, steel 80 %.

5.4.3.3 LCC

To assess the life cycle costing the net present value (NPV) is calculated for each of the alternatives so that the time value of the cash flows is accounted for through discounting at a chosen rate.

The NPV of the two alternatives is calculated according to the equation 2:

Equation 2

$$NPV = C_I + \sum_{i=1}^{n} \frac{C_n}{(1+r)^n}$$

, where C_I is the initial cost, C_n the future cash flow, *n* is year, *r* is the discount rate.

Since the investment cost is done at end of year 0, this cost is not discounted. This leaves us discounting only the residual value of alternative "replace". Which is the present value of the cash flow at year 20, see equation 3:

Equation 3

$$PV(20)_{replace} = \frac{87\ 000}{(1+0.04)^{20}} = 39\ 706 \text{ NOK}$$

5.4.4 Normalized performance score

To cope with indicators that have different a range of values and measure units, normalization is carried out on environmental and economic indicator performance, so that the performance score will be on a common scale, a number within the interval [0, 1], where 1 is better.

The normalization will be done according to the equation 4:

Equation 4

$$P_{i,\,norm} = \frac{P_i - P_{i,\,min}}{P_{i,\,\max} - P_{i,\,min}}$$

, where P_i is the performance score, and *i* is the prefix of the indicator.

It is important to be aware of the direction of the scoring with emphasis on the goal of the indicator, whether it is to minimize or to maximize. Since the goals of the environmental and economic indicators are to minimize, the normalized score is inverted (1-performance score).

The performance score after the normalization can be found in figure 12 and table 8.

Figure 12: A spider chart of the normalized performance score before weight are applied.

5.5 Overall score

To capture the preferences of the involved key players, the weighting of criteria and indicators from the survey is multiplied with the normalized performance score, following equation 5:

Equation 5

$$Ptotal = \sum_{1=n}^{n} (Wi \times Pi,norm)$$

Since the survey included a separate weighting of the TBL criteria, we may multiply the criteria weight with each corresponding indicator. This means that regardless of the performance scores within a criteria group, only a certain weight will apply to the final ranking. E.g., the social criteria that have been ranked 30.14 % will only impact 30.13 % of the final ranking. The equation is therefore updated in equation 6 and the overall score and final ranking are provided in table and figure 13:

Equation 6

$$Ptotal = \sum_{1=n}^{n} (Wci \times Wi \times Pi, norm)$$

Revison Performance score	**Replace performance score**	**Relative weight**	**Indicator Prefix**	**Normalized performance score: Revision**	**Normalized performance score: Replace**	**Inverted normalized performance score: Revision**	**Inverted normalized performance score: Replace**	**Total revision**	**Total replace**
1	0.5	22.95 %	S1	1	0.5			0.07	0.03
0.5	0.5	15.85 %	S3	0.5	0.5			0.02	0.02
0.5	0	22.68 %	S4	0.5	0			0.03	0.00
1	0.5	18.85 %	S5	1	0.5			0.06	0.03
0.5	1	19.67 %	S9	0.5	1			0.03	0.06
							SUM	**0.21**	**0.15**
						1-(normalized value)			
3312	6624	24.83 %	E1	0.19	0.45	0.81	0.55	0.08	0.05
925	1850	23.15 %	E2	0.00	0.07	1.00	0.93	0.09	0.08
980	1960	25.17 %	E3	0.00	0.08	1.00	0.92	0.10	0.09
6825	13650	26.85 %	E4	0.46	1.00	0.54	0.00	0.06	0.00
							SUM	**0.32**	**0.23**
						1-(normalized value)			
200000	400000	49.23 %	C1	0.59	1.00	0.41	0.00	0.06	0.00
38000	-87000	50.77 %	C5	0.26	0.00	0.74	1.00	0.12	0.16
							SUM	**0.18**	**0.16**

							SUM TOTAL	**Revision**	**Replace**
								<u>0.71</u>	**<u>0.53</u>**

Table 8: Performance score, normalized performance score and final ranking of the indicators.

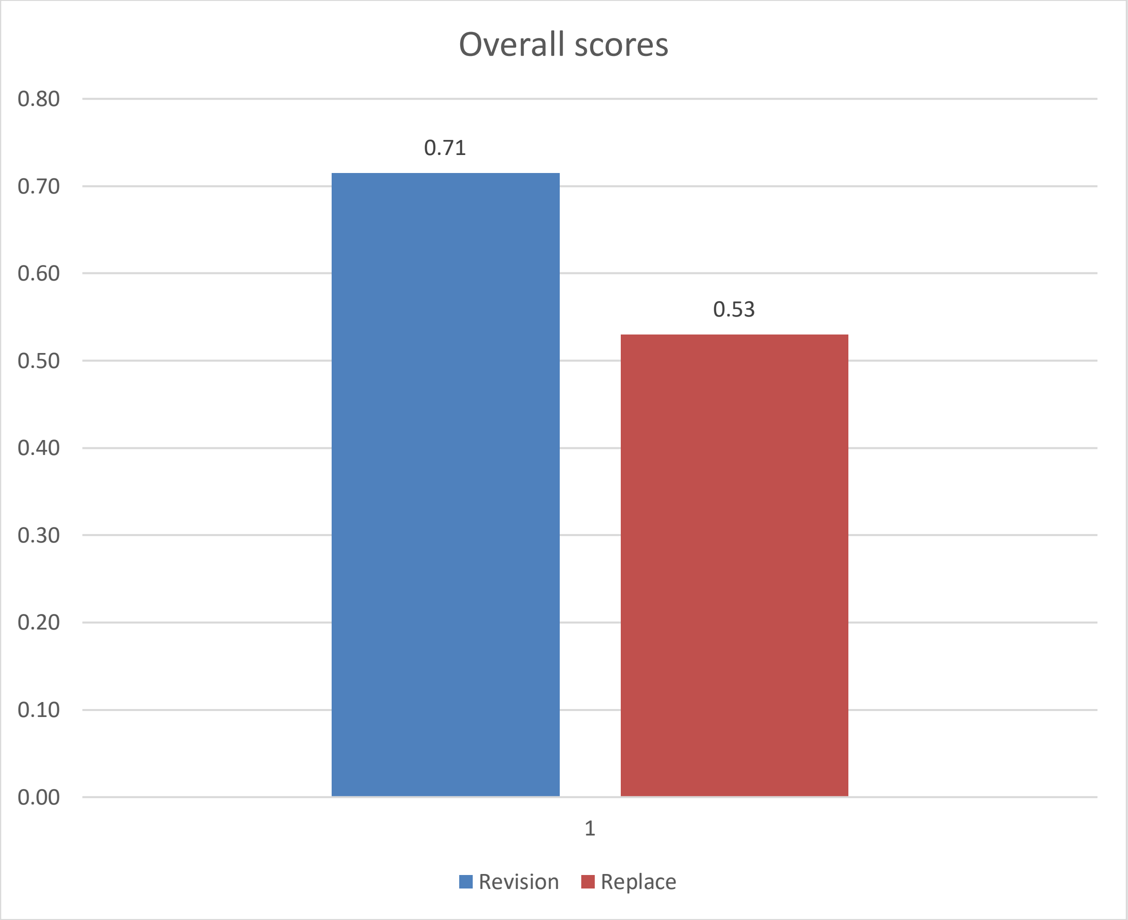

Figure 13: Overall score of each alternative.

The output of the decision model shows that a revision is the preferred alternative with 0.71 points versus the alternative of replacement which has 0.53 points.

For further details on how each alternative perform against each of the sustainable criteria of TBL, a spider chart is constructed in figure 14. The blue triangle represents a revision while the orange triangle represents a replacement, where a larger triangle means a higher total score, while also allowing interpretations of each of the TBL criteria. The figure show that both alternatives have geometric similarities, which mean that they have the same characteristics in terms of performance against the sustainability criteria of TBL.

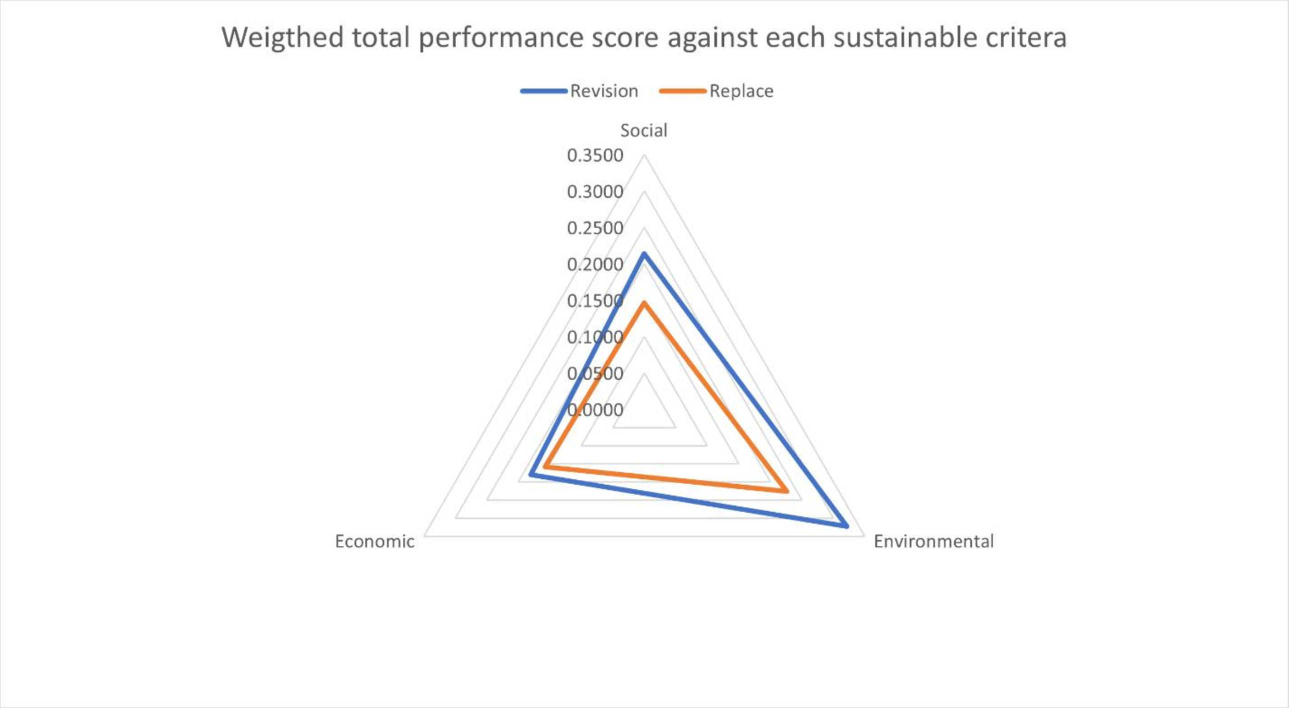

Figure 14: The weighted total performance score against each sustainable criterion.

6 Discussion

A discussion will be held for each step of the results from following the framework in chapter 2:

1) Stakeholder analysis.
2) Define indicators.
3) Assign weights.
4) Assign performance score to the alternatives.
5) Overall score – The final ranking of the alternatives.

Additionally, the applicability and generalizability of the decision model are discussed.

6.1 Stakeholder analysis

The stakeholder analysis does provide an overview of several stakeholders and their needs obtained through meetings with Hitachi ABB Power Grids and Lede. As no data was collected from other stakeholders, we cannot say that the results of the stakeholder analysis are reliable. However, the intention behind the stakeholder analysis was to get an overview and idea of stakeholders need to support the choice of the research design and is therefore considered to have a low impact on the validity of the study.

6.2 Define indicators

Indicators based on sustainable criteria were identified through both existing literature and input from the expert group. LCC and LCA are widely accepted methods and so is GRI for non-financial reporting of sustainable indicators. However, it is a challenge to successfully translate the complex reality into a simplified model. Therefore, the model based on the identified indicators should be subject to continuous improvements, adjustment, and addition of indicators.

Another challenge of identifying indicators is the consideration of their validity. Even though the indicator may be correlated to its criteria, it may have a weaker correlation with the specific case scenario, and therefore the data provided by the indicator may not be valid. Indiscriminately use of indicators may also result in non-value adding processes and waste in the organization.

It is desirable to avoid any dependency between the indicators, to avoid double counting. The merging of similar indicators in chapter 5.2 attend to this issue, however, a more formal method e.g., statistical methods if sufficient data is available can better ensure the replicability of this step.

As opposed to the LCA and LCC, GRI indicators are high-level indicators that usually represent the results of the whole corporation. In this case, the GRI indicators measure the performance of the corporation of ABB and Skagerak (Lede) as a whole. Following this argument, the existing data is not valid, and new case-specific data should be collected. However, due to the use of various sources in data collection for identifying indicators, table x presents an overview of which sources have consensus, which increases the reliability of the identification. The validity of using high-level indicators for use in a specific case scenario can undoubtedly be discussed. In general, there should be a linkage between higher and lower levels of the indicators, therefore the author chose to accept the GRI indicators as is.

6.3 Assign weights

The results of the survey have provided weights to all criteria and indicators, by capturing the preferences and perceptions of the responding key players, who have some sort of involvement in either the specific case or for other similar cases. As the questions of the survey are quite general, case-specific engagement is less important. However, there is uncertainty around the impact of other factors such as bias and human errors, and to which extent the results are affected by these.

The total number of respondents is 20 Whether this is a sufficient number of respondents may lead to another discussion, however, the study accepted the results regardless of the low sample size, due to the natural limitations in the number of available respondents, as only two case companies were invited. Furthermore, the distribution of respondents between the two companies is imbalanced, which may imply a possible bias of the results, which reduce the validity of the results.

There is also uncertainty around how well the questions in the survey were understood and interpreted. In addition, the questions of the survey were written in English, while the respondents were Norwegians. There is always a trade-off between how much time to spend on improving the quality and certainty of the data. A statistical analysis of the results might provide an interpretation that could reduce the uncertainty; however, this has not been performed systematically, besides the standard deviation was calculated and documented with the results.

6.4 Performance score

A qualitative performance score was assigned to the social indicators due to the lack of quantitative data. The score was assigned during workshops with the expert group. This implies that there is a higher degree of uncertainty around the assigned score. Nevertheless, the description has documented arguments from the workshop discussions, so that the quantitative measures can be added at a later stage.

Secondary data obtained from the LCA study has not been revalidated during this study. Its results have been used regardless and are therefore not necessarily accurate, e.g., changes in recycling grade.

Nor is the LCC accurate due to confidentiality concerning the actual costs and prices. However, the price example is to some extent proportional.

The use phase, which is not relevant for the case study, will still be important to include in other studies. As stated in the LCA study, most of the environmental impact comes from the use phase. The study has conducted no calculations or estimate on the economic and social impacts during the use phase; however, even small differences may become significant during 20 years of use.

Furthermore, the method of normalization through Min-Max scaling is highly influenced by the minimum and maximum values. This means that when the dataset (number of indicators) is low, the normalized results are biased by these outliers. For this specific case, this might be an issue during the normalization of the economic indicators where the number of indicators is two.

6.5 Overall score

The output of the decision model shows that a revision is the preferred alternative with 0.71 points versus the alternative of replacement with 0.53 points. The decision-maker should note the uncertainties associated with each step of the decision model while keeping in mind the overall score is based on a theoretical simplification and may not represent the full complexity of the case. The model is supposed to provide decision support, rather than being a sole tool for decision-making.

6.6 Applicability and generalizability

Given that the identified uncertainties are handled by the decision-maker, the decision model has been able to capture the differences of the alternatives with an emphasis on the sustainable criteria and should be applicable for the case scenario of revision or replacement of an HV CB. Some criteria or indicators that traditionally are important in PAM has not been assessed due to not being relevant in this specific case scenario, however, they are still included in the model: economic indicators C3 and C4 which can monetarize risks and failure rates from FMECA and assess different technologies e.g., condition monitoring or additive manufacturing of spare parts.

The transparency and flexibility of the model make it possible to adjust the methods and inputs in all steps of the model. Thus, making the decision model/framework generalizable for use in other repair/replace case scenarios, as well as comparison and assessment in e.g., product development, procurement, product portfolio.

Other frameworks such as Quality Function Deployment (QFD) was at an early stage considered as an alternative to the MCDA to identify indicators, due to its ability to provide intercorrelation between the stakeholder needs and the criteria and identify interrelations among indicators. However, due to its complexity, no proceedings were made on this methodology.

7 Conclusion

The main research questions that drive this thesis are:
R1 "*How can sustainable criteria be included in industrial asset management decisions*?",
R2 "*How can Hitachi ABB Power Grids and Lede enhance sustainability in repair-replacement decisions on HV circuit breakers*?

Besides some minor issues that should be discussed or resolved, the MCDA framework is able to include sustainable criteria into industry asset management decisions, validated through a case scenario on a repair-replacement decision of HV CB.

When considering only economic criteria, the final score is very even between the two alternatives, with a difference of 0.02 points, which make it hard to defend a decision based solely on economic criteria. While the difference in the score when including all sustainable criteria is 0.18 points, this tells us that social and environmental criteria have a significant impact on the overall score of the decision model, hence the model has enhanced focus on sustainability in the repair-replacement decision of HV CB.

An MCDA framework that includes the following steps has been followed:

1) Stakeholder analysis – which contributed with context and understanding of the needs of the stakeholders.

2) Identify sustainable indicators – which was identified through multiple sources: Workshops with the expert group, annual reports and GRI-reporting for social indicators, LCA for environmental indicators, LCC through the standard for maintenance within PAM for the economic indicators. 9 social, 6 environmental and 5 economic indicators were identified.

3) Weight the importance of each criterion and indicator – through a survey, with criteria weights: 30.5 % to social criteria, 37.8 % to environmental criteria, 31.7 % to economic criteria. These weights represent the prioritization of the case companies and affect the result of the decision model.

4) Assign a performance score of each indicator – through a collection of quantitative and qualitative data, the performance of each alternative is assigned to each indicator on a common scale.

5) Calculate the overall score and ranking of the decision alternatives – which ranks the alternatives against the set of criteria and indicators and is able to determine the best alternative, a revision.

When it comes to answering the case-related hypotheses:
H1: *Including sustainability in the repair-replacement decision will make a repair (revision) the more viable alternative.*

- As stated in the paragraph above, including sustainability in the repair-replacement decision makes a revision the more viable alternative and the hypothesis is accepted.

H2: *Repair (revision) of an HV CB will have a smaller environmental footprint than replacing it with a new one.*

- This question is not directly answered by the final ranking of the decision model but is still found within the steps of the MCDA framework when summarizing the performance score of the environmental indicators which are not yet weighted or normalized. The results of the environmental performance of a revision equal 12 042 kg CO2, while a replacement equals 24 084 kg CO2, hence a revision will leave a smaller environmental footprint, and the hypothesis is accepted. A replacement will have an additional emission of 12 042 kg CO2 which equals driving 141 671 km with a new fossil fuel car based on numbers from Statens Vegvesen [52].

H3: *Repair (revision) of an old HV CB has a lower total cost (LCC) than replacing it with a new one.*

- This question is not directly answered by the final ranking of the decision model but is still found within the steps of the MCDA framework when summarizing the performance score of the environmental indicators which are not yet weighted or normalized. The cost of a revision equals NOK 238 000 while the cost of a replacement equals NOK 360 000 if discounted to present value, hence the hypothesis is accepted. Note that the collected cost data is inaccurate due to confidentiality concerns.

The differences in real numbers (kg CO2-equivalents or NOK) may not seem huge, however, when multiplied by the total number of HV CB's the asset owner possess, this may have a huge impact on the environmental or economic budget of the asset owner.

This case scenario did only consider a 1-to-1 replacement. However, in reality, new technologies emerge which may disrupt or change the requirements of the asset owner. Therefore, alternatives including technologies such as condition-monitoring, additive manufacturing spare parts should be assessed. At the same time, the criteria or indicator might need to be adjusted to capture positive and negative impact when technology is integrated with maintenance strategies e.g., CBM or RCM.

Furthermore, to enhance vertical communication in the organization, efforts should be made to identify and align both high-level and lower-level environmental and economic indicators.

To cope with some of the shortcomings of the decision model and its associated data collection, further research may find interest in improving the quality and amount of data, thus increasing validity and reliability.

Uncertainties should be identified through formal methods such as the use of fuzzy numbers, confidence intervals or a distribution based on expert opinions. The same goes for assessing indicator dependency to reduce the chance of double counting. Sensitivity analysis of the results may be able to handle these issues.

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2021).

Appendices

Appendix A Survey - weighting of perceived importance - HitachiABB(1-18)_05.21

ID	Social	Environm	Economic	S1 - Social	S2	S3 - Tot.	S4	S5	S6	S7- Non-	S8	S9	E1 - LCA	E2 - LCA	E3 - LCA	E4 - LCA	E5 -	E6 -	C1 - LCC	C2 - LCC	C3 - LCC	C3.1 -	C4 - LCC	C5 - LCC
4	3	4	3	4	3	2	4	4	3	3	3	4	4	4	4	5	4	5	5	4	4	4	4	4
5	4	5	4	5	4	4	5	4	5	5	4	4	4	4	4	4	5	5	4	4	4	4	5	4
6	5	4	3	5	4	5	5	5	4	5	4	4	3	4	5	4	4	3	3	3	5	4	4	4
7	5	5	5	5	5	3	5	4	3	4	4	5	5	5	5	5	5	5	5	4	5	4	5	4
8	3	5	4	5	5	4	5	3	3	3	4	4	4	4	3	5	3	3	3	4	5	4	4	3
9	5	4	3	5	3	4	4	3	4	5	4	4	3	3	4	4	4	5	3	4	3	3	3	4
10	4	5	3	5	4	3	5	3	3	5	3	3	4	4	3	5	5	3	3	3	3	4	4	4
11	3	5	3	5	4	4	5	4	5	5	5	5	4	4	4	4	4	5	3	3	4	3	4	3
12	4	5	3	3	5	4	2	4	4	2	5	5	5	4	5	5	4	4	4	3	4	3	5	5

21	20	19	18	17	16	15	14	13
2	4	4	4	4	4	2	4	2
5	5	5	5	5	4	5	5	4
4	4	4	4	3	5	4	4	5
4	5	5	5	5	4	5	4	5
3	5	5	4	4	5	4	4	4
2	3	4	4	3	2	1	4	2
5	5	5	5	5	5	3	5	5
4	5	5	3	3	4	3	5	3
2	5	3	3	3	2	1	5	4
4	5	5	5	4	3	1	4	5
3	5	4	4	4	4	2	4	3
3	5	3	3	3	5	4	4	4
4	5	4	4	3	4	5	5	4
4	5	2	3	4	2	5	5	3
5	4	4	5	3	3	5	5	4
5	5	5	3	4	4	4	5	4
4	4	4	4	3	3	4	5	4
3	4	4	3	3	4	5	5	3
4	3	3	3	3	4	4	4	3
3	3	4	3	4	4	3	5	3
3	5	5	4	3	5	5	5	5
5	4	4	3	3	5	4	5	4
4	5	3	4	4	5	5	5	5
4	4	2	5	2	2	4	5	3

Appendix B Survey - weighting of perceived importance - Lede(1-2)_05.21

ID	Social	Environm	Economic	S1 - Social	S2	S3 - Tot.	S4 - Health	S5	S6	S7- Non-	S8	S9	E1 - LCA	E2 - LCA	E3 - LCA	E4 - LCA	E5 -	E6 -	C1 - LCC	C2 - LCC	C3 - LCC	C3.1 -	C4 - LCC	C5 - LCC
1	5	5	5	5	5	4	5	5	4	5	5	5	4	4	5	5	4	5	4	5	5	4	5	5
2	4	3	5	4	4	3	5	3	3	3	4	4	3	3	3	3	4	4	4	3	4	4	4	3