# STRATEGIC INTEGRATION OF A NEW TECHNOLOGY FOR ADVANCING SUSTAINABLE MINING

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**ABSTRACT**

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Abstract

Minerals and metals are fundamental to contemporary society, powering everything from renewable energy systems to electric vehicles. As urbanization and global population growth continue, the requirement for these materials will substantially escalate. This increasing demand highlight the critical need for sustainability and green practices, especially underscoring the urgency for sustainable mining practices.

This master's thesis explores the strategic integration of a new technology, muon imaging, into Finland's mining sector. Muon imaging provides detailed subsurface data through density variations, marking a less invasive approach to exploration and improving operational efficiency and safety. The environmental benefits and contributions to more sustainable mining practices with muon imaging are linked to improved resource extraction efficiency, reduced need for extensive drilling and the utilization of overlooked orebodies. This thesis combines research data and theoretical models, including strategic management and innovation diffusion, with tools like environmental scanning and SWOT analysis, enhanced by the AQCD framework into an iterative action research process.

This thesis aims to address two key research questions: Firstly, it seeks to understand how a strategy that integrates muon imaging into the mining sector can be developed to contribute to sustainability. Secondly, it explores how this strategy can be effectively implemented within the Finnish mining sector. The implementability and credibility of the constructed strategy is assessed with its alignment with existing EMS, incorporation of sustainability principles, focus on making well-informed choices, engagement of stakeholders, a systematic approach, and a dedication to continuous improvement.

The results collectively demonstrate how muon imaging can be strategically integrated into the mining sector to enhance sustainability, reduce environmental impact, and gain stakeholder trust, thereby advancing sustainable mining.



Key words<br>Sustainable mining, mining sector, Finland, strategic management, diffusion of innovation, strategy, muon imaging


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**TIIVISTELMÄ**

| Tekijä<br>Laura Puronaho | |
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Tiivistelmä


Mineraalit ja metallit ovat olennainen osa nykyaikaista yhteiskuntaamme, mahdollistaen kaiken uusiutuvista energiasysteemeistä sähköautoihin. Urbanisaation ja maailmanlaajuisen väestönkasvun jatkuessa näiden materiaalien tarve kasvaa merkittävästi. Tämä kasvava kysyntä korostaa kestävyyden ja vihreiden käytäntöjen kriittistä tarvetta, erityisesti kestävien kaivostoimintatapojen kiireellisyyttä.

Tämä pro gradu -tutkielma tutkii uuden teknologian, myonikuvantamisen, strategista integrointia Suomen kaivossektoriin. Myonikuvantamisen avulla on mahdollista saada yksityiskohtaista tietoa maanpinnan alaisista rakenteista tiheysvaihteluiden avulla, mikä johtaa vähemmän invasiiviseen malminetsintään parantaen toiminnallista tehokkuutta ja turvallisuutta. Myonikuvantamisen käyttö tukee kestävämpää kaivostoimintaa tarjoamalla mahdollisuuden resurssien tehokkaampaan käyttöön, kairaustarpeen vähentämiseen ja aiemmin huomiotta jääneiden malmiesiintymien hyödyntämiseen.

Tutkielma yhdistää tutkimustietoa ja teoreettisia malleja, mukaan lukien strategisen johtamisen ja innovaatiodiffuusion teoreettiset mallit, sekä työkaluja kuten ympäristöskannaus ja SWOT-analyysi, joita AQCD-kehys täydentää iteratiiviseksi toimintatutkimusprosessiksi. Tutkielman tavoitteena on vastata kahteen keskeiseen tutkimuskysymykseen: Ensinnäkin pyritään ymmärtämään, kuinka strategia, joka integroi myonikuvantamisen kaivosalaan parantamaan kestävyyskäytäntöjä, voidaan luoda. Sen jälkeen selvitetään, miten tämä strategia voidaan onnistuneesti soveltaa Suomen kaivossektoriin. Strategian soveltuvuutta ja luotettavuutta arvioidaan sen yhteensovittamisella nykyisiin ympäristöjohtamisjärjestelmiin, sisällyttämällä kestävyysperiaatteita, tekemällä perusteltuja päätöksiä, ottaen sidosryhmät mukaan, noudattamalla systemaattista lähestymistapaa ja sitoutumalla jatkuvaan kehittämiseen.

Tulokset osoittavat, kuinka myonikuvantaminen voidaan strategisesti integroida kaivosalalle kestävyyden parantamiseksi, ympäristövaikutusten vähentämiseksi ja sidosryhmien luottamuksen saavuttamiseksi, edistäen näin kestävää kaivostoimintaa.



Asiasanat
Kestävä kaivostoiminta, kaivossektori, Suomi, strateginen johtaminen, innovaatiodiffuusio, strategia, myonikuvantaminen


Säilytyspaikka
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**ABBREVIATION LIST**

AQCD – Actionable, Quantitative, Comparative, Divisional
EIA – Environmental Impact Assessment
EU – The European Union
GTK – Geological Survey of Finland (Finnish: Geologian Tutkimuskeskus)
MEAE – The Ministry of Economic Affairs and Employment of Finland
(Finnish: Työ- ja elinkeinoministeriö, TEM)
NGO – Non-Governmental Organization
SDG(s) – Sustainable Development Goal(s) by the United Nations
SLO – Social License to Operate
SWOT – Strengths, Weaknesses, Opportunities, Threats
UN – The United Nations

## TERMINOLOGY

**Muon imaging –** Depending on the research, terms such as *muography*, *muon tomography* or *muon radiography* may be used. In this thesis, "muon imaging" is chosen as a comprehensive term to emphasize the technology's potential rather than delve into its technical nuances. It serves as an overarching label for the discussion.

**Organization -** A structured entity consisting of individuals that collaborate to achieve a specific goal or objective. An organization may be a business, governmental agency, non-profit organization, or an educational institution. In this master's thesis, the term organization is used on a general level to cover all the beforementioned institutions.

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# INTRODUCTION

## 1.1 Background of the research

Sustainability has in recent years become a paramount priority and pressing mandate for businesses. Integrating sustainability into business operations is not only ethically, environmentally, and socially necessary and responsible, but also strategically advantageous since it brings resilience, drives innovation, and is more likely to bring long-term success (Heslin & Ochoa, 2008). The Brundtland Commission's (1987) widely cited definition encapsulates sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (as cited by Carroll, 2015, p. 92).

Minerals and metals constitute the backbone of modern civilization, indispensable for daily life, from renewable energy infrastructure to electric vehicles. As the global population grows and income levels and urbanization surge, the demand for these resources escalates accordingly (Hokka & Eilu, 2023; IGF, 2021). While mining is often seen as something ‘necessary evil’, it serves as the bedrock upon which our contemporary lifestyle is built and rests upon (Kaivosteollisuus, 2021). Even with an increase in recycling, which is projected to reach only 5–20 percent of the global growing demand for metals by 2040, a 100 percent recycling rate would be insufficient to meet the future demand for metals (Hokka & Eilu, 2023). Recognizing this, it becomes imperative to quickly foster sustainable mining practices that prioritize energy and resource efficiency, aiming to minimize environmental impact. Moreover, advancements in technology and digitalization within the mining sector offer promising opportunities for achieving a holistic understanding of a mine’s lifecycle, thereby enhancing sustainability and environmental and social performance (Mine.io, n.d.). Given the imperative role of mining, minerals, and metals in facilitating a green transition, Finland, with its substantial geological potential (Eilu, 2011), is well-positioned to supply essential resources both domestically and to the global market (The Ministry of Economic Affairs and Employment of Finland [MEAE], 2023a). Moreover, the Finnish National Battery Strategy 2025 sets a target for Finland to emerge as a globally significant player in the battery industry (MEAE, 2021).

In the mining industry, stakeholders are increasingly pressuring for improvements in performance due to existing social and environmental challenges (Kapelus, 2002, as cited in Ranängen & Lindman, 2017). While academia offers several models, theories, and systematic approaches, the true value of sustainability efforts becomes evident when they are practically implemented in real-world contexts. Despite the cyclical nature of the mining industry, driven by fluctuations in global raw material prices (MEAE, 2023a), there remains a growing demand for sustainable mining practices (e.g., IGF, 2021).

Muon Solutions Ltd is a privately-owned Finnish company offering muon imaging techniques (Muon Solutions Ltd, n.d.) that provide remotely scanned data on e.g., the bedrock, based on density variations allowing more detailed subsurface data (Holma et al., 2022a). In essence, muon imaging uncovers the internal details of a subject (Yang et al., 2018). Holma et al. (2022a), argues that muon imaging has significant future and current potential when it comes to geological research and geotechnical and mining engineering by contributions towards less invasive exploration, increased operational efficiency and enhanced safety. By reducing drilling and enhancing operational efficiency, environmental performance improves, thereby advancing sustainable mining. This thesis has been written in collaboration with Muon Solutions Ltd.

In this master's thesis (hereafter, “thesis”), action research is conducted to gain a holistic understanding of the mining sector in Finland, focusing on the potential environmental improvements brought by advancing a new geophysical imaging technique, muon imaging. The research data is synthesized into an actionable strategy, utilizing the theoretical framework of strategic management and innovation diffusion with the help of environmental scanning and SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, complemented with the AQCD (Actionable, Quantitative, Comparative, Divisional) framework. The strategy is designed for use by entities who employ remote sensing and/or geophysical methods, particularly within the mining sector in Finland.

## 1.2 Research design, objectives and research questions

This thesis aims to explore how muon imaging can enhance sustainability within the mining sector, with a particular focus on Finland. By collecting and analyzing data from literature, case studies, and government reports, this research will utilize action research methods to explore the benefits and obstacles associated with adopting muon imaging technology in Finland's mining sector. Given the limited research on implementing new technologies in the Finnish mining sector, the study first seeks to understand the current mining environment before integrating muon imaging into strategies. Action research is chosen for its dynamic and practical approach by bridging academic research with practical relevance. By developing a strategic framework using strategic management and innovation diffusion principles, the research aims to provide actionable recommendations for optimizing resource usage and reducing environmental impact. The strategy construction will incorporate a SWOT analysis, supported by an AQCD framework, along with environmental scanning, to ensure effectiveness and feasibility. Overall, this thesis contributes to sustainability literature, corporate environmental management, and sustainable mining in Finland by introducing innovative technology addressed in a specific context and offering actionable recommendations in the form of a strategy. The research is guided by conceptual and theoretical frameworks, thereby making a contribution to both academia and the practical realm.

Within the mining industry's history, technological innovation has played a vital role in making the mining more efficient. The current wave of technological adoption encompasses both evolutionary and revolutionary advancements, with a growing emphasis on the latter (IGF, 2021). The sustainability promises of utilizing muon imaging to enhance the mining sector lies in its potential to revolutionize exploration and monitoring practices in a non-invasive way while minimizing environmental impact. Ultimately, the goal is to contribute to more sustainable mining that consider economic viability, environmental concerns, and social responsibility. By muon imaging, actors in the mining sector can gain valuable insights into subsurface structures without as extensive a need for drilling and excavation, reducing resource consumption and habitat disturbance (Holma et al., 2022a). The various actions of the green transition and the growth of societal digitalization increase demand and raw material needs (MEAE, 2023a). Global uncertainty (such as the Russian invasion of Ukraine and climate change) acts as strong drivers for raw material self-sufficiency (MEAE, 2023a; OECD, 2023). Political, economic, and environmental factors are not the sole drivers of the need for innovations; the increasingly complex geology of ore deposits is also necessitating new technological advancements to enable efficient mining (IGF, 2021).

The topic is relevant since muon imaging holds potential to contribute to more sustainable mining not only in Finland but globally. Furthermore, this thesis explores the processes of adaptation and adoption of muon imaging into the Finnish mining sector. It investigates how the sector is incorporating (adopting) this cutting-edge technology for more efficient mineral exploration and environmental performance of the Finnish mining environment. Within this context, adoption refers to the sector's acceptance of muon imaging as a novel technological approach. In the coming years, Finland anticipates the opening of new mines (Tuusjärvi et al., 2014, as cited in Ruokonen, 2020), emphasizing the growing need to ensure a stable supply of metals and mineral raw materials for the nation's economic development, growth, and competitive edge (VTV, 2021; Ruokonen, 2020). Finland, geologically situated within the Fennoscandian Shield and possessing considerable potential for new ores and mining ventures (Eilu, 2011), also holds a pivotal position in the European Union's (EUs) raw materials policy (MEAE, 2023a; Ruokonen, 2020).

Given this context, the following research questions (RQ) were formed:

**RQ1.** *How can a strategy be developed where muon imaging is integrated into the mining sector to enhance sustainability practices?*

Followed by:

**RQ2.** *How can this strategy be implemented in the Finnish mining sector?*

It is essential to note that while this study addresses social responsibility through stakeholder considerations, it does not cover aspects such as labor conditions and health and safety measures in mining operations. Furthermore, economic and cultural dimensions, which are integral to a comprehensive understanding of sustainability, are also excluded from this study. In this thesis, 'environmental sustainability' refers to the maintenance of the natural world and its resources to ensure the health and viability of ecological systems for both current and future generations.

## 1.3 Disposition

The thesis commences with a brief overview of the mining sector and its environmental aspects in Finland in chapter 2. Thereafter, the standards and initiatives within the mining sector discussed in this thesis are summarised. Chapters 3 to 5 will introduce the theoretical framework, consisting of three (3) different theories, commencing with an exploration of strategic management. Strategic management (1) will cover the process of defining, formulating, and implementing strategies, with a particular focus on how sustainability aspects and stakeholder engagement influence strategic construction and decision-making. The second part of the theoretical framework comprises strategic tools (2), including a SWOT analysis complemented by the AQCD framework and environmental scanning. A SWOT analysis will be conducted and complemented by the AQCD framework, specifically targeting the mining sector in Finland to assess how muon imaging could facilitate the adoption of more sustainable practices within the sector. Additionally, environmental scanning will be employed to provide further support for the implementation of the proposed strategy. Innovation diffusion serves as the third part (3) of the theoretical framework because it addresses the process by which new technologies, like muon imaging, are adopted and integrated into existing practices.

Chapter 6 introduces muon imaging and its geotechnical applications, focusing on its use in mining contexts. The exploration of how muon imaging contributes to the promotion of sustainable mining practices across various stages of mineral exploration is examined.

Chapter 7 focuses on the research methodology, highlighting the selection of the active research method as the most suitable approach for integrating muon imaging into the mining sector. The iterative nature of action research facilitates continuous adaptation and improvement of strategies, crucial for addressing the dynamic challenges in the mining sector, aligning well with the aim of this thesis.

In Chapter 8, the results will present an implementable strategy constructed from the research conducted in this thesis, while Chapter 9, the discussion, will delve into further addressing and evaluating the strategy. The thesis will conclude with final remarks and recommendations for future research in Chapter 10.

# 2 FINNISH MINING SECTOR

This chapter offers a brief overview of the Finnish mining sector and minerals sector. Following this, mineral exploration is explained to emphasize the interdisciplinary approach of this thesis that integrates corporate environmental management and geology. Subsequently, it discusses the environmental implications of mining activities. In this thesis, the terms *mining sector* and *mining industry* are differentiated based on their scope. The *mining sector* encompasses a broad range of dimensions, including industrial and commercial activities, regulatory frameworks, contributions to overall economic development, socio-economic interactions with stakeholders, and environmental impacts. In contrast, the *mining industry* specifically refers to the commercial aspects of mining, highlighting technological advancements and market dynamics. This distinction clarifies the comprehensive approach of the thesis, addressing both the business operations of mining and its wider implications on society and the environment. The examination of the Sustainable Development Goals (SDGs) established by the United Nations (UN) from the viewpoint of the mining industry in Finland serves the purpose of aligning sustainability initiatives within Finland with global commitments. This perspective is vital for developing practical recommendations and strategies that are aligned with both national priorities and global sustainability goals. The chapter also outlines the key standards, initiatives, and regulations relevant to the mining sector, which are referred to later on in this thesis.

## 2.1 Mining sector

The mining industry significantly contributes to the Finnish economy by supplying metals and minerals essential for various sectors of the export industry (Mining Finland, n.d.). According to MEAE (2023b), in 2022, 22 mining companies reported activity in 43 mining sites in Finland, with a total excavation amount of 119,4 million tonnes. The investments in the mining sector in Finland were 304 million euros in 2022 (MEAE, 2023a). The total turnover of companies in the mining sector was 2.93 billion euros in 2022, representing an increase of approximately 0.5 billion euros compared to the year 2021 (MEAE, 2023a). Additionally, mining operations generate economic activity in regions where they are situated (Kokko, 2014; MEAE, 2010, as cited in Ruokonen & Temmes, 2019). The outlook for Finland's mining industry has remained stable due to strong demand for raw materials (MEAE, 2023a). Finland has a mining cluster comprising of over ten mining-related universities and research organizations, in addition to more than 200 mining technology and service providers, along with over 40 mines and ten smelters and steel mills (Mining Finland, n.d.). The Finnish government encourages research organizations and private companies to find solutions, develop, and come up with innovations for sustainable mining practices by e.g., project funding, investment promotion, and innovation- and consulting services (Mining Finland, n.d.). Current research and technological developments within the mining industry are geared towards e.g., minimizing the industry's environmental impact (Endl et al., 2020, as cited in Ruokonen, 2021), addressing water-related challenges (Krogerus & Pasanen, 2016, as cited in Ruokonen, 2021) and waste management (Kiventera, 2019; Obenaus-Emler et al., 2019, as cited in Ruokonen, 2021). Moreover, there is increasing attention on raw materials' traceability and sustainable sourcing (e.g., IEA, 2023a).

Finland is located on a geological formation called the Fennoscandian shield which indicates a strong exploration potential (Eilu, 2011). Fennoscandia possesses known and estimated metallic mineral resources that based on 2007 consumption levels, could fulfill EU demand for chromium, lithium, niobium, nickel, rare earth elements, tantalum, titanium, and vanadium for over 50 years (Eilu, 2011). Fennoscandia comprises Norway, Sweden, Finland, and northwestern Russia (Russian Karelia and Kola Peninsula) (Eilu, 2011). Additionally, Fennoscandia could satisfy EU’s demand for iron ore, cobalt, platinum, palladium, and uranium for 10–30 years (Eilu, 2011). The region also boasts easily exploitable resources of copper, gold, manganese, molybdenum, silver, zinc, and zirconium, making it a significant future metal supplier and a resource base for Europe as a whole (Eilu, 2011).

## 2.2 Minerals sector

The minerals sector consists of extractive, mining- and metal processing industries (MEAE, n.d.a). Exploration, extraction of industrial minerals and metal ores, and the production of concentrates is a part of the mining industry (MEAE, n.d.a).

Finland holds a prominent position as a mineral producer within the EU, particularly in five key metals: chromium, cobalt, platinum, palladium, and nickel - either the sole producer or the largest producer of these metals by a significant margin (MEAE, 2023a). For instance, in 2021, Finland contributed approximately 90% of the EU's nickel production (MEAE, 2023a). Finland's global contribution to most produced metals remains relatively low, accounting for less than one percent of global production in most cases (MEAE, 2023a). Moreover, despite Finland's mining activities, Finland remains highly dependent on the import of raw materials (MEAE, 2023b).

Critical minerals such as e.g., copper, lithium, nickel, cobalt, and rare earth elements (REE) are crucial minerals needed by clean energy production (IEA, 2023a). To answer the global demand for lithium, graphite, and cobalt, a production increase of more than 450 percent is required from the levels recorded in 2018 by the year 2050 (World Bank, 2020). In Finland's Minerals Strategy, the following minerals are listed as critical and there is either ongoing production or projects regarding them: cobalt, niobium, and platinum group metals (IEA, 2023a). Low-carbon technologies are in other words mineral-intensive (IGF, 2021), and a shortage of a specific mineral supply may affect the speed and scale by which certain technologies are deployed globally (World Bank, 2020).

### 2.2.1 Definition of mineral exploration

Mineral exploration, or simply exploration, is the search for mineral deposits beneath the Earth's surface aimed at finding ore deposits - economically viable concentrations of minerals, metals, industrial minerals, or gemstones (SGU, 2018). This process employs a variety of methods such as geological mapping, geophysical surveys, geochemical analysis, drilling, and remote sensing to identify and assess potential mineral resources for mining (Tukes, 2019). Mineral exploration involves inherent risks, significant time commitments, and substantial investments, with just one in a thousand projects leading to the discovery of commercially viable deposits (Kaivosteollisuus, 2021). Each ore deposit is distinct, with unique mineralogy, shape, size, ore concentration, and environmental impacts based on its location and the surrounding ecosystem (Ruokonen & Temmes, 2019; SGU, 2018). An ore becomes economically viable for extraction based on economic factors rather than geological ones, often influenced by global market fluctuations, such as metal prices (MEAE, 2023a; Tukes, 2019; SGU, 2018). The feasibility of mining an ore deposit depends on various factors, including the grade and size of the deposit, geological features, societal considerations, extraction costs, and the volume of waste rock that needs to be removed (Kaivosteollisuus, 2021; SGU, 2018). Geological characteristics, such as the deposit's shape, depth, mineralogy, texture, and whether it is polymetallic (multiple metal elements in the same ore body), significantly affect mining economics (SGU, 2018). Mining methods may include river stream mining, open-pit mining, underground mining, or a combination thereof (SGU, 2018).

Geological drilling for mining and exploration involves drilling boreholes to collect rock, mineral, and soil samples from the subsurface, which are analyzed to obtain information about the Earth's crust (SGU, 2018). An active mine may encompass thousands of boreholes (Holma et al., 2022a), with exploration often relying on geophysical methods or remote sensing and a deep understanding of local geology (Lechmann et al., 2021).

Mineral exploration is categorized into greenfield and brownfield based on the stage of project development (Holma et al., 2022a). Brownfield exploration occurs near operational or previously closed mines, focusing on areas with known mineral deposits (Holma et al., 2022a). In contrast, greenfield projects target regions that are unexplored or insufficiently explored, often encompassing parklands, agricultural fields, or undeveloped spaces near urban areas, and typically lack mining infrastructure (Holma et al., 2022a; GRGE, 2022, as cited in Dorsey, 2003). Expanding environmental discourse to encompass both brownfield redevelopment and greenfield protection is crucial, as rehabilitating brownfields can benefit natural environments and reduce development pressures on pristine greenfields (Dorsey, 2003).

## 2.3 Environmental considerations

Mining operations result in various environmental consequences, including alterations to the landscape, water pollution, air emissions, and significant water and energy usage (SGU, 2018). These challenges are closely interconnected with concerns such as the loss of biodiversity, climate change, and the depletion of water and natural resources (Ruokonen & Temmes, 2019). Mining activities can have adverse effects on the well-being and health of nearby communities, known as environmental health effects (GTK, 2015). These effects and associated risks are specific to each mine and depend on factors such as the type of mine, its processes, and its proximity to the population and surrounding environment (SGU, 2018; GTK, 2015). Additionally, the operation of the mine can cause nuisance through noise and odour, and potentially lead to environmental pollution and restrictions on the use of natural resources such as lake waters and fishing areas (GTK, 2015). Concerns related to emissions, such as uncertainty and potential health risks, as well as socio-economic impacts (SGU, 2018) like property devaluation and stress, further contribute to the adverse effects on the environment and local communities (GTK, 2015). Mining is often associated with fear, suspicion and doubt, which has a significant impact on people's preconceptions and perceived disadvantages (GTK, 2015). The criticism from non-governmental organizations (NGOs) and citizens towards new mining projects has increased (MEAE, 2023a). Companies should therefore continually increase transparency and describe the overall impacts of their operations on the local environment and people (MEAE, 2023a; SGU, 2018).

The statutory process of environmental impact assessment (EIA) involves collecting data on the existing environmental conditions of the area to understand project implementation conditions and constraints, establishing a baseline for evaluating environmental impacts, tracking operational effects, and observing post-operation environmental changes and rehabilitation objectives (Government Decree on the Environmental Impact Assessment Procedure, 277/2017). By the integration of EIAs, stakeholders can work towards achieving sustainable outcomes that benefit both present and future generations (SGU, 2018). It is essential to conduct a current state survey in all mining projects, ideally in the early stages of the mining life cycle before any activities that alter the environment begin (SGU, 2018). The primary goal of the EIA procedure is to mitigate or eliminate the negative environmental impacts of the project (GTK, 2015). An EIA assesses various implementation alternatives, including the possibility of not proceeding with the project at all (Government Decree on the Environmental Impact Assessment Procedure, 277/2017).

## 2.4 Integration of UN's SDGs with the Finnish mining sector

In 2015, the UN Member States outlined a vision for achieving sustainable development through the 2030 Agenda for Sustainable Development, comprising 17 interlinked and ambitious Sustainable Development Goals (SDGs) (Figure 1) covering economic growth, social inclusion, and environmental protection (UN, 2023). The 17 SDGs are important as they offer a holistic framework to tackle global challenges, serving as a blueprint for creating a more sustainable and equitable future for all (UN, 2023). These goals are designed to guarantee access to decent work, quality healthcare, and education for all, reduce environmental harm, and promote inclusive policies, emphasizing that from world leaders to individuals, everyone plays a crucial role in fostering sustainable development for our shared future (UN, 2023). The global mining industry affects all the 17 SDGs, with potential positive or negative impacts (The Global Goals, n.d.; UNDP et al., 2016). From the perspective of the Finnish mining sector, the SDGs number 8 and 9 have the most positive direct impact, whereas the direct negative effects are related to SDGs 6, 11, 13 and 15.


Figure 1. The global goals for sustainable development (globalgoals.org/resources.)

*SDG 7*, which focuses on ensuring access to affordable and clean energy, is indirectly supported by the mining sector through the provision of essential raw materials required for the green transition (MEAE, 2023a; AGEMERA, n.d.). The mining industry plays a pivotal role in this process by extracting minerals and metals critical for renewable energy technologies, such as solar panels, wind turbines, and batteries for electric vehicles. By utilizing renewable sources of energy within its own operations, the mining sector can further contribute to this goal. The positive effects on *SDG 8* concerning economic growth relates to mining activities contributing to economic growth in Finland, by employment, revenue generation and creating investments to infrastructure and service (MEAE 2023a; VTV, 2021). Employment opportunities contribute to well-being of especially communities in remote regions, with limited job opportunities (MEAE, n.d.b.). Incorporating strategies into SDG 8 that drive economic growth by educating local suppliers to answer corporate supply demands and ensuring local contractors have fair access to bidding opportunities is essential (UNDP et al., 2016). *SDG 9* concerning industry, innovation and infrastructure, relates to mining industry by the mining operations requiring advanced technological solutions (MEAE, 2023a; VTV, 2021) and infrastructure (UNDP et al., 2016) and moreover, this drives innovations and fosters the development of high-tech mining solutions in Finland (MEAE, 2023a; Mining Finland, n.d.). Implementing muon imaging technology within Finland's mining industry presents an opportunity to align with *SDG 12*, which emphasizes responsible consumption and production. This alignment with SDG 12 can be achieved by enhancing resource efficiency in exploration and mining processes, where muon imaging, as Holma et al. (2022a) claim, enables the detection of previously undiscovered or unused ore bodies for a more targeted and efficient extraction process. This not only reduces waste by ensuring that fewer resources are consumed in the search for viable mining sites, but it also potentially minimizes environmental disruption associated with traditional exploration methods.

The negative effects are mostly related to environmental concerns, such as *SDG 6*, water quality and sanitation, where mining activities can contaminate nearby water sources with runoffs and leaches containing heavy metals and toxic chemicals (GTK, 2015). Sustainable cities and communities, *SDG 11*, may be counted to either positive or negative effects of mining activities based on possible arising social tensions between the mining company and the local stakeholders (Ruokonen, 2021). While mining can provoke disputes and challenge sustainable urban development accepted by local communities (Pettersson & Suopajärvi, 2018; SGU, 2018), positive outcomes are possible when local stakeholders are involved in decision-making and the mining company makes financial or other beneficial contributions to the community (MEAE, n.d.b.). Meaningful engagement of stakeholders is necessary to foster mutual understanding and work towards sustainability goals in the mining sector (Matikainen, 2022; SGU, 2018). *SDG 13*, climate action, relates to the large energy consumption mining activities require and transportation relying on fossil fuels, thus contributing to greenhouse gas emissions (MEAE, 2023a). SDG 13 is linked to SDG 7 concerning affordable and clean energy, where mining sector provides the raw materials needed for e.g., electric vehicles therefore eventually reducing the need for fossil fuels. *SDG 15*, focusing on life on land, highlights environmental degradation originating from water pollution, habitat destruction, soil erosion, and air pollution, including dust (The Global Goals, n.d.). Additionally, noise, tremors, and increased traffic are recognized as contributing factors to environmental degradation under this goal (GTK, 2015).

## 2.5 Standards, Acts and Initiatives within the mining sector

There are numerous standards, initiatives and legislation for the mining industry. In the following, the most relevant for this thesis are briefly summarized.

Established in 2004, the Towards Sustainable Mining (TSM) standard is a globally recognized sustainability program (TSM, 2024). It supports mining companies in managing environmental and social risks with the primary goal of empowering them to meet society's demand for minerals, metals, and energy products in a manner that is socially, economically, and environmentally responsible (TSM, 2024, 2022). They provide the companies with a set of tools and indicators on responsibility on several levels, with the focus on two key areas that are communities & people and environmental stewardship (TSM, 2024). TSM is used globally, and in Finnish, this standard is known as *Kaivosvastuu*, and is adjusted to fit the Finnish legislation (TSM, 2024). It helps in building the capacity of the environmental and social performance of the mining companies and it motivates the whole industry to raise the bar when it comes to e.g., corporate responsibility (TSM, 2022). According to a study conducted by Ruokonen (2020), 78% of the survey respondents (mainly mine managers) agreed that TSM covers all relevant sustainability aspects. Despite the implementation of TSM, securing a societal license to operate (SLO) necessitates collaborative endeavours among society, industry, and government to foster dialogue, relationship-building, and trust (Lesser, 2021, as cited in Ruokonen, 2022).

*Mine.io - A holistic digital mine 4.0 Ecosystem* is a project with the objectives to address key challenges and drive innovation in the mining industry. It is co-funded by the EU and focuses on the sustainable development, industrialization, and informatization of the mining sector covering the whole value chain from exploration to post-mining activity (Mine.io, n.d.). The project has 25 partners, 7 pilot use cases and a budget of 14 million euros (Mine.io, n.d.). The project focuses, among all, on extending the use of digital twinning into the mining industry that will support the decision-making by providing detailed information by predicting and testing the behaviours of these so-called twins in a real-life scenario (Horizon Europe, 2022). By having a digital environment in a cloud, the systematisation, robotisation and automatization are going to be enhanced from the stages from exploration, production, mining and post-mining activities (Horizon Europe, 2022). Muon Solutions Ltd is a partner in this project, by offering muon imaging applications in amongst all underwater exploration (Mine.io, n.d.).

An Environmental Management System (EMS) is a structured framework designed to guide organizations in systematically managing and enhancing their environmental performance to improve sustainability, as outlined by the International Organization for Standardization, ISO (ISO, n.d.). The core objectives of an EMS are to assess environmental performance, ensure compliance with legal requirements, and continually refine sustainable practices within the organization (ISO, n.d.). Involvement of stakeholders is integral to the decision-making process within an EMS (ISO, n.d.). EMS implementation not only improves environmental performance but also yields significant financial benefits (SFS, n.d.). Integrating environmental considerations into mining operations via an EMS promotes sustainability and ensures long-term viability in the sector (ISO, n.d.). In this thesis, an EMS is relevant as the strategy builds upon the assumption that it exists within the company that integrate muon imaging into its operations.

The European Commission (EC) has created a list, subject to regular review and update, of critical raw materials (CRM) that are extensively utilized across various industries and holds a key role in the European economy, but their procurement poses significant risks (EC, 2023). EU depends significantly on imports of these CRM from non-EU countries, which are difficult to substitute and largely sourced from outside Europe (EC, 2023; AGEMERA, n.d). This dependency, combined with the escalating global demand driven by the shift towards a digital and environmentally sustainable economy, exposes supply chains to vulnerabilities (EC, 2023). For instance, 97% of EU's magnesium supply is sourced from China and 71% of EU's platinum group metals is provided by

South Africa (EC, 2023). In the long term, this presents a threat to Europe’s and therefore EU’s resilience and autonomy, as numerous sectors, including health, defense, aviation, and telecommunications, rely on them (AGEMERA, n.d.). Finland's participation in EU initiatives is important as the EU seeks to secure a sustainable supply of CRM for its industries. Given Finland's strong mineral potential, as highlighted by Eilu (2011), its participation is indispensable in mitigating EU's dependencies and strengthening the resilience of its supply chains amid the transition to a digital and green economy.

# 3 STRATEGIC MANAGEMENT

This chapter explores the first part of the conceptual theoretical framework, strategic management, which represents one-third of the overall theoretical framework for this thesis. It includes defining strategy, its formulation, implementation, and the integration of sustainability into strategies within the mining sector, along with considerations for stakeholder engagement. Strategic management is essential for promoting sustainability within the Finnish mining sector by enabling long-term planning, mitigating risks, optimizing resource usage, engaging stakeholders, ensuring compliance, and gaining a competitive edge.

## 3.1 Definition of strategy

The definition of strategy is argued and does not fit into one sentence due to its complexity and wide range of contexts (Khalifa, 2021). One widely cited definition of strategy, as described by Porter (1996), involves making choices, including decisions about what not to pursue. The principal dimensions of defining a strategy consist of positioning an organization to gain advantages when it comes to competition, selecting the markets to be present in, and how the allocation of resources is managed (De Kluyver et al., 2015). The paramount object of a strategy is to provide enduring value for shareholders and stakeholders by delivering customer value (De Kluyver et al., 2015). Furthermore, as argued by Khalifa (2021), strategy is intentional and a concept that applies to an entire system rather than its individual components. Strategy is distinguishable from priorities, goals, plans, mission, and vision; instead, it represents the outcome of executive decisions regarding what offerings to provide, where to operate, and how to succeed, all aimed at optimizing long-term value creation (De Kluyver et al., 2015). Strategy in the form of guiding decisions enables the summarization of strategy into a brief statement that is easily communicable and understandable (Collis & Rukstad, 2008, as cited in

Khalifa, 2021). This thesis adopts Khalifa's (2021) definition of strategy, which conceptualizes it as an entity's selected approach for engaging with its environment to overcome challenges related to survival and prosperity.

Competitive strategy revolves around differentiation, involving the deliberate selection of a distinct set of activities aimed at providing a unique combination of value (Porter, 1996). Competitive advantage through strategy can also be gained when an organization operates at the intersection of its business objectives and environmental and societal well-being (De Kluyver et al., 2015). Creating profit for shareholders while simultaneously safeguarding the environment and improving the lives of other stakeholders, is not only an essential part of the organization's corporate social responsibility (CSR) but also a strategic edge (Heslin & Ochoa, 2008). Competitors may have the capacity to react to the organization's actions but lack insight into the strategic rationale behind the organization's decisions, especially how future environmental factors are perceived in the organization and why (Tighe, 2019). Therefore, the strategic perspective represents a valuable corporate asset (Tighe, 2019).

## 3.2 Strategy formulation and implementation

The focus when formulating a strategy is value creation for the community, shareholders, customers, suppliers, partners, and employees by answering the wants and needs better than the competitor(s) (De Kluyver et al., 2015; Heslin & Ochoa, 2008). Value undergoes redefinition with the entry of new competitors or increased customer knowledge in the market, necessitating constant product or service development and maintenance to prevent a decline in value (De Kluyver et al., 2015). Even if the competitive advantage might seem superior, the changes in the strategic surroundings might erode the value, if the current advantages are not protected against competitors and the capabilities to formulate the next stance are not invested in (Porter, 1996). Therefore, maintaining a competitive strategy is an ongoing process (Tighe, 2019; De Kluyver et al., 2015).

When a strategy is formulated, options are created, since the predictability of some outcomes are more likely (De Kluyver et al., 2015). Different contingencies must be considered to maintain a degree of flexibility, as the learning process that occurs when the strategy is implemented allows the organization to understand how the chosen direction affects competitive advantage (De Kluyver et al., 2015). Constructing scenarios is most effective when undertaken by diverse teams, as the range of experience, knowledge, and opinions enhances the likelihood of generating valuable strategic insights (Tighe, 2019). According to the model by De Kluyver et al. (2015), the formulation of strategy consists of defining three main points, *the current position*, *the desired position*, and *how the position is reached*.

*The current position* requires an assessment of the organization and the state of the business. It aims to answer the most fundamental questions such as what the mission is, who the most important stakeholders are, and what the long-term vision of the company looks like. It also requires an evaluation of the broader environment: economic, technological, sociopolitical and legal operational environment. A SWOT analysis of the industrial environment (opportunities and threats) and the internal (strengths and weaknesses) supports the strategy formulation process. (De Kluyver et al., 2015)

*The desired position* is based on the evaluation of the current position and what strategic alternatives it has generated. It identifies the driving force and steers the business concept in order to move the organization forward and closer to the desired position. This phase includes adjusting the business portfolio, evaluating processes and philosophies, the possible collaboration with other companies, and choosing which market segments to concentrate on. (De Kluyver et al., 2015)

*How the position is reached* addresses the capability gap and how the bridge between the desired and current organizational capabilities and skills is addressed. It focuses on finding the key success factors when strategically aligning the emerging market needs with the organization's core competencies. This phase leads to a comprehensive set of initiatives for executing the strategy and ensuring discipline and control throughout its implementation. (De Kluyver et al., 2015)

Tighe (2019) argues that too much emphasis has been placed on the designing stage of strategy rather than on the equally important component, execution (Figure 2). Treating design and implementation as equally crucial and interconnected components is essential for achieving strategic success, as failure to do so often leads to shortcomings in strategy execution (Tighe, 2019). Outstanding execution cannot offset design deficiencies and similarly, an exceptional design is not capable of compensating for inadequate execution (Tighe, 2019).


Figure 2. Achieving strategic success necessitates treating design and implementation as integrated and equally important components of the strategy (Tighe, 2019, p. 61).

Therefore, when developing a roadmap and considering the current and desired positions along with the necessary steps in between (De Kluyver et al., 2015), it is crucial to address them in a manner that facilitates effective strategy execution in practice (Tighe, 2019). Implementing practices and strategies that foster sustainable business growth, minimize environmental impact, and improve the well-being of communities and employees is integral to achieving sustainability (Stoiconi, 2024).

## 3.3 Integrating sustainability into strategies

Business sustainability refers to a company's ability to pursue its long-term objectives across economic, social, and environmental domains while preserving resources for future generations (Stoiconi, 2024). Businesses have gradually been recast as key stakeholders in the conversation on sustainable development, alongside government, civil society, and NGOs, as the perspective has shifted over time (Murthy, 2012). While it is crucial to integrate sustainability into a company’s mission, values, strategies, and goals, this alone is insufficient to fully establish sustainability as a central element of strategic management (Galpin & Hebard, 2018). Corporate sustainability strategies must be customized to suit the circumstances of the organization (Engert & Baumgartner, 2016). Business leaders must foster collaborative dialogue among diverse stakeholders and promote organizational learning at all employee levels to achieve sustainability goals effectively, as an incremental approach is unlikely to accomplish the intended outcomes (Crews, 2010). As Crews (2010) argues, and what is crucial to keep in mind, is that just as there does not exist a singular measure for assessing financial performance, sustainability also lacks a universal metric. Additionally, focusing solely on measurement or reporting can lead to the misconception that achieving specific metrics is the ultimate goal, rather than recognizing progress as part of an ongoing sustainability journey (Crews, 2010).

Developing sustainability-related resources and capabilities are important for gaining strategic competitive advantage, leading to improvements in social welfare, ecological impact reduction, and achievement of organizational goals (Sharma, 2003, as cited in Murthy, 2012). Strategic capabilities, which set a firm apart from its competitors, involve the structuring of activities, often necessitating investments to establish and maintain such structures (Galpin & Hebard, 2018). These types of capabilities cannot be effortlessly purchased or bought, but rather be built (Winter, 2003, as cited in Galpin & Hebard, 2018). Research (e.g., Bernal-Conesa et al., 2017) supports the claim of a competitive advantage of including sustainability in the strategy and a firm’s operational model. Bernal-Conesa et al. (2017), claim that the adoption of a CSR-oriented strategy not only significantly enhances organizational performance but also influences the competitiveness and sustainability of technology companies.

Engert & Baumgartner (2016) underline that the implementation of the sustainability strategy into practice is only one component in a big and complex puzzle and thus a ‘wicked problem’. Epstein and Roy (2001, as cited in Engert & Baumgartner, 2016) suggest that effectively bridging the gap between corporate sustainability strategy formulation and execution necessitates the translation of strategy into actionable steps. This translation is facilitated by the development of suitable plans, programs, systems, and performance metrics that play a crucial role in defining sustainability objectives (Engert & Baumgartner, 2016). Implementation of management systems, such as ISO 14001 and EMS, offers guidance for directing the implementation of environmental strategy (Epstein and Roy, 2001, as cited in Engert & Baumgartner, 2016). On a managerial level, integrating sustainability into strategic management is challenging, due to the variation in actions and attitudes among the management (Sharma & Sharma, 2011). Furthermore, even when there is agreement on the importance of sustainability, the decision-makers within a company often possess conflicting views on the most effective ways to integrate sustainability into the firm's strategic management components (Sharma & Sharma, 2011).

The concept of sustainable business models (SBM), increasingly relevant today, encouraged organizations to enhance their impact across the three pillars of sustainability: economic, social, and environmental (Stoiconi, 2024) also referred to as the triple bottom line (TBL) with people, planet, and profit (Crews, 2010). SBM outlines the different ways through which organizations generate, deliver and capture value within the pillars (Vitalie, 2023, as cited in Stoiconi, 2024). According to Crews (2010), the pillars of sustainability are frequently seen as conflicting, resulting in an emphasis on trade-offs instead of pursuing a synergistic approach for mutual benefits. Moreover, creating models to address these pillars is challenging due to the potential conflicts among them (Cardeal, 2020, as cited in Stoiconi, 2024).

Crews (2010) argues that constant organizational change has led to weariness among all the employees, who may perceive sustainability, like other new initiatives, as merely another passing trend. This ongoing cycle can lead to resistance to change, as individuals struggle to adapt amidst frequent transitions and thus, it is crucial to give the involved stakeholder(s) time to adjust (Crews, 2010). Therefore, before effectively communicating a unified purpose and direction to all stakeholders, it is essential for the content of a company's mission, values, goals, strategy, and capabilities to be aligned with each other (Galpin & Hebard, 2018). When there is misalignment among the strategic management components, it may lead to confusion among both internal and external stakeholders regarding the company's sustainability agenda (Galpin & Hebard, 2018).

Research shows that improved firm performance is a result of aligned strategic management (Wu et al., 2014, as cited in Galpin & Hebard, 2018) and that achieving efficient and socially responsible growth extends beyond gaining a competitive edge; it involves integrating sustainability into business practices (Stoiconi, 2024; Bernal-Conesa et al., 2017).

## 3.4 Incorporating stakeholder engagement to strategies

Individual organizations cannot independently address complex sustainability challenges but must engage with their stakeholders to establish resilient and sustainable business models (Dentoni et al., 2020; Senge et al., 2008, as cited in Fobbe & Hilletofth, 2021). Recognizing and incorporating stakeholder needs and expectations is considered important as it impacts both the choice and implementation of strategies (Engert & Baumgartner, 2016). Stakeholder engagement has increasingly attracted scholarly attention in recent decades and has been recognized as a foundational aspect of organizational sustainability (Fobbe & Hilletofth, 2021, and the references therein). Different forms of stakeholder interaction range from low to high degrees, including merely informing and communicating with stakeholders, consultation, participation, and partnerships, to cooperation and collaboration with various stakeholders (Fobbe & Hilletofth, 2021, and the references therein). Exploring how an organization can achieve benefits for all stakeholders, despite conflicting demands and interests, is valuable (Dess et al., 2008, as cited in Crews, 2010) since stakeholders rely symbiotically on each other for their success and well-being (Crews, 2010). The symbiosis demands leaders to incorporate the needs and interests of all stakeholders, rather than addressing them through trade-offs (Crews, 2010). Stakeholders in organizational value-generation activities addressing sustainability issues are categorized as internal (employees and management) or external (customers, suppliers, and competitors), comprising individuals, groups, or organizations that either influence or are impacted by these activities (Fobbe & Hilletofth, 2021, and the references therein).

Meeting the growing demand from stakeholders, sustainability implementation fosters resilience and ethical operations throughout the value chain for businesses with complex supply chains (Stoiconi, 2024). Implementing sustainability strategies is vital for ensuring compliance with tightening environmental regulations by governments worldwide, thereby avoiding possible penalties for not meeting the regulations (Stoiconi, 2024) and thus, reputational challenges (Pineiro-Chousa et al., 2017). Expectations for sustainable operations from customers, investors, employees, and the broader community are on the increase, thus underscoring the importance for businesses to maintain positive stakeholder relationships (Stoiconi, 2024; Pineiro-Chousa et al., 2017). Furthermore, sustainable businesses have the capacity to draw in individuals who are inspired by the organization's dedication to responsible practices (Stoiconi, 2024).

The ever-increasing global awareness of reporting of a company's sustainability practices has led to a competition for credible and quality sustainability reporting (Galpin & Hebard, 2018). When a company discloses its information regarding its sustainability, they are more likely to possess higher market value compared to companies not disclosing their sustainability actions (Wang & Li, 2016, as cited in Galpin & Hebard, 2018). Furthermore, voluntary environmental reporting is crucial as it allows environmentally conscious companies to mitigate potential reputational risk (Pineiro-Chousa et al., 2017). By actively communicating with stakeholders and observing them regularly, it is easier for the company to adapt the strategy to match the external sustainability drivers (Galpin & Hebard, 2018) and therefore, report accordingly.

## 3.5 Strategic environmental management in the Finnish mining sector as a means towards sustainability

In this chapter, Ruokonen's (2022) doctoral thesis and its associated publications are referenced because they offer a comprehensive and up-to-date examination of the combination of the Finnish mining sector and strategic environmental management, making them one of the few available sources on this topic.

Ruokonen's (2022) research on the managerial perspective of strategic environmental management in the Finnish mining industry reveals a positive trend towards adopting sustainable practices. The research highlights the increasing influence of environmental and social factors on companies' business strategies, demonstrating a clear dedication to environmental concerns. However, despite efforts to create value through environmental considerations, such as improving internal efficiency and addressing customer needs, there has been minimal progress in environmental and social disclosures over time (Ruokonen, 2022). Contributions to circular economy, climate change mitigation and biodiversity preservation are also largely overlooked, according to Ruokonen (2022). Furthermore, the study identifies a gap between strategic intentions and implementation, as companies often lack systematic management practices for environmental and social commitments, leading to limited site-specific information provided (Ruokonen & Temmes, 2019).

When it comes to the Social License to Operate (SLO), exceeding the legislative requirements beyond the minimum remains to be solved and balanced in the mining companies (Ruokonen, 2022). According to Pettersson & Suopajärvi (2018), local acceptance in mining communities in Finland is achieved when there are no conflicts, negative feedback, critical media coverage, or social media controversies regarding daily operations, indicating that the operator does not need to justify its presence or activities. Given the immobility of mining operations, gaining trust and maintaining the SLO is crucial for the stakeholder's acceptance regarding the mining industry (Thomson & Boutilier, 2011, as cited in Ruokonen, 2022). Another significant finding by Ruokonen (2022) underscores the Finnish mining industry's adoption of a comprehensive approach to environmental issues, with a strong strategic emphasis on earning SLO through minimizing the emissions to air and water. The shift is most likely originating from amongst all increased external pressure towards the mining companies, underscoring the importance of gaining an SLO and aligning it with societal expectations (Ruokonen, 2021, MEAE, n.d.b.). Meaningful stakeholder engagement in the mining sector overall necessitates deeper interactions beyond surface-level interactions, emphasizing constructive dialogue and collaboration, especially with stakeholders who do not inherently oppose mining operations (Matikainen, 2022).

# 4 SWOT ANALYSIS, AQCD FRAMEWORK AND ENVIRONMENTAL SCANNING

This chapter delves into the second part of the conceptual theoretical framework of this thesis, beginning with definitions of the three (3) strategic tools used to develop an implementable strategy. The first tool is (1) SWOT (strengths, weaknesses, opportunities, threats) analysis that is further filled in with the (2) AQCD (actionable, quantitative, comparative, divisional) framework. Environmental scanning (3) is used to get a broader context. While these tools may have weaknesses and subjective aspects, they are valuable tools to gain insights into the Finnish mining sector, providing a foundation for strategic decision-making and understanding of where new the technology, muon imaging can be positioned. By leveraging these tools collectively, their limitations can be mitigated, as they are viewed as dynamic processes that facilitate strategy development (Pickton & Wright, 1998). This approach in this thesis ensures a comprehensive assessment of internal strengths and weaknesses, external opportunities and threats, actionable insights, quantitative analysis, comparative evaluations, and contextual understanding through environmental scanning.

## 4.1 Definition of a SWOT analysis

A SWOT analysis is a strategic planning tool used to evaluate and identify the *strengths*, *weaknesses*, *opportunities*, and *threats* in several different contexts, in e.g., a business environment context (e.g., Pickton & Wright, 1998). Strengths and weaknesses are internal and refer to activities within an organization (Pickton & Wright, 1998) that are controllable and are executed either exceptionally well or poorly (Barney, 1991, as cited in David et al., 2019). Opportunities and threats are external and primarily influenced by factors external to an organization (Perrnwanichagun et al., 2015, as cited in David et al., 2019). By conducting a SWOT analysis, it is easier to develop strategies that underline the strengths, recognize the weaknesses, make the most out of opportunities, and mitigate the threats (Coman & Ronen, 2009). Without a SWOT analysis, businesses risk overlooking critical factors that could impact their performance and survival, making it an essential tool for enhancing strategic decision-making and ensuring business viability and success (Coman & Ronen, 2009). A SWOT analysis is esteemed for its simplicity and effectiveness in recognizing critical factors influencing business growth and development (Pickton & Wright, 1998) and additionally, it aids in formulating appropriate business strategies particularly at the managerial level (Coman & Ronen, 2009). While it can be instrumental in identifying strategic influences, its simplicity imposes limitations (Coman & Ronen, 2009; Pickton & Wright, 1998). It may prioritize quantity over quality of factors, potentially overlooking impactful elements, and lacks guidance on their relative importance (Coman & Ronen, 2009), potentially resulting in strategic oversights if not employed with other more comprehensive analysis (Pickton & Wright, 1998).

Strengths represent the fundamental internal competencies through which the organization can optimize its potential for value creation and may include factors such as a strong brand or technical competence (Coman & Ronen, 2009). Weaknesses are internal attributes that limit or hinder the ability to achieve an organization's objectives on the market and concerns factors such as slow reaction to competitive threats or lack of innovation (Coman & Ronen, 2009). Opportunities are external factors that could benefit a firm and should be capitalized (David et al., 2019), like growing demand for the organization's products or services and alliances with other e.g., organizations. Threats include external factors that should be mitigated or avoided (David et al., 2019), such as reputational damage or disruptions in the supply chain.

SWOT analysis, integrating both internal and external factors, facilitates the development of these distinct strategies: SO (strengths-opportunities) strategies, WO (weaknesses-opportunities) strategies, ST (strengths-threats) strategies, and WT (weaknesses-threats) strategies (David et al., 2019). Pairing external factors alone lacks significance as firms have no control over them (David et al., 2019). Conversely, pairing internal factors alone would not effectively inform strategy generation without external stimuli (Koo et al., 2011, as cited in David et al., 2019). The SO strategies capitalize on strengths to maximize returns from the market, while the WO strategies identify market opportunities and address weaknesses to exploit these opportunities (University of Hertfordshire, n.d.). The ST strategies emphasize leveraging strengths to counteract market threats, and the WT strategies focus on mitigating market threats and minimizing the impact of recognized weaknesses (University of Hertfordshire, n.d.). Therefore, aligning external with internal factors forms the foundation for devising strategies that best serve the firm's interests (Choo, 1999; Jogaratnam & Law, 2006, as cited in David et al., 2019).

## 4.2 Definition of an AQCD framework

Integrating AQCD (actionable, quantitative, comparative, divisional) criteria with a SWOT analysis enhances the depth and precision of strategic planning (David et al., 2019). An AQCD framework ensures that the analysis yields actionable insights, utilizes quantitative data for evaluation, enables comparative assessments against competitors, and allows for divisional analysis to tailor strategies (David et al., 2019). This integration fosters more informed decision-making, precise resource allocation, and strategic alignment with organizational goals, ultimately enhancing the effectiveness of strategic initiatives (David et al., 2019). Despite its importance, the necessity for specificity is often neglected in strategic planning (David et al., 2019).

The term *actionable* emphasizes that each internal and external factor should be meaningful and useful in guiding strategic decisions (David et al., 2019). These factors should be specific and within the control of management to be considered actionable (Coman & Ronen, 2009). *Quantitative* analysis entails incorporating percentages, ratios, currencies, and numerical data for both internal and external factors (David et al., 2019). This quantification enables strategists to accurately evaluate the scope of opportunities and threats, ensuring that strategies are rooted in precise factual information for effective decision-making in strategic planning (David et al., 2019). *Comparative* refers to the necessity of including factors that show changes over time or in comparison to competitors or industry averages (David et al., 2019). Comparative terms help in understanding the evolution of factors and make informed decisions and they play a crucial role in recognizing unique competencies (Kumar et al., 2006, as cited in David et al., 2019). *Divisional* analysis involves segmenting a firm's products and regions to gain insights into the performance of specific products and regions (David et al., 2019). This distinction is crucial as strategic management responsibilities are increasingly delegated to divisional levels (Grant, 2003, as cited in David et al., 2019). Effective resource allocation across segments, regions, or products is a pivotal strategic decision for companies to facilitate the allocation of resources (David et al., 2019).

## 4.3 Definition of environmental scanning

Environmental scanning involves acquiring and using information about trends, events, and relationships within an organization's external environment to assist management in planning the organization's future course of action (Song et al., 2024; Yu et al., 2019). Organizations conduct environmental scanning to comprehend external forces of change, such as environmental concerns and evolving stakeholder demands, enabling them to formulate effective strategies to enhance or safeguard their future position (Liao, 2018, as cited in Song et al., 2024). Given that an organization's ability to adapt to its external environment hinges on understanding and interpreting ongoing external changes, environmental scanning serves as a fundamental method of organizational learning (Choo, 1999). Environmental scanning complements, yet differs from, activities like competitor intelligence, competitive intelligence, and business intelligence, each serving distinct purposes in information gathering (Choo, 1999).

An environment can be segmented into two layers which are the task environment, which involves direct interactions with entities such as markets, competitors, suppliers, and customers; and the general environment, which encompasses broader external factors such as demographic, economic, and social sectors (Daft et al., 1988, as cited in Yu et al., 2019). While it is essential to understand which environments to scan and to identify weak signals (Daft et al., 1988, as cited in Yu et al., 2019), Hambrick (1982, as cited in Yu et al., 2019) emphasizes that the ability to act upon this environmental information is what truly provides a distinct competitive advantage.

Competitor intelligence, business intelligence, and environmental scanning are distinct yet interrelated concepts in strategic management. Competitor intelligence focuses on understanding the strategies and behaviors of competitors, while business intelligence extends its scope to include areas like acquisitions and risk assessments (Choo, 1999). Environmental scanning takes a broader approach, analyzing various external factors beyond competitors, such as technological advancements, economic conditions, and regulatory landscapes, to inform strategic planning and decision-making for the organization's future (Choo, 1999). Environmental scanning data plays an increasingly integral role in shaping the strategic planning efforts of both business and public-sector entities, with studies showing a correlation between environmental scanning and improved organizational performance (Choo, 1999). In order to endure in the contemporary dynamic and competitive market landscape, organisations must possess a comprehensive understanding and adept interpretation of the signals originating from the external environment (Garg et al., 2003, as cited in Song et al., 2024). They should systematically engage in the identification, collection, analysis, and processing of external environmental information (Yu et al., 2019, and the references therein).

### 4.3.1 Difference between a SWOT analysis and environmental scanning

A SWOT analysis and environmental scanning are both strategic management tools used to assess factors that may impact an organization's performance and strategic direction, but they differ in their scope, focus, and methodology.

When it comes to scope, a SWOT analysis focuses on assessing internal strengths and weaknesses as well as external opportunities and threats, evaluating specific factors within and outside the organization that may affect its performance (e.g., Pickton & Wright, 1998). Environmental scanning takes a broader approach by systematically gathering and analysing information about various aspects of the external environment, including economic, technological, social, political, and regulatory factors, along with industry trends and competitive dynamics (Song et al., 2024; Choo, 1999). In other words, a SWOT analysis provides a snapshot of the organization's current situation, whereas environmental scanning offers ongoing monitoring and analysis of external changes and trends to inform strategic decision-making.

In terms of focus, a SWOT analysis emphasizes identifying and analysing the organization's internal strengths and weaknesses, as well as external opportunities and threats, to inform strategic decision-making (Pickton & Wright, 1998). Environmental scanning concentrates on monitoring and analysing external factors and trends that may impact the organization, providing insights into the broader business environment and potential challenges and opportunities (Song et al., 2024 and the references therein; Yu et al., 2019).

In methodology, a SWOT analysis typically includes brainstorming and evaluating internal and external factors within a structured framework, often utilizing techniques like stakeholder interviews, surveys, and data analysis to identify and prioritize key factors (Pickton & Wright, 1998). Environmental scanning involves systematically gathering information from various sources, such as market research reports, industry publications, news sources, and expert opinions (Choo, 1999).

The integration of a SWOT analysis with environmental scanning provides a holistic understanding of the factors influencing the adoption of muon imaging in the mining industry. This combined analysis identifies internal capabilities and external challenges, aiding strategy construction and strategic decision-making.

# 5 DIFFUSION OF INNOVATION

In this final chapter of the conceptual framework in this thesis, the diffusion of innovation is discussed. Most of the theory is based on Roger's (2003) book, Dearing & Cox's (2018) and Driessen & Hillebrand's (2002) research regarding the theory. The chapter begins with definitions and key elements regarding diffusion and moves on to the adoption of new technologies within the mining sector. By comprehending patterns of adoption, overcoming obstacles, and incorporating principles of sustainability, organizations can optimize the effectiveness and influence of their innovations within a specific business setting.

## 5.1 Definition of diffusion of innovation

Diffusion refers to the systematic dissemination of innovation among members of a social system over time, representing a distinct mode of communication aimed at transmitting new ideas (Rogers, 2003). A social system may consist of individuals, organizations, subsystems, and/ or informal groups and they are bound together by sharing a common objective such as accomplishing a common goal or solving a common problem (Rogers, 2003). An innovation is defined by Rogers (2003) as an object, idea or practice that is perceived as novel by an individual or another unit of adoption. Furthermore, the definition of innovation can have diverse forms. It might be a tangible entity such as an energy-saving compact fluorescent lightbulb (Driessen & Hillebrand, 2002), or it could be intangible, like a service or a behavioral pattern (Dearing & Cox, 2018; Driessen & Hillebrand, 2002). In human behaviour, the objective novelty of an idea, based on its time of discovery or initial use, holds little significance; rather, it is the perceived novelty of the idea to the individual that influences their response, qualifying it as an innovation if it appears new to them (Rogers, 2003).

Diffusion acts as a catalyst for social change, representing the process through which modifications emerge in the structure and operation of a social system (Dearing & Cox, 2018; Rogers, 2003). With the introduction, dissemination, and acceptance or rejection of new ideas, significant shifts occur, ultimately driving societal transformation (Rogers, 2003). Adoption and diffusion are interconnected, with adoption addressing individual decisions and diffusion analyzing widespread dissemination (Rogers, 2003). Diffusion theory, often quantitative (Driessen & Hillebrand, 2002), emphasizes two key effects that are the innovation effect, which governs innovators' speed of adoption, and the imitation effect, dictating the pace of adoption among other adopter categories (Rogers, 2003). Understanding adoption is crucial for comprehending diffusion, as adoption decisions propel diffusion processes forward (Rogers, 2003). The primary distinction between adoption and diffusion theories lies in the level of aggregation they address: adoption theory concerns the decisions made by individual units at a detailed level, whereas diffusion theory analyzes dissemination at a collective level (Rogers, 2003). The theory of diffusion of innovation can provide insights into why marketing strategies and public policy interventions yield differing effects on the success of green innovation (Driessen & Hillebrand, 2002).

## 5.2 Key elements within the diffusion of innovation

The benefits or the superiority of technological innovation may not be clear for the potential adopters when they initially learn about it and therefore, it raises questions about the innovation, how and why it works, the advantages and disadvantages, and consequences of it (Dearing & Cox, 2018; Rogers, 2003). According to Rogers (2003), the four main elements in the diffusion of innovation are the innovation itself, the channels it is communicated through, a period of time and a chosen social system. Furthermore, innovations perceived by individuals to offer greater *relative advantage*, *compatibility*, *trialability*, and *observability*, and to possess lower *complexity*, are more likely to be adopted rapidly compared to other innovations (Rogers, 2003). This chapter focuses on the factors that facilitate the rapid adoption of an innovation.

Economic terms, convenience, social prestige factors, and satisfaction are possible measurable factors in *relative advantage* (Rogers, 2003). Individuals' perception of the benefits of an innovation often surpasses its objective advantages, leading to a faster rate of adoption when the innovation is perceived to offer a greater relative advantage (Rogers, 2003). Perceived environmental friendliness, or "greenness," can provide a relative advantage, especially in energy-saving innovations (Driessen & Hillebrand, 2002). However, the importance of environmental factors differs across product categories, with functionality often outweighing environmental considerations in consumer markets (Driessen & Hillebrand, 2002). While environmental friendliness may not drive purchases in some markets, the perception of a product as harmful to the environment could discourage consumers from buying it (Driessen & Hillebrand, 2002). Environmental impacts are often intricate and challenging for consumers to comprehend, making it difficult to discern the overall effect (Mohr et al., 2001, as cited in Driessen & Hillebrand, 2002).

*Compatibility* of the innovation is greater when the innovation fits the existing values and needs of the potential adopter and the norms of the surrounding social system (Rogers, 2003). Greater obstacles to adoption arise when an innovation lacks compatibility, which can extend to technical aspects (Driessen & Hillebrand, 2002). For example, the initial versions of energy-saving lightbulbs were not universally suitable for all lamp types, leading to limited adoption (Driessen & Hillebrand, 2002).

A *triable* innovation reduces uncertainty for potential adopters by offering the opportunity for learning through experimentation, thereby providing a limited basis for testing the innovation (Rogers, 2003). This is especially applicable to innovations with high visibility and uncertainty, such as energy-saving measures (Driessen & Hillebrand, 2002), where the user can only perceive the advantage of the innovation after a prolonged use (Darley & Beniger, 1981, as cited in Driessen & Hillebrand, 2002).

The *observability* of the innovation motivates discussion or innovation evaluation, in the social setting and with visible results, the innovation is more likely to be adopted (Rogers, 2003). When the effects of adopting an innovation are evident to everyone, users are more likely to embrace it, especially if these effects are positive (Rogers, 2003). However, green innovations, particularly those implementing minor changes to reduce environmental impact, often lack visibility, making them indistinguishable from less eco-friendly alternatives, such as a vehicle with a fuel-efficient engine resembling one with an older, fuel-inefficient counterpart (Driessen & Hillebrand, 2002).

New, easily understandable innovations are adopted more promptly and thus, the *complexity* of the innovation is perceived as comprehensible (Rogers, 2003). Innovations that are difficult to use and understand often require developing new skills and thus less likely to be adopted by the members in a social system (Rogers, 2003). Certain green innovations, such as unbleached coffee filters, are straightforward, requiring no specialized knowledge for their use, thus being less complex and more likely to be adopted (Driessen & Hillebrand, 2002).

According to Rogers (2003), the primary determinants of adoption rates include five qualities, with relative advantage and compatibility playing particularly significant roles in explaining the rate of adoption of an innovation. Certain individuals and organizations exhibit faster adoption of specific innovations than others (Rogers, 2003; Driessen & Hillebrand, 2002). Depending on the promptness of their adoption, they can be categorized into early adopters—those who embrace innovations early—from late adopters or non-adopters (Driessen & Hillebrand, 2002). In environmental management literature, a prevailing viewpoint suggests that adopting a proactive innovation strategy can benefit both the environment and the organization (Porter & Van der Linde, 1995, as cited in Driessen & Hillebrand, 2002). This perspective advocates for staying ahead of governmental regulations and customer expectations rather than constantly playing catch-up (Driessen & Hillebrand, 2002).

## 5.3 Adoption of new technologies within the mining sector

The mining industry plays a crucial role in supplying metals for the low-carbon economy (IEA, 2023b), yet it also faces the imperative to reduce its own emissions (Hodgkinson and Smith, in press, as cited in Ruokonen, 2021). In the last five years, driven by increasing demand and high prices, the global market size of crucial energy transition minerals has doubled to USD 320 billion by 2022 (IEA, 2023b). This transition stems from various factors, including increasingly challenging geological conditions, diminishing ore reserves, the imperative to counteract a prolonged productivity decline, the necessity to enhance safety measures for miners (IGF, 2021), and the imperative to mitigate environmental impacts (Ruokonen, 2022). The mining industry faces new opportunities amidst a rapid increase in demand, yet the combination of fluctuating prices, geopolitical uncertainties and supply chain bottlenecks poses significant risks to achieving secure and swift energy transitions (IEA, 2023b). Despite entering the arena later than other sectors, the mining industry is poised for significant transformation, aligning with the Fourth Industrial Revolution (IGF, 2021), characterized by the integration of new technologies to enhance connectivity, information access, and resource utilization efficiency, undergoing fundamental changes comparable to those seen in other industries (IEA, 2023b; IGF, 2021).

Several factors influence the adoption of new technologies within the mining sector; for example, surface mining is usually more mechanized than underground mining, which affects the feasibility of technological implementation (IGF, 2021). Market conditions, such as price volatility and capital costs, also impact companies' financial capacity to invest in technology (IEA, 2023b; IGF, 2021). Large-scale projects and greenfield operations with longer lifespans may be more inclined to invest in technology (IGF, 2021), while social considerations and community expectations also impact adoption decisions (IEA, 2023b). Universities, research centers, and technological hubs are expected to play a larger role in offering innovative solutions, while technological innovation from diverse fields beyond mining is likely to influence expertise and foster collaborations (Mining Finland, n.d.).

In Finland, the innovations in mining industry are related to finding circular economy solutions such as material reuse and metal recovery from low-grade ores and waste (MEAE, 2023a; VTV, 2021). Furthermore, ongoing projects relate to technological advancements (e.g., drill core handling, water management), supporting digitalization of process industry ecosystems and enhancing the attractiveness of the sector and improve workforce availability (MEAE, 2023a). Moreover, the EU-wide projects, such as Mine.io are affecting mining-related innovations in participating countries, including Finland (Mine.io, n.d.).

Continuous innovation in mining processes is imperative in ensuring the ongoing and sustainable operation of mining endeavors (IGF, 2021).

# 6 MUON IMAGING

This chapter explores muon imaging and its various applications in geotechnical and mining contexts. To simplify, muon imaging reveals the information inside a target (Yang et al., 2018). In this thesis, muon imaging is a broad term encompassing various techniques for using muons to create images. Depending on the research, terms such as *muography*, *muon tomography* or *muon radiography* may be utilized. Muon tomography refers to the process of reconstructing three-dimensional (3D) imaging data based on muon data, whereas muon radiography concerns two-dimensional (2D) imaging (Lechmann et al., 2021). This thesis opts for the broader term *muon imaging* to emphasize environmental considerations over technical distinctions between methods and therefore the term muon imaging is utilized. Consequently, even if the articles cited in this chapter employ more specific technological terms, the term muon imaging is consistently used. While there exists research on muon imaging and its diverse applications across different fields, this thesis primarily focuses on its geotechnical applications, particularly in mineral exploration, mining, and rock engineering.

## 6.1 Definition of muon imaging

Muon imaging is a technique that uses naturally occurring cosmic-ray muons to create density images of the targeted structures and materials (Holma et al., 2022a; Lechmann et al., 2021). Muons are elementary particles, similar to electrons but approximately 207 times heavier (Yang et al., 2018). They form in the upper atmosphere when cosmic rays collide with air molecules, mostly nitrogen (Holma et al., 2022a). These collisions create what are known as extensive air showers (EASs), which are streams of particles that travel toward the Earth almost at the speed of light (Holma et al., 2022a). Most of the charged particles that reach sea level are muons and electrons (Figure 3) (Holma et al., 2022a). Generated continuously in the Earth's atmosphere, muons can be measured as they pass through structures or objects using detectors, providing valuable imaging data (Holma et al., 2022a; Kaiser, 2019). Muon imaging reconstructs the internal geometry of e.g., a volcano, a large house (Yang et al., 2018) or a geological body by analyzing muon penetration and detecting the attenuated muon flux with sensors as they traverse the target body (Lechmann et al., 2021). Muon imaging techniques are non-destructive, based on remote sensing methods.

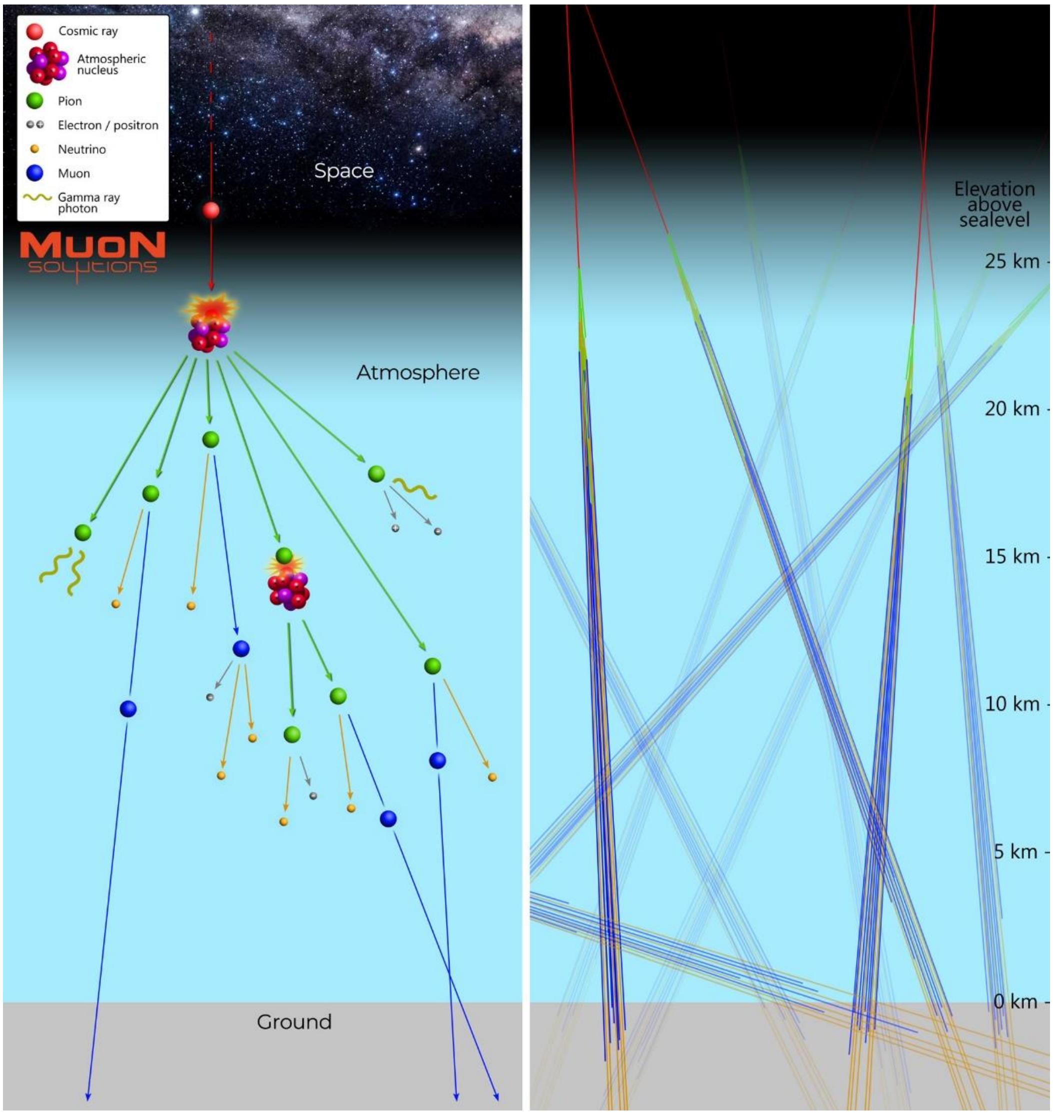


Figure 3. On the left, an illustration of an air shower depicts the schematic transformation of particles. The illustration on the right uses a scale that represents elevation above sea level. Image courtesy of Muon Solutions Oy / Jarmo Korteniemi.

As muons traverse material, they lose energy and speed, eventually decaying into other particles (Holma et al., 2022a). Increasing material density leads to greater energy loss, causing inhomogeneous muon fluxes and density variations, resulting in decreased muon intensity with longer path lengths and fewer muons observed at greater depths (Holma et al., 2022a; Lechmann et al., 2021). Additionally, differences in muon fluxes can occur depending on the observation angle, even with similar path lengths in rocks (Holma et al., 2022a; Zhang et al., 2020). Muons primarily originate from above and exhibit a consistent decrease in number as their angle of entry becomes more oblique (Holma et al., 2022b). While horizontal arrivals are possible, their frequency is generally too low for effective statistical analysis (Holma et al., 2022b). For practical imaging applications, a muon count is sufficient if the entry angle is at least 10° above the horizon (Holma et al., 2022b). Currently, three different types of muon detectors exist; (1) large, approximately the size of a truck, detector systems used to e.g., scan cargo containers, (2) medium-size, with a width of one to two meters, called muon telescopes used in e.g., geoscientific research in tunnels, and (3) small diameter, borehole detectors used in e.g., gaining data through a drill hole (Figure 4) (Holma et al., 2023).

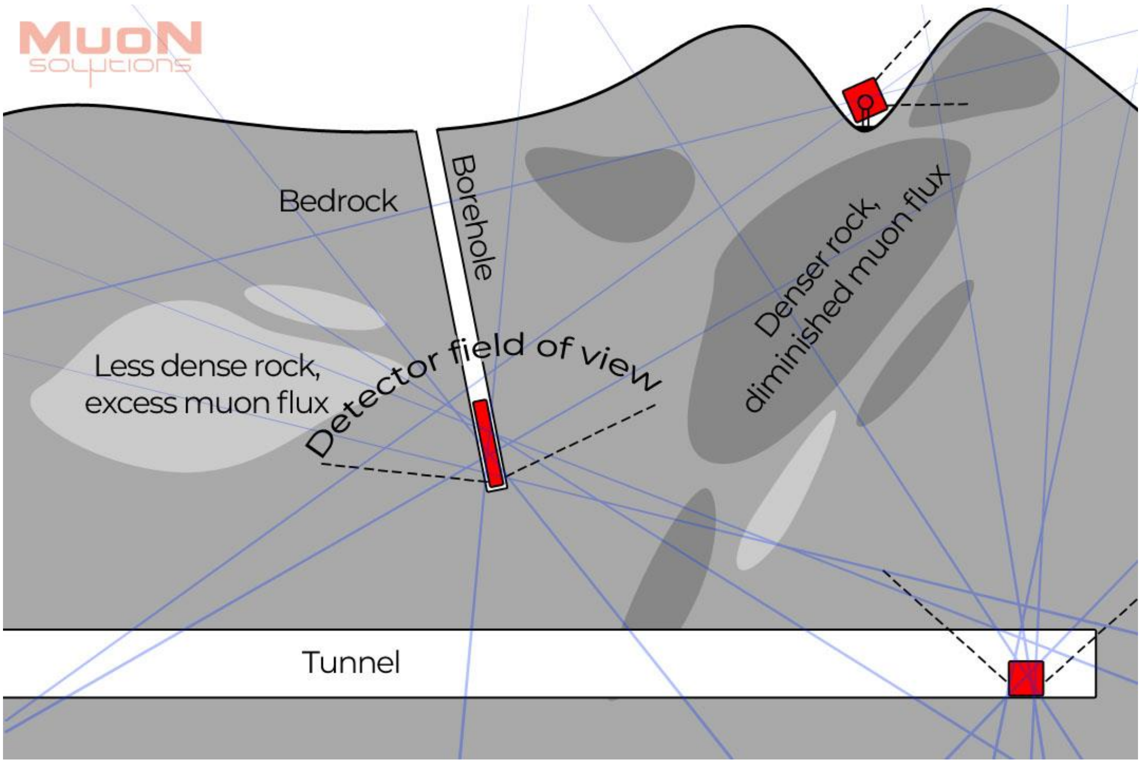


Figure 4. An illustration of muon imaging where a borehole device is situated in the borehole, one telescope is situated on the surface and another in the tunnel. The blue lines in the illustration represent muon particle tracks. Image courtesy of Muon Solutions Oy / Jarmo Korteniemi.

There are three different modes in which muon imaging can be performed in: absorption, deviation and transmission (Procureur, 2018, as cited in Holma et al., 2022a). For example, absorption muography closely resembles X-ray radiography, commonly recognized by the public as X-rays, where the result of the study can be observed as a density image (Holma et al., 2022a). Cosmic-ray muons possess high penetration capabilities, with an average energy approximately 10,000 times greater than that of a typical X-ray, enabling them to traverse hundreds of meters of rock (Kaiser, 2019). Providing an exact value for the time required or the resolution of muography measurements is challenging due to factors such as depth, detector size, and object size (Lechmann et al., 2021; Zhang et al., 2020). Measurement durations can vary from a few weeks to several months at depths of around 100 meters, depending on density differences (Zhang et al., 2020).

Muon imaging has several claimed promising current and future applications in several fields, including the fields of geosciences, mining- and rock engineering (Holma et al., 2022a; Lechmann et al., 2021), where it offers both technical and economic advantages (Zhang et al., 2020). Muon imaging is a relatively new geophysical method and thus only a few geoscientists or mining engineers are familiar with the principles and applications of it, partly because it originates outside conventional geophysics and classical physics (Holma et al., 2022a). Muon detectors operate passively since they do not generate the muons they detect (Holma et al., 2022a) and therefore this imaging technique is automatically compliant with health and safety regulations (Zhang et al., 2020; Kaiser, 2019). Additionally, muons are cost-free and indefinitely available on human timescales (Zhang et al., 2020; Kaiser, 2019). Muon imaging can also be utilized when monitoring volcanoes, in groundwater research, or nuclear waste site characterization (Holma et al., 2022a, and the references therein). In the future, Holma et al. (2022a) anticipate that muography will experience increased usage and commercial availability, becoming as essential to geophysics as traditional methods are today. Furthermore, Kaiser (2019) argues that in instances where no alternative can yield comparable outcomes, coupled with commercial incentives, successful commercialization is anticipated. Research by Beni et al. (2023) demonstrate that even one measurement utilizing transmission-based muography can give useful information regarding an ore deposit.

## 6.2 Geotechnical applications of muon imaging

The density of the bedrock in a given area may be higher than average, depending on the mineralogical composition and the abundance of denser minerals. The presence of ore minerals, such as base metal sulphides and iron oxides, increases the bulk density of rocks (GTK, 2010), leading them to block more muons than less dense country rocks (Holma et al., 2022a; Zhang et al., 2020). These mineral and rock densities are primarily influenced by their iron content. While heavy minerals like pyrrhotite (4.58–4.65 g/cm$^3$), hematite (hematite; 5.26 g/cm$^3$), and galena (7.60 g/cm$^3$) exhibit higher densities (Mindat.org, n.d.a, n.d.b, n.d.c.), common silicate minerals like quartz and feldspars, which comprise most of the Earth's crust, have a lower density of approximately 2,70 g/cm$^3$ (GTK, 2010). This variation in density facilitates muon imaging applications in mineral exploration by affecting muon penetration through the rock material (Holma et al., 2022a).

The diverse electrical conductivity, resistance, and magnetic properties across different soil beds and rock formations enable the application of a variety of conventional geophysical methods for subsurface characterization (Holma et al., 2022a). Geophysics encompasses a range of well-established methods such as seismology, gravimetry, and electromagnetic techniques, each tailored to detect specific geological properties such as density or electrical resistivity (Lechmann et al., 2021). Muon imaging, as emphasized by Holma et al. (2022a, and the references therein), often work alongside traditional geophysical methods, benefiting from the additional information they provide, thus enhancing the overall effectiveness of geological surveys.

Muon imaging, applicable at various exploration stages, detects density anomalies in rock volumes, aiding in the identification of drilling targets across exploration phases (Beni et al., 2023; Zhang et al., 2020). Muon imaging has the potential to significantly decrease expenses by optimizing drilling patterns and expediting exploration processes (Holma et al., 2022a). While drilling provides essential subsurface data, it is time-consuming and expensive, and the information obtained is generally confined to the borehole location or, at best, its immediate vicinity (Holma et al., 2022a; Zhang et al., 2020). Human resource savings may be notable when unnecessary drilling and drill logging is reduced (Holma et al., 2022a; Zhang et al., 2020). Muon imaging, particularly through borehole detectors, offers an alternative or complementary method for assessing density variations underground, benefiting various geological and engineering projects (Holma et al., 2022a; Lechmann et al., 2021; Zhang et al., 2020). Additionally, an advantage of muon imaging is its capability to collect data from regions beyond the immediate vicinity of the borehole, thereby offering a more extensive view of structures beneath the earth's surface (Holma et al., 2022a; Zhang et al., 2020). However, constraints such as depth, density discrepancies, and space limitations impact its application, with factors like temperature (areas with high geothermal activity) and pressure (flooded boreholes) posing additional challenges in certain environments (Holma et al., 2022a). Therefore, to enhance geological insights, a balance between drilling, sampling, and geophysics is essential (Holma et al., 2022a).

In the terms of geological research, muon imaging offers superior spatial resolution compared to gravimetry (Holma et al., 2022a), but its detectors can only capture data from above their positions and thus, the detectors have to be positioned below the target area (Lechmann et al., 2021). It should be noted that a muon telescope can be positioned at the Earth's surface level next to a high topographic feature, such as a volcano, to collect data from muons arriving almost horizontally (Nagamine et al., 1995, as cited in Holma et al., 2022b). Gravimetry is often combined with muon imaging (Holma et al., 2022a), since both methods respond to material density, i.e., the same physical parameter (Lechmann et al., 2021). Although both techniques can be applied in boreholes, the diminishing muon flux with depth often limits muon imaging’s practicality beyond 1 km in mineral exploration and geotechnical and mining engineering (Zhang et al., 2020). Nonetheless, Holma et al. (2022a), argues that depths of up to approximately 2 km remain feasible for long-term monitoring purposes.

There are two forms of practical classifications for end-users unfamiliar with muon imaging; muon telescopes and borehole detectors (Holma et al., 2022a). Muon telescopes are large detectors, either stationary or mobile, with sizes of 1 $m^3$ or more which can be installed either at ground level or in underground spaces, such as natural or man-made tunnels (Holma et al., 2022a, and the references therein). Muon telescopes have large detection areas to compensate for the modest muon flux (Holma et al., 2022a). Borehole detectors, on the other hand, complement research instruments by providing muon imaging in areas inaccessible through other means (Holma et al., 2022a; Lechmann et al., 2021).

Lechmann et al. (2021), have constructed best practice guidelines regarding how geoscientists may proceed when applying muon imaging techniques on a technical level and on a more practical level. The practical steps, relevant in the scope of this thesis, concern its *applicability*, *alternative methods* and *accessibility*. Assessing the *applicability* of muon imaging is crucial as it determines its suitability for addressing specific research objectives; muon imaging is sensitive to density contrasts but has a limited ability to accurately resolve material compositions (Lechmann et al., 2021). Therefore, muon imaging is a valuable tool, when constructing 3D density structures, but falls short when detailed information is required (Lechmann et al., 2021). When considering *alternatives* and determining whether to prioritize other geophysical methods or muon imaging, one might inquire if muon imaging could serve as a valid supplementary technique, given that numerous exploration projects utilize a combination of geophysical methods (Lechmann et al., 2021). Location-based accessibility concerns the requirement of placing a muon detector beneath the target object, necessitating accessibility from below, such as in mines or tunnels (Lechmann et al., 2021). Technology-based accessibility relates to the expertise needed to interpret data and operate the detector effectively (Lechmann et al., 2021).

Saracino et al. (2018) studied underground cavities with muon imaging methods in an ancient archaeological site. The study found that all known cavities were successfully identified, and the capacity to investigate the characteristics of hidden cavities was demonstrated by precisely recreating the muographic image of a sequence of chambers. The results were claimed promising as they were obtained in a challenging underground context filled with multiple anthropogenic cavities situated in a highly urbanized area, where conventional surveying methods may not always be applicable. The study demonstrated muon imaging's ability to detect cavities and replicate their shapes with high precision, achieving sensitivity within a few meters over distances exceeding 30 meters of rock thickness. While the research by Saracino et al. (2018) focused on an environment not directly analogous to mining operations, it showcased muon imaging’s effectiveness in intricate settings.

## 6.3 Applications of muon imaging in different stages of mineral exploration

By utilizing muon imaging before other methods, such as geophysical and geochemical techniques, it can help prioritize subsequent exploration actions (Holma et al., 2022a; Zhang et al., 2020). Areas with previous exploration or mining activity (brownfields), particularly those with numerous boreholes, offer enhanced opportunities for muon imaging (Kaiser, 2019), since in areas with a history of mining activities, the abundance of boreholes may surpass thousands (Holma et al., 2022a). Conversely, in less explored regions, the availability of boreholes is limited, often numbering only a few (Holma et al., 2022a). Given that muon telescopes can be installed in underground tunnels, natural or man-made, the prior mining operations in the brownfield area offer increased opportunities for detecting muon flux, due to the already existing drillholes (Holma et al., 2022a). With the help of muon imaging, detection of hydrothermal alteration, structural geologic features, remaining ores in operating mines and fractures can, amongst all, be detected (Holma et al., 2022a; Zhang et al., 2020). Because numerous geological, geotechnical, and mining engineering endeavors already have some degree of bedrock data, correcting potential inaccuracies in muon flux calculations can be relatively simple with careful preparation, claimed by Holma et al. (2022a). This is further underscored by Beni et al. (2023), who emphasize the importance of comprehending rock densities and geometries when implementing muon imaging when it comes to mining applications. When planning exploration projects, it is crucial to know the duration of muon data acquisition, enabling the subsequent scheduling of project steps (Lechmann et al., 2021). Lechmann et al. (2021) conducted a study with three muon detector sites, aiming for a spatial resolution of 60 meters given the 600-meter thickness of overlying rock. This required an exposure time ranging from 100 to 200 days.

### 6.3.1 Use of muon imaging in operating mines

Limited exploration efforts during initial geological surveys often result in overlooking small ore bodies near or isolated from larger ones, posing a risk of missed deposits in active mining operations (Holma et al., 2022a). Muon imaging serves as a valuable tool for identifying these overlooked ore bodies and residual ores, potentially preventing ore losses (Holma et al., 2022a). If anomalies are detected, geological drilling can be utilized to delineate boundaries more precisely, resulting in a reduced number of boreholes required, thus minimizing exploration costs and time (Holma et al., 2022a; Zhang et al., 2020). Telescope and borehole muon imaging not only provide density data but also offer potential benefits in optimizing borehole placements and reducing drilling requirements (Holma et al., 2022a). Even a slight reduction in drilling can result in notable time and cost savings, while comprehending density distributions improves the likelihood of pinpointing optimal drilling targets and mitigates the risk of overlooking crucial features (Holma et al., 2022a). Annually, significant ore loss of up to 20% of the total occurs in mass mining operations like sublevel caving, especially in large mines (Holma et al., 2022a; Zhang et al., 2020). The movement and location of these lost ores within the caved rocks have remained unclear due to the constant motion they experience during the extraction process (Zhang et al., 2020). Identifying and locating the remaining ore is a challenge that muon imaging has the potential to address (Holma et al., 2022a).

Undiscovered water reservoirs during tunnelling operations, whether in mining or other projects, can result in accidents and financial setbacks if encountered unexpectedly during drilling or excavation (Holma et al., 2022a). Water masses can be detected using muon imaging, provided that their density differs from that of the average bedrock (Holma et al., 2022a). Furthermore, muon imaging aids in monitoring rock masses susceptible to fracturing and deformation, especially in active mining areas where such activity may occur frequently (Zhang et al., 2020). Early detection of fractures allows for the implementation of preventive measures to minimize further damage and uphold ore recovery rates (Holma et al., 2022a). Without proper management, extensive deformation may lead to the formation of large fractures, increasing the risk of collapses in underground spaces (Holma et al., 2022a; Zhang et al., 2020). Muon imaging offers a solution for identifying these fractures by detecting density changes in fractured rock masses, since the density of a fractured rock is reduced compared to the non-fractured rock (Holma et al., 2022a). Moreover, identifying weak zones for the implementation of appropriate rock support designs is also a crucial aspect to avert possible collapses (Holma et al., 2022a; Zhang et al., 2020).

Mineral exploration is essential to sustain in mine operations as long as resource potential exists (Holma et al., 2022a). Additionally, a closed mine may reopen due to factors like fluctuations in metal prices, revised deposit assessments, or advancements in exploration techniques driving renewed interest (Holma et al., 2022a).

# 7 DATA AND METHODOLOGY

In this chapter, the methodology, data gathering, and data analysis are presented and explained. The chapter commences by explaining action research, a methodology that combines academic research techniques with practical implications, as employed in this thesis. The action research cycle, along with the quadrant utilized in this research and the process of change facilitated by action research, offer the methodologies for constructing a strategy academically. Lastly, the reasoning behind data collection and the conduction of data analysis is explored.

## 7.1 Research Methodology

The purpose and objectives of this research were described in Chapter 1.2., and the research questions were the following: **RQ1.** *How to develop a strategy to integrate muon imaging into the mining industry to enhance sustainability practices?* and **RQ2.** *How can this strategy be implemented in the Finnish mining sector?*

The data for this research was acquired by conducting action research. Action research is suitable for research when diverse methods are needed to gain knowledge and address problems and when the research aims to develop a theory about practice (Eriksson & Kovalainen, 2008). Action research can be subdivided into smaller categories, subtypes, and quadrants, as determined by various authors, reflecting the complex nature of this research approach. In this thesis, the main frame for action research structure is built upon Eriksson & Kovalainen's (2008) and Coghlan's & Brannick's (2014) theories on action research, briefly complemented by other researchers.

## 7.2 Action research

Action research is not simply a research method; it is better characterized as an approach emphasizing engagement, close relationships with the research subject, and active participation as foundational elements in the research process consisting of a group of methodologies (Eriksson & Kovalainen, 2008). This approach employs diverse methods for acquiring knowledge and addressing problems (Coghlan & Brannick, 2014). Depending on the author(s), various models exist to illustrate the typical forms of involvement and participation in action research projects. It is an iterative process that is shaped during the research process as more knowledge is gained (Eriksson & Kovalainen, 2008). The research procedure is iterative, real-time planning includes acting, observing, and reflecting followed by revised planning, action-taking, and observation over again leading to changed actions and patterns of thinking (Coghlan & Brannick, 2014). Furthermore, the evaluation process may hold several layers, from theoretical aspects to practical solution-finding (Eriksson & Kovalainen, 2008).

Action research is seen as suitable for research questions related to processes of development, change, or improvement of a problem (Coghlan & Brannick, 2014). It is used to understand problems related to real-life and business activities and therefore theoretical interests are not the guiding principle, due to the practicality of the research question (Coghlan & Brannick, 2014; Eriksson & Kovalainen, 2008). Action research usually aims for a change in a specific setting or context (Coghlan & Brannick, 2014). The material in action research may include operational statistics, policy documents, and data from the organization besides theoretical articles, published and peer-reviewed papers, and the like (Eriksson & Kovalainen, 2008).

According to Eriksson & Kovalainen (2008), action research has five main labels that encompasses participatory inquiry, action inquiry, critical action research, industrial action research, and participatory action research. The differences between the labels are related to research settings, emphasizing varying aspects and the grade of researcher involvement (Eriksson & Kovalainen, 2008). In the research process, there are variations in how the local members of the community/organization/group of experts are involved, as well as differences in the degree of emphasis on problem-solving versus participation (Eriksson & Kovalainen, 2008). However, these methodological differences are not inherently significant (Eriksson & Kovalainen, 2008). In this research, *industrial action research* fits the addressed research questions, since it takes complex and larger problems and systems into account.

The strength of action research is the proximity to research objects. Therefore, action research does not necessarily impose a clear difference between research and action (Coghlan & Brannick, 2014). Furthermore, some argue that the closeness holds power, since the results are not only empowering for the science community but also for the participants (Eriksson & Kovalainen, 2008). To meet the academic requirements, tools and language requirements must be used when translating the analysis and making the data transparent (Eriksson & Kovalainen, 2008). The data quality needs to be assessed when collecting and analysing the data to make sure the data used in the research is valid and to rule out a biased inclination (Eriksson & Kovalainen, 2008). There are diverse perspectives regarding the alignment between consultancy and action research, with some advocating for close integration and others highlighting distinct differences (Eriksson & Kovalainen, 2008). Critics therefore suggest that action research closely resembles consulting with limited research connections (Eriksson & Kovalainen, 2008). Clarifying the distinction, particularly between participatory action research and consulting, is seen as essential (Coghlan & Brannick, 2014; Eriksson & Kovalainen, 2008). Gummesson (2000, as cited in Eriksson & Kovalainen, 2008), highlights the following four (4) points, to highlight the differences between consultancy and action research: (1) consultants work with a limited time for a project, whereas researchers engage with the subject and reassess the findings of several times. (2) Consultancy is often linear while action research provides an iterative cyclical approach. (3) Research is based on theoretical rationality whereas consultancy necessitates empirical support and (4) research has specific standards for documentation and reassurances for intact research, thus not harmed by consultancy.

## 7.3 The action research cycle

The main steps in an action research cycle can vary depending on the author(s). This thesis adopts the model proposed by Coghlan & Brannick (2014) due to its structured approach that effectively integrates theory and practice. This model is particularly well-suited for studies in organizational settings, as it emphasizes reflective practice and iterative learning, both of which are crucial for the real-world application of research findings. According to Coghlan & Brannick (2014), the four (4) main steps in action research (Figure 5), consist of *constructing*, where stakeholders are engaged to construct the base for planning and implementing actions with subsequent iterations allowing for adjustments. The second step of *planning action* ensues from exploring the project's context and purpose, aligning with the constructed issue, which may entail focusing on an initial step or a series of steps (Coghlan & Brannick, 2014). The third step of *taking action*, is the stage where the implementation of plans and collaborative interventions take place (Coghlan & Brannick, 2014). *Evaluating action* involves examining both intended and unintended outcomes to assess if the original construct was aligned, if the actions executed corresponded to the construct, if the actions were conducted appropriately, and to determine inputs for the subsequent cycle of constructing, planning, and action (Coghlan & Brannick, 2014). This iterative nature extends to the process of change, where the four steps mentioned earlier are critically reviewed multiple times (Coghlan & Brannick, 2014).

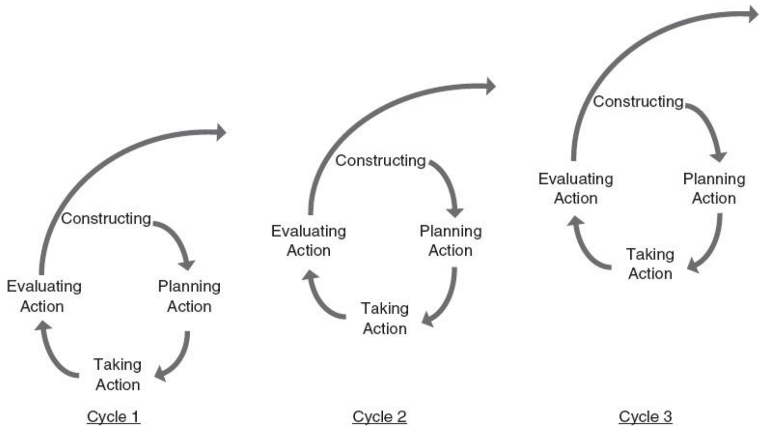


Figure 5. Spiral of cycles in action research, from Coghlan & Brannick (2014, p. 11).

Action research concerns a real-time change of what is taking place and involves two goals: to resolve an issue and contribute to science (Coghlan & Brannick, 2014). It requires a preunderstanding of the organizational environment, the dynamics and structure of operating systems, and understanding the conceptual framework of these systems (Coghlan & Brannick, 2014).

When conducting action research, one must clarify the system's and one's commitment to learning-in-action and to which degree self-study and reflection are engaged (Coghlan & Brannick, 2014). According to Coghlan & Brannick (2014), the type of focus of the researcher and system may be divided into four (4) quadrants (Figure 6). Quadrant 1 is defined by the absence of intentional self-reflection in action by both the researcher and the system, where studies may take place but are not deliberately integrated into action (Coghlan & Brannick, 2014). In this scenario, the researcher approaches the system's perspective, issues, or problems as if they were external, without actively engaging in self-reflection as part of the research process (Coghlan & Brannick, 2014, and the references therein). The researcher may be writing a case study, research statistical data or focus on a specific strategic initiative whereafter established methodologies are used for analyzing the gathered data (Coghlan & Brannick, 2014). The research in this thesis is conducted as the researcher employing a temporary facilitative role as an externality to the organization.

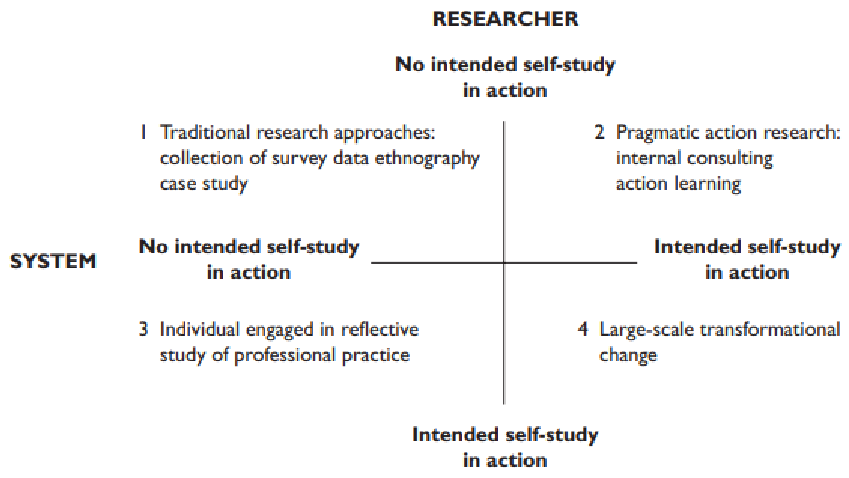


Figure 6. Focus of the system and the researcher. The four different quadrants and their positioning to each other (Coghlan & Brannick, 2014, p. 123).

Quadrant 2 research involves observing a system without deliberate self-study (Coghlan & Brannick, 2014). Coghlan (2003, as cited in Coghlan & Brannick, 2014) describes this as mechanistic-oriented action research, where the focus is on managing change or solving a specific problem identified beforehand. Quadrant 3 research occurs when the researcher conducts intentional self-study, while the system remains unchanged (Coghlan & Brannick, 2014). This approach involves the researcher reflecting on and examining their own assumptions during actions, aiming to enhance professional practice (Coghlan, 2014) and the researcher adopts a 'reflective practitioner'-role (Schon, 1983, as cited in Coghlan, 2014). Quadrant 4 research occurs when both the researcher and the system are actively involved in intentional study in action (Coghlan & Brannick, 2014). Within this system committed to or undergoing change, there is a culture of reflection and learning, where the researcher actively contributes to collective reflection and learning alongside the system (Coghlan & Brannick, 2014).

## 7.4 Implementing action research through process of change

Implementing action research through 'process of change' in this thesis is based on Beckhard's framework, as outlined by Coghlan & Brannick (2014). The framework for the process of change consists of four phases: (1) determining the need for change, (2) defining the future state, (3) assessing future needs by evaluating the current situation to identify necessary tasks, and (4) managing the transition (Beckhard and Harris, 1987; Beckhard and Pritchard, 1992, as cited in Coghlan & Brannick, 2014).

The first step within the framework involves examining the context for change within the organization, its units, or subunits, with a crucial focus on identifying the need for change and its underlying causes (Coghlan & Brannick, 2014). Identifying external forces such as global market demands or evolving customer needs is crucial for assessing their origin, strength, and impact on the system, aiding in distinguishing between significant and minor drivers of change (Coghlan & Brannick, 2014).

In this thesis, the *determination for the need for change* originates from Muon Solutions Ltd. The imperative for change arises from the utilization of muon imaging, initially limited to a few entities within the Finnish mining sector, with the goal of transforming it into a globally adopted imaging technique. Another critical factor in assessing the necessity for change involves considering the degree of choice regarding whether to implement change or maintain the current state (Coghlan & Brannick, 2014). In order to bring to knowledge and to commercialize the muon imaging technique and contribute to more sustainable mining practices, the need for change is justified. To effectively address the established need for change, the focus shifts to *defining a desired future state*. Articulating the envisioned post-change state of the organization, unit, or subunit is vital, as it positively directs attention and energy towards future aspirations (Coghlan & Brannick, 2014). The desired outcome is muon imaging used not only to better sustainability initiatives within the mining industry, but also in other aspects where it may prove useful and minimize the environmental impact. In the future, muon imaging may e.g., monitor underground reservoirs and aquifers, offering real-time data on water levels and quality (Holma et al., 2022a, and the references therein). This innovation could transform water resource management, ensuring sustainable access to clean water for various sectors worldwide.

*Assessing future needs by evaluating the current situation* is crucial for effectively identifying areas requiring change, involving prioritization of change issues, identification of relevant subsystems needing change, and evaluation of readiness and capacity for the proposed change (Coghlan & Brannick, 2014). In practice, this entails prioritizing areas, sectors, and industries where muon imaging could have the most substantial impact on sustainability, such as resource management or climate change mitigation efforts. Furthermore, an assessment of these sectors' capacity to adopt muon imaging technology is necessary. This thesis specifically focuses on the mining sector, exploring the technological, economic, and regulatory aspects that could either facilitate or hinder the adoption of muon imaging technology.

The final step of *managing the transition* involves navigating the transition from the present to the desired future state, a period often marked with challenges as the old ways become obsolete and the new vision has yet to materialize (Coghlan & Brannick, 2014). Effectively managing this transition involves implementing both a strategic and operational plan, delineating goals, activities, structures, and projects to facilitate the change process, as well as a commitment plan to secure organizational buy-in and support for the change initiative from key stakeholders (Coghlan & Brannick, 2014). In practice, this entails devising a comprehensive and detailed strategy to integrate muon imaging across diverse industries and sectors, which should address challenges associated with transitioning from traditional imaging methods. In this thesis, this step is addressed by the construction of an implementable strategy where muon imaging is introduced to a real-world setting. Furthermore, this step emphasizes the importance of prioritizing and securing commitment and support from key stakeholders such as industry authorities, policymakers, and prospective clients. This may involve providing training, resources, and assistance to demonstrate the effectiveness of the new technology in addressing sustainability issues. Consequently, this establishes a connection and serves as a bridge to the theory of innovation diffusion, where an innovation is perceived to offer greater *relative advantage*, *compatibility*, *trialability*, and *observability*, and to possess lower *complexity*, are more likely to be adopted rapidly compared to other innovations (Rogers, 2003).

## 7.5 Data collection

The objective of this thesis is to investigate how the strategic integration of muon imaging within the Finnish mining industry can improve environmental performance and enhance sustainability. To address the research questions effectively, it is required to have a comprehensive understanding of the Finnish mining environment. The data collection process employs qualitative methods, with a particular emphasis on document analysis. This approach was selected for its ability to provide a diverse range of data sources, ensuring a thorough exploration of the chosen scope of the research. The research initiative commenced with an exploration of the mining sector in Finland, with a specific focus on identifying environmental challenges and assessing the potential of introducing new technologies to enhance environmental performance, thereby fostering sustainability within the sector. The data in this thesis encompasses various sources such as peer-reviewed articles, a doctoral thesis, book chapters, and publicly available data from governmental organizations such as the Ministry of Economic Affairs and Employment of Finland (MEAE) and Geological Survey of Finland (GTK). This systematic approach ensured the categorization of information into different themes. This stage is recognized as the phase of gaining access (Eriksson & Kovalainen, 2008). Some articles were sourced from the reference lists of previously read articles, with each selected article contributing to the research questions and fulfillment of research objectives. To ensure the data's currency, the most recent reports from governmental organizations and actors, primarily originated from the years 2022-2023, were utilized. In the table below (table 1), the publications used are divided into data collection phases, according to the themes in this thesis. The table shows how the strategy is informed by both academic and industry sources. It highlights the thesis's rigor, provides quick reference points for understanding the context of the research, and ensures transparency and replicability. Additionally, it supports the thesis's arguments and analyses, and sets a groundwork for future research. This inclusion enhances the thesis's academic integrity and practical value in the field. The table includes the key references for the empirical results, with a complete list of all references used available at the end of this thesis.

Table 1. A table of the used references, divided into data collection phases.

| Publisher | Publication | Publication Year |
|---|---|---|
| **Data collection phase: Background research for the Finnish mining industry** | | |
| Eilu | Metallic mineral resources of Fennoscandia | 2011 |
| GTK | Hyviä käytäntöjä kaivoshankkeiden ympäristövaikutusten arvioinnissa | 2015 |
| Hokka & Eilu | Raw Materials and Security of Supply – It Is Time to Act, Now | 2023 |
| Mining Finland | Website | n.d. |
| Pettersson & Suopajärvi | Sosiaalinen toimilupa kaivos-, metsä- ja matkailualalla Toimialojen paikallinen hyväksyttävyys Lapissa | 2018 |
| Ruokonen | Advancing Sustainability in Mining | 2022 |
| Ruokonen | Managerial perspectives on strategies for advancing environmental considerations in the mining industry | 2021 |
| Ruokonen & Temmes | The approaches of strategic environmental management used by mining companies in Finland | 2019 |
| MEAE | Sector Report on the Mining Sector | 2023 |
| MEAE | Green transition accelerates EU's raw material objectives – Industry outlooks – mining 9.6.2023 | 2023 |
| MEAE | National Battery Strategy 2025 | 2021 |
| VTV | Näkökulmia kestävään kaivostoimintaan Suomessa – Valtiontalouden tarkastusviraston näkökulmat 2/2021 | 2021 |
| **Data collection phase: Mining industry in general** | | |
| IEA | Critical Minerals Market Review 2023 | 2023 |
| IGF | New Tech, New Deal: Mining policy options in the face of new technology | 2021 |
| Towards Sustainable Mining Initiative | Website | 2024 |
| **Data collection phase: Definitions, standards, initiatives, SDGs** | | |
| ISO | The benefits of implementing an environmental management system for your business | n.d. |
| SFS ry | ISO 14000 Environmental Management Standard Series | n.d. |
| SGU | Chapter 9: Ore Deposits Geology | 2018 |
| The Global Goals | Website | n.d. |
| UN | What is sustainable development? | 2023 |
| **Data collection phase: Strategic management** | | |
| Bernal-Conesa et al. | CSR Strategy in Technology Companies: Its Influence on Performance, Competitiveness and Sustainability: Empirical study from Spain | 2017 |
| Crews | Strategies for implementing sustainability: Five leadership challenges | 2010 |
| De Kluyver et al. | Strategic Management | 2015 |

| | | |
|---|---|---|
| Engert & Baumgartner | Corporate sustainability strategy – bridging the gap between formulation and implementation | 2016 |
| Fobbe & Hilletofth | The role of stakeholder interaction in sustainable business models. A systematic literature review | 2021 |
| Galpin & Hebard | Strategic management and sustainability | 2018 |
| Heslin & Ochoa | Understanding and developing strategic corporate social responsibility | 2008 |
| Khalifa | Strategy, nonstrategy and no strategy | 2021 |
| Matikainen | Addressing Sustainability in the Mining Industry Through Stakeholder Engagement | 2022 |
| Murthy | Integrating corporate sustainability and strategy for business performance | 2012 |
| Pineiro-Chousa et al. | Managing Reputational Risk through Environmental Management and Reporting: An Options Theory Approach | 2017 |
| Porter | What is strategy? | 1996 |
| Stoiconi | Strategies for Implementing Sustainability in Entrepreneurial Businesses | 2024 |
| Tighe | Rethinking Strategy | 2019 |
| **Data collection phase: SWOT, AQDC, ES** | | |
| Choo | The Art of Scanning the Environment | 1999 |
| Coman & Ronen | Focused SWOT: Diagnosing critical strengths and weaknesses | 2009 |
| David et al. | What is the Key to Effective SWOT Analysis, Including AQCD Factors | 2019 |
| Pickton & Wright | What's swot in strategic analysis? | 1998 |
| Song et al. | Environmental scanning, cross-functional coordination and the adoption of green strategies: An information processing perspective | 2024 |
| Wu et al. | Environmental scanning, supply chain integration, responsiveness, and operational performance: An integrative framework from an organizational information processing theory perspective | 2019 |
| **Data collection phase: Diffusion of innovation** | | |
| Dearing & Cox | Diffusion Of Innovations Theory, Principles, And Practice | 2018 |
| Driessen & Hillebrand | Adoption and Diffusion of Green Innovations | 2002 |
| Rogers | Diffusion of innovations | 2003 |
| **Data collection phase: Muon imaging** | | |
| Beni et al. | Transmission-Based Muography for Ore Bodies Prospecting: A Case Study from a Skarn Complex in Italy | 2023 |
| Holma et al. | On the verge of a new kind of geophysics: Part 1 — Muons and the most common applications of muography | 2023 |
| Holma et al. | Future Prospects of Muography for Geological Research and Geotechnical and Mining Engineering | 2022a |
| Holma et al. | On the Verge of a New Kind of Geophysics: Part 2 — Muon detectionand the basic principles of muography | 2022b |
| Kaiser | Muography: Overview and future directions | 2019 |
| Lechmann et al. | Muon tomography in geoscientific research – A guide to best practice. | 2021 |
| Saracino et al. | Applications of muon absorption radiography to the fields of archaeology and civil engineering | 2018 |

| | | |
|---|---|---|
| Yang et al. | Novel muon imaging techniques | 2018 |
| Yu et al. | Environmental scanning, supply chain integration, responsiveness, and operational performance: An integrative framework from an organizational information processing theory perspective | 2019 |
| Zhang et al. | Muography and Its Potential Applications to Mining and Rock Engineering | 2020 |

To ensure objectivity and mitigate bias, data from mining companies' websites was deliberately excluded, thus avoiding any potential inclination towards biased information. Data gathering in action research should involve a diverse range of procedures to ensure comprehensiveness, validity, and reliability of it (Eriksson & Kovalainen, 2008). Access to documents was facilitated through personal credentials provided by JYU for accessing JYKDOK and various publishing sources therein. Additionally, Muon Solutions Ltd supplied some articles related to muon imaging that was not available through JYKDOK.

To outline the conceptual theoretical framework, the selection of suitable theories was guided by their relevance to the research objectives. Strategic management theory was chosen to provide a structured framework for academically constructing a strategy, ensuring a robust foundation for the research. Additionally, the theory of innovation diffusion was selected to facilitate understanding of the dynamics of innovation adoption and diffusion, crucial for driving progress and development across various domains relevant to the study. In order to gain a comprehensive understanding of the strategic tools necessary for constructing an implementable and practical strategy, a combination of a SWOT analysis together with the AQCD framework, and environmental scanning were utilized. These methodologies were chosen for their effectiveness in strategic planning processes and their ability to provide valuable insights into organizational environments and potential opportunities and threats. The suitability of the chosen theories and methodologies was thoroughly discussed and validated in thesis seminars, ensuring that the research approach was well-founded.

Given the rapid development of sustainability-related issues, particular emphasis was placed on selecting sustainability and environmental strategy-related articles and books that were published as close to the current year as possible. This approach ensured that the research findings would be informed by the most up-to-date knowledge and trends in the field of sustainability.

## 7.6 Data analysis

The collected data underwent thorough analysis to ensure its validity and reliability. Critical reflection was systematically applied throughout to minimize bias, enhancing the integrity of the data analysis. In action research projects, providing data feedback to the studied organization or community is crucial, involving them in analysis, action planning, and evaluation (Eriksson & Kovalainen, 2008). Muon Solutions Ltd evaluated the strategy constructed for muon imaging, ensuring its practical feasibility. An interdisciplinary perspective combining natural sciences (geology and muon imaging), social aspects (stakeholder considerations), and corporate environmental management (conceptual theoretical framework and feasibility of the strategy) was used in data analysis. This comprehensive perspective allowed for a more holistic understanding of the data, acknowledging that complex and interdisciplinary issues often require insights from multiple fields.

The action research cycles, as illustrated in Figure 5 by Coghlan & Brannick (2014), proceeded in a structured sequence. The initial phase involved detailed discussions with the organization, focusing on the core issues and the potential integration of muon imaging to promote sustainability in mining operations. These discussions were important in aligning the research with the specific needs and objectives of the organization, thereby setting a solid foundation for strategy development. In the subsequent phase, the necessity for a strategic framework was addressed. This phase involved defining the scope and objectives of the strategy within the context of the mining industry, with a particular focus on operations within Finland. This stage was crucial for establishing a clear direction and ensuring that the strategy was tailored to address the unique challenges and opportunities presented by the Finnish mining sector. The third phase of the research involved the formulation of a comprehensive strategy that included aspects of implementation, sustainability, and stakeholder engagement. This involved identifying and involving relevant stakeholders to ensure their perspectives were considered in the strategy development process. Recognizing and analysing key stakeholders facilitated the integration of diverse viewpoints, leading to more relevant and applicable outcomes. The key stakeholders were viewed from a Finnish point of view and therefore, e.g., reindeer herders were recognized as one key stakeholder, due to many mining operations taking place in northern Finland. The final stage of the action research involved assessing the credibility and viability of the developed strategy. This assessment was crucial to confirm that the strategy was not only theoretically sound but also practically feasible and capable of achieving the desired outcomes. The author's prior experience in Finland's mining sector provided informed insights, enriching the interpretation and analysis of environmental considerations within the industry. This background proved beneficial for understanding the nuanced impacts of mining operations and developing strategies that are both environmentally sustainable and responsible towards stakeholders.

Throughout the research process, the action research cycles were continuously reviewed and adjusted, as emphasized by Eriksson and Kovalainen (2008). This iterative nature of action research is vital for adapting to changes within the research setting and modifying the data-gathering process as required (Eriksson & Kovalainen, 2008). Such flexibility is essential to address emergent issues and refine the strategy based on ongoing feedback and reflections. In this thesis, multiple revisions and reflections occurred, underscoring the dynamic and responsive nature of action research in practical settings. This iterative process ensured that the strategy remained relevant and aligned with both academic rigor and practical industry needs.

In this thesis, action research follows an inductive approach, as detailed by Hair et al. (2015), where the primary aim is for researchers to develop their theories or conceptual frameworks from the data they collect. This inductive methodology offers flexibility, allowing for various data types and sample sizes (Hair et al., 2015), which is particularly advantageous in fields requiring adaptability to diverse and dynamic environments. Unlike deductive research, it does not necessitate the pre-establishment of hypotheses or theories, thus enabling a more open-ended exploration of phenomena (Hair et al., 2015). To ensure that the research questions were both relevant and practical, they were discussed with Muon Solutions Ltd. These discussions took place during remote meetings in the autumn of 2023 and spring of 2024, providing important industry insights. Such collaboration is essential in action research, as it ensures that the investigation is grounded in real-world problems and their potential solutions. Gummesson (2000), as cited in Eriksson & Kovalainen (2008), emphasizes the significance of maintaining close connections with industry practices within business research. Gummesson (2000, as cited in Eriksson & Kovalainen, 2008) further states that the roles played by academic research and management consulting are closely aligned, highlighting the practical application of academic inquiries. This perspective supports the thesis's approach, which combines academic study and practical industry application, ensuring that the research remains relevant to current sustainability-related challenges.

# 8 RESULTS

This chapter presents the principal discoveries derived from the theoretical frameworks presented in this thesis, practical implications drawn from the data analysis, and the potential application of muon imaging in geotechnical contexts to promote sustainability in mining. The SWOT analysis, complemented by the AQCD framework, serves as the foundation for devising the strategy in conjunction with strategic management principles. Environmental scanning is employed to evaluate the current state within Finland's mining sector. The diffusion of innovation theory will inform the implementation process and facilitate the adoption of muon imaging within the mining industry. The chapter features visual representations of the research findings.

## 8.1 A SWOT analysis complemented with the AQCD framework

In this thesis, the integration of a SWOT analysis, complemented by the AQCD framework is essential for gaining a thorough understanding of both the advantages and limitations of integrating muon imaging in the Finnish mining sector. In Figure 7, a SWOT analysis is conducted based on the integration of muon imaging in the Finnish mining sector. Additionally, categorizing the information into the AQCD framework information into two main categories—advantages and qualities, and constraints and drawbacks—provides a clear and concise overview, facilitating easier comprehension.

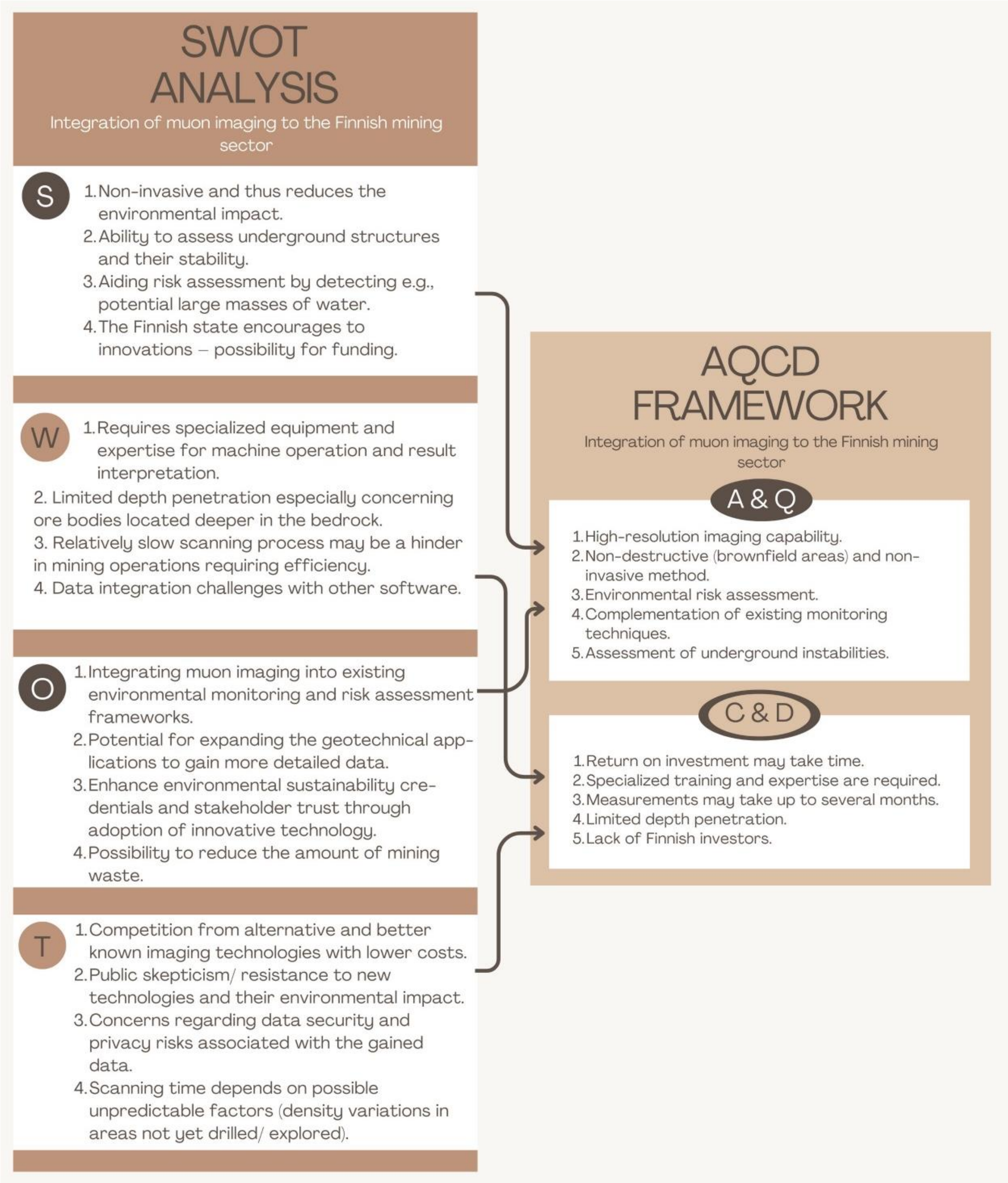


Figure 7. An illustration of the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis complemented by the AQCD (Actionable, Quantitative, Comparative, Divisional) framework.

A SO (strengths – opportunities) strategy would mean to leverage the non-invasive muon imaging and to integrate it into existing environmental monitoring and risk assessment frameworks. This would add value to the environmental management practices of the company. By utilizing muon imaging's ability to assess underground structures and detect potential large masses of water (Holma et al., 2022a), mining companies can enhance their environmental sustainability and gain better stakeholder trust. By expanding the geotechnical applications of muon imaging to gain more detailed data, there is an opportunity to reduce the environmental impact of mining activities and minimize the amount of ore going to waste. Moreover, with the Finnish state encouraging innovations and offering funding possibilities (MEAE, 2023a), mining companies can capitalize on this support to implement muon imaging technology effectively in their operations, further solidifying their commitment to sustainability and innovation.

The ST (strengths – threats) strategy tries to mitigate potential threats and capitalize strengths. This involves emphasizing the capability of muon imaging to reduce environmental impacts through decreased drilling and the potential to integrate the use of muon imaging alongside conventional geophysical methods. Such integration can lower the barrier to adopting new technologies, as combining muon imaging with established geophysical methods on site enhances both reliability and credibility. Other factors include demonstrating muon imaging's capability to assess underground structures and their stability as a competitive advantage. Positioning muon imaging as a superior risk assessment tool, especially effective in detecting potential water masses, can significantly address safety concerns. Data security concerns can be addressed by implementing data handling protocols and assuring the technology's safety and reliability thus mitigating the risk for potential reputational damage. Cyber safety is important to address hackers' interest to manipulate commodity markets by spreading misleading or false information, affecting investment decision, and causing financial losses for stakeholders.

A WO (weaknesses – opportunities) strategy addresses the weaknesses and highlights the opportunities. For the effective use of muon imaging, this implies investing in training programs to develop more experts. With more skilled professionals available, it becomes easier to overcome the challenges associated with specialized knowledge. Resource allocation for research and development (R&D) to improve the efficiency of depth penetration in ore bodies located deeper in the bedrock could unlock new opportunities for exploration. Highlighting muon imaging's role in enhancing environmental monitoring and reducing mining waste strengthens its credibility and appeal to stakeholders. Data integration with other software is managed by identifying the data formats and determining if there are specific operational procedures, for example, already existing within the software.

The WT (weaknesses – threats) strategy mitigates threats by recognizing the weaknesses. Investing in training programs and improving equipment accessibility are important measures for staying competitive and thriving in a dynamic and fluctuating market landscape. Well-trained professionals with up-to-date knowledge and tools are better prepared to utilize muon imaging. Given the increasing emphasis on sustainability and corporate responsibility in public discussions, fostering transparency and open communication with stakeholders, is crucial (MEAE, 2023a). Additionally, safeguarding sensitive data is paramount, to avoid data leaks that have serious consequences.

Advantages and qualities of muon imaging include its high-resolution imaging capability, which provides valuable insights into underground structures. Its non-destructive and non-invasive nature minimizes environmental impact, making it conducive to sustainable practices in brownfield areas and aligning with green transition goals. Moreover, muon imaging provides valuable insights that aid in environmental risk assessment and complement existing monitoring techniques. Its ability to accurately assess underground stability and detect environmental risks early enhances proactive mitigation measures. Additionally, Finland's mining cluster fosters collaboration among industry professionals, offering the potential to raise awareness about the benefits of muon imaging.

However, muon imaging also faces certain constraints and drawbacks. Its higher initial costs may lead to a longer return on investment, potentially deterring some companies. Moreover, specialized training and expertise are required for the operation and interpretation of muon imaging data, which may pose challenges for some organizations. Additionally, the time required for measurements can be lengthy, ranging from weeks to several months, potentially affecting project timelines. Furthermore, muon imaging exhibits limited depth penetration compared to alternative imaging technologies, especially in deeper mining operations. Economic constraints, including a lack of investment from Finnish investors, may further limit the adoption of innovative environmental technologies such as muon imaging.

Furthermore, the SO (strengths-opportunities), ST (strengths-threats), WO (weaknesses-opportunities), and WT (weaknesses-threats) strategies for muon imaging in mining offer a comprehensive approach to leveraging its strengths while addressing potential weaknesses and threats. By highlighting the capabilities of muon imaging, such as enhancing mineral extraction precision and reducing environmental impact, these strategies advance sustainability in mining. Investing in R&D can lead to the discovery of new geotechnical approaches for muon imaging, thereby offering new and innovative opportunities for sustainable mining practices. Addressing concerns related to adaptability and technical complexities ensures the resilience of muon imaging in mining practices.

## 8.3 Environmental scanning

Environmental scanning is facilitated by a structured approach, integrating muon imaging into strategies, with the factors pinpointed in the SWOT analysis complemented by AQCD framework. The scanning initiates by identifying environmental issues related to the Finnish mining sector, encompassing ecological aspects such as water management, reclamation of former mining sites, utilization of mining by-products, energy conservation, value conflicts, nature-based revenue, and the Talvivaara environmental crisis in 2012 (MEAE, 2023a; MEAE, n.d.b.). As this thesis has a focus on the environmental and technological factors, the scanning also includes a scanning of the technological factors related to mining industry in Finland. The technological factors include issues like the energy transition (green transition), utilization of battery minerals and the battery cluster in Finland, energy efficiency and technological advancements to name a few (MEAE, 2023b; MEAE, 2021). Other factors such as political, economic, social and cultural are also affecting the operational mining environment in Finland but are outside the limits of this study.

Environmental scanning relates to mines utilizing the best available techniques (BAT) to prevent or reduce negative environmental impacts. Muon imaging, being an innovative technology with promising potential for advancing sustainability—such as reducing the amount of required drilling and serving as a tool in identifying ore reserves within active mining sites—may be qualified as a BAT. Reducing the amount of drilling in the exploration stage – operational stage is essential for promoting sustainability by minimizing environmental impact (ecosystems), conserving resources (energy and water), improving energy efficiency (lower energy consumption), achieving cost savings (resource intensive), and enhancing community relations (reduced impact on the ecosystems, better community acceptance). As muon detectors are passive, since they do not generate the muons they detect (Holma et al., 2022a; Zhang et al., 2020) and therefore, does not produce radiation to the surrounding environment. The detectors demand energy (electricity) to operate and the source of energy may be chosen to originate from renewable sources, thus minimizing its operational environmental effects.

Geological bedrock mapping is usually the first step when conducting exploration in an area and it provides foundational data for environmental scanning, enabling a comprehensive understanding of the natural environment. Therefore, the exploration permit granted by the mining authority is assumed to have been carried out and other notifications related to exploration and field work in the area set in the Finnish Mining Act (621/2011) to have been successfully completed. In the context of geotechnical applications of muon imaging during exploration in Finland, muon imaging is typically not performed until after drilling has taken place, since the detectors have to be installed in depth before the muon flux can be recorded (Holma et al., 2022a). This implies the presence of an exploration permit in the area. In other words, solely muon imaging is not taking place, it requires to be combined and completed with other methods that provide geological and often also geophysical background data about the area, such as drilling or other geophysical methods.

In simplified terms, after the bedrock mapping stage of exploration, drilling occurs. The effectiveness of muon imaging can then be assessed based on the data obtained from drilling. Other geophysical imaging techniques can be carried out simultaneously, previously or after the bedrock mapping. As muon imaging can be combined to other geophysical methods to significantly better the interpretation of gained data (Holma et al., 2022a, and the references therein) and the harmful effects to the nearby environment can be reduced. This data contributes to environmental scanning by enabling more precise assessments and mitigations of environmental impacts.

Environmental scanning should also include risk assessment, cost-benefit analysis, and stakeholder engagement. The use of muon imaging does not itself introduce risks to the exploration process, but rather helps in recognizing them in form of more accurate depiction of the bedrock. As muon imaging is a novel technology, any clear cost-benefit analysis does not yet exist. Considering the potential savings in discovering ore bodies, the cost-benefits are expected to be positive. Stakeholder engagement is related to the mining industry as a whole and the exploration taking place in a specific area. Muon imaging can address some concerns originating from the local communities, environmental organizations and governmental agencies, by assuring the effective utilization of the ore body and muon imaging serving as a tool to monitor e.g., process waters and other structures in the mine and nearby areas (Holma et al., 2022a).

The last step in environmental scanning is the monitoring and evaluation of the environmental effects of muon imaging over time. Gaining data from operations provides data for comparing to what degree muon imaging is saving environmental and financial resources and contributing to more efficient utilization of the ore body. Continuously assessing its effectiveness in advancing sustainability and adjusting as necessary contributes to more sustainable mining.

## 8.4 Strategy

The strategy is designed to be utilized by entities who employ remote sensing and/or geophysical methods, particularly within the mining context of Finland. The strategy for implementing muon imaging is divided into seven (7) steps and it operates under the assumption that the company already possesses an environmental management system (EMS), established according to standards such as ISO 14001. Using suitable management systems that take environmental issues into consideration, offers guidance when it comes to implementing the strategy (Engert & Baumgartner, 2016). A company possessing an EMS sees crucial for its operations to minimize its environmental impacts and contribute to mitigate climate change. The strategy also assumes that an environmental impact assessment (EIA) is conducted and the required permits from different laws and acts are obtained, thus complying with the Finnish legislation.

The strategy outlined in this thesis is constructed based on the themes examined throughout the research. Derived from strategic management principles, the formulation, integration of sustainability and stakeholders, and implementation of the strategy are built upon. The foundation for this strategy is established through a combination of a SWOT analysis, complemented by the AQCD framework, and environmental scanning to examine how muon imaging fits into the Finnish mining environment. Furthermore, insights from the diffusion of innovation theory inform the likelihood of adopting and adaptation of new technologies such as muon imaging.

Strategy Implementation Steps:

1. **Understanding the current state regarding the environmental sustainability aspects**

A comprehensive evaluation of the organization's current environmental footprint is already existing in the organization's EMS. This includes the identification of both sustainable and unsustainable practices, particularly in the exploration phase where remote sensing and/ or geophysical methods are used. This phase recognizes the potential of innovative technology to improve sustainability throughout the mining lifecycle, from the exploration stage and operational period to the monitoring of the site post-closure. By using muon imaging a better image of the underground structures is gained and therefore the interpretation of the geological structures is better understood. Based on the arguments by Holma et al. (2022a), Zhang et al. (2020) and Kaiser (2019), muon imaging has the possibility to answer to the following aspects: A smaller amount of invasive bedrock drilling is required, especially in brownfield mining areas, where previous drillholes may be utilized for muon imaging purposes. Muon imaging can be utilized to assess the stability of underground structures and tunnels originating from past exploration activities, along with the detection of potential large masses of water. By doing this, the safety of the area increases, when potential instabilities of structures are located along with other possible safety hazards. The use of muon imaging may also be used on ground level when monitoring tailings or process waters. This adds to not only environmental considerations but also worker safety.

A SWOT analysis for this stage reveals that muon imaging, with its non-invasive nature, presents strengths such as minimal environmental impact and improved safety assessments of underground structures, thereby increasing resource extraction efficiency. However, weaknesses stem from the requirement for specialized expertise and equipment. Opportunities arise from integrating muon imaging into existing environmental monitoring frameworks, facilitating improved data collection and analysis. Yet, threats persist due to the novelty of muon imaging, with the mining industry potentially lacking familiarity with its capabilities.

2. **Stakeholder engagement**

Maintaining an open discussion with stakeholders and clearly communicating how integrating muon imaging into the sustainability strategies demonstrates a commitment to innovation, utilization of best available technology (BAT), environmental stewardship, and responsible mining practices is crucial. Transparent communication with stakeholders regarding the environmental impacts of mining and the mitigation measures undertaken is crucial. This type of collaborative efforts involving stakeholders, not only fosters trust but also cultivates strong relationships with them (Coghlan & Brannick, 2014). Stakeholders may be several or all of the following examples: local communities, governmental agencies, mining companies, environmental and non-governmental organizations (NGOs), shareholders and investors, reindeer herders, indigenous communities, labor unions, media, academic and research organizations, service providers and suppliers. They may be concerned of socio-economic impacts, environmental degradation, land use, health and safety risks, permits, sustainability, addressing communities' concerns, traditional territories for e.g., reindeer herding, maintaining an operational infrastructure to the mine, fluctuations in mineral and metal prices or other controversies. Addressing these concerns from diverse stakeholders' perspective is important to achieve a mutual understanding for all the involved parties. Sustainable mining practices does not solely rely on environmental factors, social and financial considerations are equally important. Additionally, philanthropic measures taken should not be overlooked.

An AQCD framework for this stage reveals that the advantages of muon imaging include engaging stakeholders to communicate its benefits for environmental risk assessment and management. Highlighting its potential for early detection of environmental risks and proactive mitigation measures builds stakeholder trust. However, drawbacks involve addressing concerns regarding initial investment costs and specialized training through transparent communication.

3. **Definition of the vision and goal**

Defining the vision and goal of sustainability within the mining industry by using muon imaging consists of different sustainability goals. The goals may include factors such as reducing emissions, promote local employment, enhancing responsible land use, using resources efficiently, and maintaining transparent governance. Presenting the outcomes of using muon imaging to locate ore bodies directly aligns with the vision and goal of enhancing mining sustainability and efficiency. By demonstrating how muon imaging can reduce the need for extensive drilling, it supports the objective of minimizing environmental impact and optimizing resource extraction processes. The vision and goal may involve leveraging traditional geophysical methods alongside, rather than exclusively relying on muon imaging for acquiring bedrock data (Holma et al., 2022a).

A SWOT analysis identifies strengths in the improved resource efficiency achieved by utilizing muon imaging to locate ore bodies, resulting in more efficient resource extraction, waste reduction, and minimized environmental impact. Weaknesses emerge from the complexity of implementing sustainability goals with muon imaging technology, since not many are familiar with utilizing muon imaging. Embracing muon imaging technology offers opportunities for the organizations to improve environmental performance and becoming frontrunners in innovation and sustainability. However, the challenge lies in overcoming a possibly negative public perception of mining activities, which, despite efforts to articulate sustainability goals, may affect the social license to operate and relationships with stakeholders.

4. **Pilot projects and awareness**

This step includes projects serving as a showcase for sustainable mining practices to demonstrate and highlight the benefits of muon imaging. As discussed in the innovation diffusion theory, an innovation is more likely to be adopted when it is perceived to offer greater relative advantage, compatibility, trialability, and observability, and to possess lower complexity (Rogers, 2003). In a pilot project, mining companies are provided with data from the project(s), accompanied by clear communication of its benefits, applicability of muon imaging in existing drill holes, its potential for trial implementation on-site, and how the results from muon imaging can inform decision-making processes. Furthermore, by demonstrating how it can reduce the need for drilling and thus contributing to more sustainable mining practices, the innovation is more likely to be adopted. By organizing demonstrations and presentations to highlight muon imaging's capabilities to stakeholders and the public, utilizing visual demos supported by case studies or pilot projects bring awareness. Mining companies or organizations employing remote sensing typically follow established procedures for geophysical and geological exploration in new areas. Integrating muon imaging alongside existing geophysical methods maintains these routines while enhancing data collection with supplementary information. Launching educational campaigns with research facilities to inform about muon imaging's potential in mining is a way to involve academia and introduce researched information regarding muon imaging. The non-profit association Mining Finland promotes the export of Finnish mining technology, facilitates research and development, and fosters educational collaborations within the mining sector in Finland (Mining Finland, n.d.). It could serve as a valuable platform for raising awareness about muon imaging not only in Finland but also globally, positioning it as a complementary and synergistic geophysical tool. Integrating muon imaging, instead of trying to outcompete and replace existing methods, can facilitate easier adoption.

A SWOT analysis reveal that the strengths include emphasizing the imaging capability and non-destructive nature of muon imaging therefore attracting interest and support from stakeholders. Highlighting these qualities showcases muon imaging as an innovative technology that aligns with industry and societal sustainability goals. Opportunities include a possible future scenario, where muon imaging gains momentum and emerges as a pivotal remote sensing method. Weaknesses are the low amount of skilled personnel operating with muon imaging, limiting a widespread and effective adoption. Threats, therefore, are the logistical challenges in deploying and maintaining muon equipment in remote mining sites (especially greenfield mining projects) and the availability of technical support in the research sites. The weaknesses and threats have to be addressed to overcome these types of obstacles.

5. **Compliance with policies, regulatory work, standards and initiatives**

The Towards Sustainable Mining (TSM) initiative's purpose to encourage the mining industry towards more sustainable practices could benefit from the use of muon imaging. According to the national battery strategy, in 2025, Finland's battery cluster is a pioneer, producing expertise, innovations, sustainable economic growth, well-being, and jobs in Finland (MEAE, 2021). A prerequisite for this is the production of battery raw materials, which demands mining operations, where muon imaging could serve as a useful tool. Mine.io aims to advance the mining sector's sustainable development through various digital solutions, encompassing all stages of mining from exploration to post-mining activities (Mine.io, n.d.). Muon imaging produces data that could digitally be utilized when trying to comprehend the different stages in a mining project. Aligning the use of muon imaging with existing EMS, industry standards, and regulatory frameworks is a strategic approach that enhances sustainability, operational integrity, stakeholder trust, and risk management in the mining sector. On a broader level, as a member of the EU, Finland aims to establish a resilient and sustainable source of critical raw materials (CRM), with sustainable mining practices that muon imaging has the capability to contribute to.

6. **Evaluation**

Reviewing and updating strategies based on outcomes presents opportunities to identify areas for improvement and adaptation. An iterative approach to strategy enhancement ensures that practices remain relevant and effective in achieving desired sustainability goals. Collaborating with different stakeholders such as researchers, developers and scientists to improve and assess the outcome from the data may bring expert insights to e.g., enhance the effectiveness of adaptation and adoption of muon imaging on a larger scale. Assessing stakeholders like NGOs, local communities, and public opinion is vital for fostering positive relationships, community expectations and transparency. Collecting feedback on transparency, promptness, and communication is crucial for addressing concerns effectively. Despite possible uprising challenges and time required, engaging stakeholders ensures accountability, trust, and a stronger relationship with the community (Pettersson & Suopajärvi, 2018).

7. **Continuous improvement**

Due to tightening environmental regulations, proactive measures are necessitated to prevent penalties (Stoiconi, 2024). Developing industry expertise and investing in muon imaging know-how not only mitigates the risk of falling behind in sustainability standards but also contributes to a culture of continuous learning and improving of the current practices. Allocating resources to training and development initiatives serves as a strategic approach, enabling the organization to enhance their workforce's capabilities and knowledge, thus responding to the weakness of a low amount of skilled personnel and the unfamiliarity of muon imaging for e.g., geoscientists. This investment guarantees that staff members are adequately prepared to fully leverage muon imaging technology, leading to improvements in operational effectiveness, safety measures, and sustainable practices.

The strategy is presented in a visual format for enhanced understanding, as summarized in Figure 8.

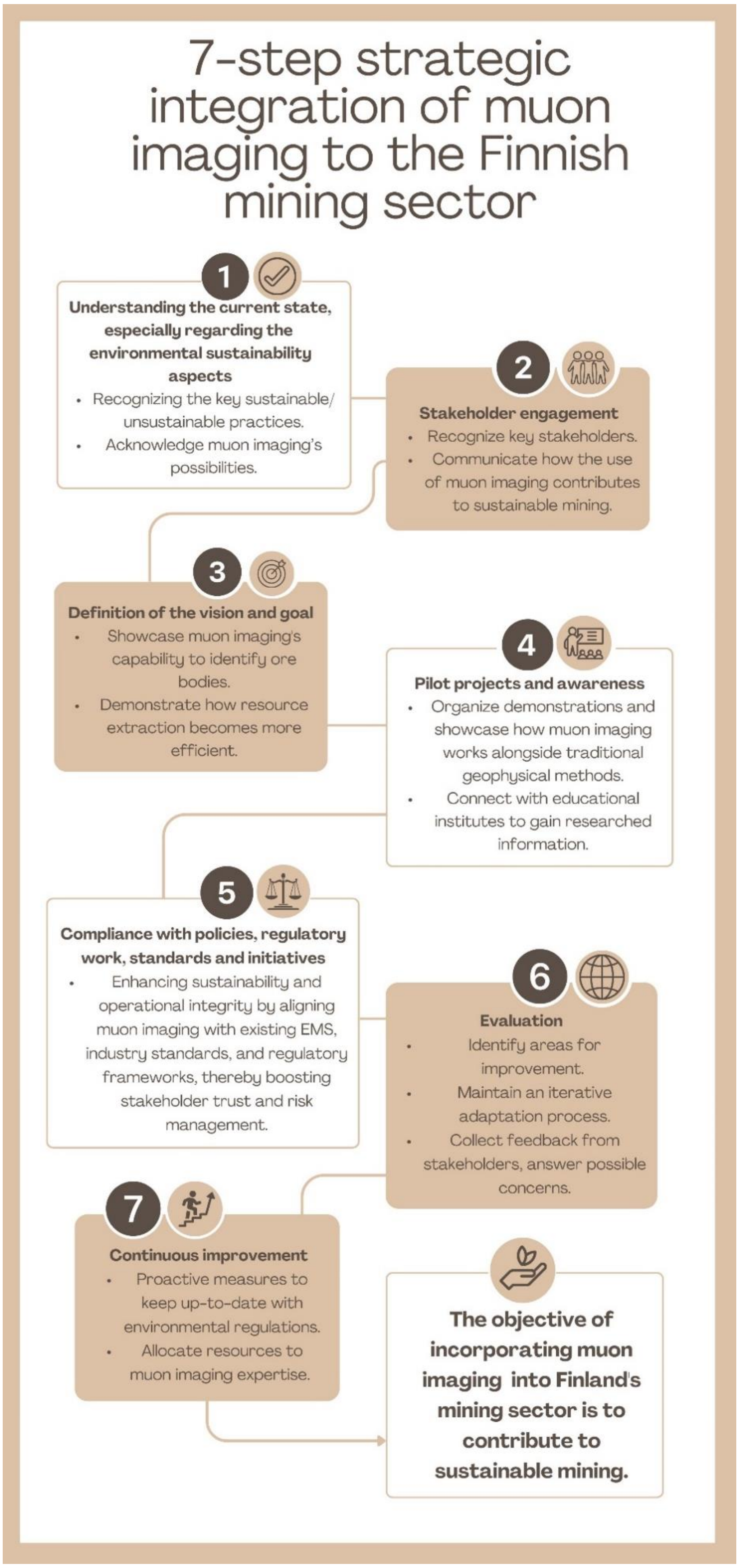


Figure 8. A visualization of the seven-step strategy on how to integrate muon imaging to the Finnish mining sector.

Challenges such as environmental degradation, highlighted in the UN's Sustainable Development Goals (SDGs) 6, 11, 13, and 15 (UN, 2023), underscore the need for innovation and adaptation of more sustainable mining practices within the mining sector. By integrating muon imaging to the mining sector, Finland not only addresses these challenges but also aligns with SDGs 7, 8, and 9 by promoting economic growth, industry innovation, and infrastructure development, thus enhancing the sector's sustainability. A comprehensive approach ensures that the integration of muon imaging technology aligns with broader objectives of enhancing environmental sustainability, improving safety standards, and driving sustainability innovation in the mining industry in Finland. Therefore, the proposed strategy serves as a fundamental aspect of this thesis, offering a structured framework for analyzing and addressing complex issues at the convergence of technology, sustainability, and industry practices.

## 8.5 The diffusion of muon imaging as an innovative technology

The diffusion of muon imaging technology in the mining sector is strategically addressed through the application of Rogers' (2003) diffusion of innovation theory, which emphasizes five main themes: *relative advantage*, *compatibility*, *trialability*, *observability*, and *lower complexity*. The seven (7) different strategy steps from chapter 8.4., are referred to in the text and they are 1. Understanding the current state, especially regarding the environmental sustainability aspects, 2. Stakeholder engagement, 3. Definition of the vision and goal, 4. Pilot projects and awareness, 5. Compliance with policies, regulatory work, standards and initiatives, 6. Evaluation and 7. Continuous improvement.

The *relative advantage* of muon imaging is underscored through the evaluation of the current environmental practices and pilot projects (strategy step 1), highlighting its non-invasive nature, and its ability to enhance safety and environmental management—making it a preferable choice over traditional exploration methods (strategy step 3). The pilot projects (strategy step 4) further validate its benefits in terms of resource efficiency and safety, promoting its adoption.

In terms of *compatibility*, the strategy for integrating muon imaging aligns with existing EMS and adheres to current mining practices and regulatory standards, ensuring that the technology fits seamlessly within the mining industry's operational, environmental, and safety protocols (strategy step 5). This is the assumption that the strategy is constructed upon (strategy base).

*Trialability* is facilitated through pilot projects (strategy step 4), which allow for hands-on experimentation and assessment of muon imaging's practicality and effectiveness in real mining environments, essential for gauging the technology's applicability on a smaller scale before broader implementation.

*Observability* is achieved by showcasing the outcomes and benefits of muon imaging through these pilot projects (step 4), educational campaigns, and public presentations, making the advantages of muon imaging visible to a broad audience, including stakeholders (strategy step 2) and the general public.

Addressing the *lower complexity*, continuous investment (strategy step 7) in training and development aims to enhance industry understanding and proficiency in muon imaging, simplifying the technology for professionals within the sector.

Together, five main themes grounded in Rogers' (2003) diffusion of innovation theory with the proposed strategic steps, illustrate a coherent approach to facilitating the adoption of muon imaging into the mining sector. They highlight the technology's relative benefits, ensure compatibility with existing systems, allow for its trial and assessment, increase its visibility among stakeholders, and address challenges related to its complexity—thereby making a compelling case for muon imaging as a practical and innovative choice for sustainable mining practices.

## 8.6 Contribution to sustainability strategies

This thesis connects the adoption of muon imaging technology to broader sustainability objectives, demonstrating its potential to enhance responsible consumption and production, foster industry innovation, and support climate action. By incorporating empirical data and theoretical frameworks, it enriches the sustainability discourse, particularly in showing how technological advancements can improve environmental and social outcomes in industry settings. This is crucial for addressing the global challenges of unsustainable resource use and environmental degradation, as highlighted by sustainability scholars such as Carroll (2015) and organizations like the United Nations (2023).

Engert & Baumgartner (2016) emphasize the necessity of tailoring corporate sustainability strategies to fit the specific circumstances of an organization. This thesis responds to this requirement by first understanding the specific mining environment in Finland and then constructing an implementable strategy tailored to that context. This approach aligns with Sharma's (2003, as cited in Murthy, 2012) statement that developing sustainability-related resources and capabilities is vital for gaining a strategic competitive advantage, which not only leads to improvements in social welfare and ecological impact reduction but also helps in achieving organizational goals.

When assessing the broader impact of this thesis on sustainability strategies, it is evident that the integration of muon imaging not only addresses specific environmental impacts of mining but also serves as a model for how emerging technologies can be integrated into traditional industries to meet sustainability objectives. The strategic application of muon imaging, as illustrated in this thesis, showcases the effectiveness of strategic planning, stakeholder involvement, and compliance with regulatory frameworks in driving the shift towards more sustainable practices across various sectors. This aligns with the views of Bernal-Conesa et al. (2017), who claim that adopting a

Corporate Social Responsibility (CSR)-oriented strategy not only enhances organizational performance but also boosts the competitiveness and sustainability of technology companies.

In conclusion, this thesis contributes to sustainability literature by providing an actionable framework for the technological integration of muon imaging within the mining industry. The insights provided are supported by empirical and theoretical underpinnings from sources such as Crews (2010) who discusses the importance of viewing sustainability as an ongoing journey rather than a finite goal, and Galpin & Hebard (2018), who highlight the challenges of integrating sustainability into strategic management due to varying actions. This comprehensive approach ensures that the thesis not only adds to the academic discussion on sustainability but also provides practical pathways for industries looking to incorporate sustainable practices effectively into their operational models.

# 9 DISCUSSION

The discussion section revisits the data collection and analysis from literature, case studies, and governmental sources, using action research to investigate the adoption of muon imaging technology in the mining sector. Given the limited research on the implementation of new technologies within the Finnish mining industry, an understanding of the current mining environment with incorporation of muon imaging through a strategy was formed. This chapter further aims to evaluate the feasibility and credibility of the proposed strategy, assess its implementability, and consider its potential impact within the Finnish mining industry context.

## 9.1 Strategic integration of muon imaging in the Finnish mining industry

The increasing emphasis on sustainability in recent years, driven by ethical, environmental, and social considerations (Ruokonen, 2021), highlights the strategic importance of integrating sustainability into the mining sector, both on a global scale and in Finland. Recognizing the indispensable role of minerals and metals in modern civilization, alongside the escalating demand due to population growth and urbanization (MEAE, 2023a), the significance of sustainable mining practices is underscored. Furthermore, technological advancements within the mining sector such as muon imaging and digitalization through projects like Mine.io, present promising opportunities to comprehensively understand a mine's lifecycle, thus enhancing sustainability and improving environmental and social performance.

The future potential of muon imaging, as suggested by Holma et al. (2022a), shows promise in contributing to sustainable mining practices. Despite its novelty, muon imaging shows promise in aiding mineral exploration and mining operations by enabling the investigation of density contrasts in large rock volumes (Holma et al., 2022a), thereby reducing unnecessary drilling, saving costs and time, and providing valuable geological insights through the detection of density anomalies (Holma et al., 2022a; Zhang et al., 2020). It complements traditional geological drilling by optimizing borehole placements and reducing exploration costs. As muon imaging becomes more widely adopted, more data will become available, sparking interest in comparing it with traditional geophysical methods.

Given the claimed potential of muon imaging, the mining industry should consider its application in mining operations and its incorporation as a sustainability-enhancing element in their Environmental Management Systems (EMS). As highlighted by Heslin & Ochoa (2008), ensuring environmental protection, generating profits for shareholders, and enhancing the well-being of stakeholders confer a strategic advantage. Thus, integrating muon imaging into strategies for organizations in the mining sector positively contributes to all three pillars of sustainable development: people, planet, and profit.

In the context of Finland, leveraging strategic management tools such as a SWOT analysis, complemented by the AQCD framework and environmental scanning, reveals certain weaknesses and constraints associated with the adoption of muon imaging in the mining sector. Specifically, significant barriers exist, including economic investments needed to initiate muon imaging projects. In Finland's context, however, where there is a focus on sustainable development and environmental stewardship, these investments would align with the country's goals and priorities, such as the National Battery Strategy 2025 (MEAE, 2021). There is a shortage of professionals with the necessary expertise to operate muon imaging equipment and interpret its results accurately. Addressing this shortage requires targeted training programs and educational initiatives to build a skilled workforce capable of effectively utilizing muon imaging technology. Additionally, the scanning duration associated with muon imaging can pose challenges, particularly in a fast-paced industry like mining where time is of the essence. Finally, the absence of comparative numerical data compared to more traditional imaging techniques presents a hurdle in demonstrating the efficacy and reliability of muon imaging to stakeholders in the Finnish mining sector. Overcoming these constraints will require collaborative efforts between industry stakeholders, academia, and government agencies to invest in research, development, and training initiatives aimed at unlocking the full potential of muon imaging in the Finnish mining industry.

## 9.2 Assessment of the strategy’s implementability

Assessing implementability is key to validating the practicality of strategic plans and enhancing their success rate. The strategy acknowledges the pre-existence of an EMS, aligned with e.g., the ISO 14001 standard within the organization implementing the strategy. This foundational element ensures that the forward-thinking strategy builds upon established environmental management practices. By incorporating suitable management systems and conducting environmental impact assessments as per Finnish legislation, the strategy demonstrates compliance with regulatory requirements, laying a foundation for implementation. Furthermore, the strategy draws upon strategic management principles, including a SWOT analysis, complemented by the AQCD framework, and environmental scanning, to assess the suitability and adaption of muon imaging within the Finnish mining context. Insights from the diffusion of innovation theory inform the strategy's likelihood of adoption, enhancing its potential for implementation.

The stepwise approach outlined in the strategy begins with understanding the current environmental landscape and identifying key sustainable practices, thereby providing a solid foundation for integrating muon imaging into mining operations. This is based on data and reports derived from governmental agencies such as Ministry of Economic Affairs and Employment of Finland (MEAE) and the Geological Survey of Finland (GTK). Stakeholder engagement is identified as a critical component, acknowledging the diverse interests and concerns of stakeholders ranging from local communities to governmental agencies and investors. Transparent communication regarding the environmental benefits and potential challenges of muon imaging technology builds trust and facilitates collaboration, essential for successful implementation. Pilot projects and awareness campaigns serve to showcase the benefits of muon imaging, addressing concerns regarding initial investment costs and technical complexity. By leveraging existing and known platforms such as Mining Finland, the strategy aims to raise awareness and promote the adoption of muon imaging technology within the Finnish mining sector. As the advantages of muon imaging become more evident, its adoption will naturally gain momentum as the economic savings and environmental sustainability benefits become increasingly apparent to the public. Moreover, the strategy emphasizes compliance with policies, regulatory frameworks, and industry standards, aligning with initiatives such as the TSM initiative. This alignment ensures that the use of muon imaging contributes to broader sustainability objectives while maintaining regulatory compliance. Evaluation and continuous improvement mechanisms enable the strategy to adapt to evolving circumstances and address emerging challenges. By engaging stakeholders and investing in workforce development, mining companies can optimize the utilization of muon imaging technology, driving sustainability innovation in the industry.

In conclusion, the strategy for integrating muon imaging into the Finnish mining sector demonstrates a structured approach that aligns with existing practices, regulatory requirements, and stakeholder expectations. While challenges may arise during implementation, the structured framework provided by the strategy enhances its reliability and implementability in the Finnish mining context. Moreover, on a larger scale, by participating in EU’s initiatives aimed at securing a sustainable supply of critical raw materials (CRM), Finland can leverage its expertise and resources to support collective efforts towards achieving EU's strategic objectives. A broader context emphasizes the strategic importance of the proposed strategy and further justifies its relevance and potential impact.

The mining sector, including Finland's sector, significantly impacts the UN's SDGs, contributing both positively and negatively to diverse sustainability dimensions. Strategically incorporating the SDGs into Finnish mining sector research on muon imaging is justified because it aligns with international sustainability initiatives, offering a holistic framework to assess the environmental, economic, and social advantages of muon imaging. This approach not only enhances the thesis's relevance within Finnish context but also extends its applicability and significance on a global scale.

## 9.3 Credibility and reliability of the strategy

Overall, the strategy outlined in this thesis introduces an approach to enhancing environmental sustainability, improving safety standards, and driving innovation in the Finnish mining industry. The strategy is considered credible and reliable due to its alignment with established practices, incorporation of sustainability principles, emphasis on informed decision-making, stakeholder engagement, a structured framework, and provisions for continuous improvement. However, the actual implementation and success of the strategy would depend on factors such as resource availability, stakeholder cooperation, and effective leadership.

The credibility and reliability of the strategy may also be assessed by the action research framework for 'process of change' (discussed in chapter 7.4) consists of four phases; (1) *determining the need for change*, (2) *defining the future state*, (3) *assessing future needs by evaluating the current situation to identify necessary tasks* and (4) *managing the transition* (Beckhard and Harris, 1987; Beckhard and Pritchard, 1992, as cited in Coghlan & Brannick, 2014). Step 1 in the strategy *understanding the current state regarding the environmental sustainability aspect* answers to the framework's phase 1, *determining the need for change*. Adopting muon imaging might not represent a drastic change for an organization already familiar with remote sensing or geophysical methods, but it signifies a step, a change, towards enhancing sustainability in mining operations. Phase 2, *defining the future state*, in the framework answers strategy steps 2, *stakeholder engagement* and 3, *defining the vision and goal*. By engaging key stakeholders, a strong relationship is built with them with the aim to achieve a mutual vision and goal regarding sustainable mining practices. Phase 3, *assessing future needs by evaluating the current situation to identify necessary tasks*, is linked to strategy steps 4, *pilot projects and awareness*, step 5, *compliance with policies, regulatory work, standards and initiatives*, and step 6, *evaluation*. Step 1, *understanding the current state regarding the environmental sustainability aspect*, is also linked to this phase. The identified necessary tasks proposed in phase 3 are directly linked to raising awareness of the potential of muon imaging and making sure they comply with e.g., policies. The whole phase is evaluated (strategy step 6), to make sure the strategy is iteratively updated. Phase 4, *managing the transition*, is linked to strategy step 7, *continuous improvement*. The link between managing the transition and continuous improvement can be understood through the process of integrating new practices or technologies into existing operations and the ongoing efforts to refine and enhance these changes over time.

Applying Rogers' (2003) diffusion of innovation theory to the strategic integration of muon imaging revealed that its adoption is influenced by factors such as relative advantage, compatibility, trialability, observability, and simplicity. These factors are mirrored in the strategic steps identified for integrating muon imaging into mining operations, ranging from understanding the current environmental context to engaging with stakeholders and continuous improvement efforts.

# 10 CONCLUSIONS

In the final chapter, this thesis summarizes its objectives and responses to the research questions posed. It also outlines the study's limitations and offers recommendations for future research derived from the thesis's findings.

## 10.1 Concluding remarks

In conclusion, the strategic incorporation of muon imaging to the Finnish mining sector is a measure towards advancing sustainable mining. This thesis has navigated through the development and implementation of a strategy aimed at enhancing sustainability practices through the integration of muon imaging, addressing two critical research questions in the process.

**RQ1:** *How can a strategy be developed where muon imaging is integrated into the mining sector to enhance sustainability practices?*

To develop a strategy that integrated muon imaging into the Finnish mining sector for enhanced sustainability, this thesis utilized action research methods, examining the benefits and challenges through data from literature, case studies, and government reports. This approach, grounded in strategic management and innovation diffusion principles, aimed to integrate muon imaging to Finland's mining environment, considering existing environmental management practices and regulatory standards. By conducting a SWOT analysis, supported by the AQCD framework and environmental scanning, the strategy was designed to be both effective and feasible. It emphasized stakeholder engagement, showcasing muon imaging benefits through pilot projects and awareness campaigns, and aligned with policies, regulatory frameworks, and industry standards with a focus on continuous improvement. Concentrating on improving environmental sustainability, safety protocols, and promoting muon imaging as an innovation, the strategy aims to maximize the efficiency of resource utilization, minimize environmental impacts, and encourage innovation across the industry, making a contribution to both the sustainability discourse and practical mining activities in Finland.

**RQ2:** *How can this strategy be implemented in the Finnish mining sector?*

Implementing this strategy within the Finnish mining sector necessitated a multi-faceted approach. Firstly, ensuring the strategy's compatibility with existing EMS and regulatory standards was essential. This alignment facilitates a more seamless integration of muon imaging into the Finnish mining sector's operational and environmental management frameworks. Secondly, stakeholder engagement and transparent communication play critical roles in fostering acceptance and support for the technology. This includes partnerships with educational institutions, which provide solutions in driving innovation and facilitating the technology's adoption through researched information. Lastly, pilot projects serve as a practical means to demonstrate muon imaging's benefits, enabling trialability and observability, and ultimately supporting the strategy's and therefore, muon imaging's broader implementation.

The strategic integration of muon imaging, as discussed in this thesis, represents a novel approach to addressing the evolving challenges and opportunities within the mining sector. This technology harnesses its sustainability-enhancing capabilities in response to a variety of factors, including geological diversity (across different ores and environments), environmental regulatory pressures, safety requirements, and the fluctuations in market and supply chains. These factors underscore the critical need for adopting cutting-edge technologies such as muon imaging in the mining sector. The strategy outlined in this thesis is grounded in theoretical frameworks, aligning with EMS and stakeholder expectations, and offers practical and societal relevance. It underscores the crucial role of continuous innovation and adaptability in advancing sustainability within the mining sector. By engaging in partnerships, particularly with educational institutions, this research facilitates sector-wide innovation and eases the integration and acceptance of groundbreaking technologies like muon imaging. This approach marks an advancement in sustainable mining practices in Finland and potentially beyond, filling an existing gap by providing a comprehensive model for the strategic adoption of an innovative technology in the mining sector.

## 10.2 Suggestions for further research

As the volume of data obtained through muon imaging increases, the opportunity arises to undertake detailed numerical analyses in comparison with traditional geophysical imaging methods when it comes to geological and/or geotechnical research. This enables comprehensive life-cycle analysis within a mining context, where the application of muon imaging may more directly be compared to conventional imaging techniques. Such an analysis could provide critical insights into the sustainability impacts of employing muon imaging over other methods in the mining sector. This comparative study would not only illuminate the environmental and economic benefits but also outline the practicalities and challenges of integrating muon imaging into existing mining operations. Furthermore, future research could focus on case studies where muon imaging has been implemented, analyzing the outcomes, challenges, and overall impact on sustainability. Additionally, examining the barriers to adoption, including technological, regulatory, and economic factors, could provide a roadmap for a more widespread implementation and integration.

## 10.3 Limitations

This thesis primarily focuses on environmental considerations and the integration of muon imaging technology into the Finnish mining sector, specifically excluding social, cultural, and certain technical details such as muon scanning exposure times and the exact costs of muon imaging methods. Although social and cultural dimensions are significant, they fall beyond the study's defined scope.

Furthermore, while the study acknowledges some initiatives at the national, EU, and global levels aimed at enhancing sustainability in the mining sector, the developed strategy is specifically designed for the Finnish mining sector. The potential to broaden the strategy to encompass the EU, particularly in alignment with the EU's Green Deal Strategy, was considered. However, variations in legislation and mining practices across regions limited this expansion. Projects focused on reducing the EU's dependency on mineral supplies and enhancing resilience are indeed crucial for Finland but were not included in this thesis or its strategy due to their broader focus.

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