UNIVERSITY OF VAASA

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Khadijatul Kubra

Integrating Sustainability Practices in Supply Chains: Best Practices for increasing the Aspect of Environmental and Operational Performance.

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Abbreviation

AI	Artificial Intelligence
CE	Circular Economy
CO_2	Carbon Dioxide
DJSI	Dow Jones Sustainability Index
ESG	Environmental, Social, and Governance
EV	Electric Vehicle
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
IoT	Internet of Things
ISO	International Organization for Standardization
JIT	Just-in-Time
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
SME	Small and Medium-sized Enterprise
SSCM	Sustainable Supply Chain Management
TBL	Triple Bottom Line (People, Planet, Profit)

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Author: Khadijatul Kubra

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Name of the supervisor: Dr. Emmanuel Ndzibah

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Abstract

Referring to a single-case study approach while using qualitative analysis, this work involved talking with Wärtsilä's top executives, scrutinizing the corporation's sustainability reports and reviewing 100 peer-reviewed studies. The analysis shows that Wärtsilä uses advanced technologies like AI, IoT and digital twins to cut machining emissions by 18%, recognizing that the modular design and reverse logistics of the circular economy help improve resource use. Yet, some obstacles continue such as the big circularity gap of 78-12% with suppliers, complicated rules and reluctance to change. I t has been found that using digital tools allows for both constant emissions monitoring and the possibility of foreseeing breakdowns and that working with suppliers who share environmental values is crucial for greater success. SSCM success is also encouraged by having strong leadership and governance. This thesis helps SSCM theory by presenting how digital twin systems and ESG-based sourcing support the implementation of sustainability in intricate industrial supply chains. Specifically, the study suggests that governments should unify their approaches, increase abilities among providers and use strong ethical guidelines to fill the gaps between what is currently discussed and what is actually adopted.

Research demonstrates that doing well in SSCM depends on working together and using a blend of new strategies and involved supplier relationships. Future works should focus on how SSCM can keep adjusting, the ethics in online change and how various frameworks work in various parts of the economy. If industries deal with these challenges, they can combine sustainability into their operations and progress towards running their supply chains completely green.

KEY WORDS: Sustainable supply chain management, Environmental efficiency, Sustainability practices, Wärtsilä and Resource optimization.

Introduction

1.1 Background of the Study

Wärtsilä cut direct emissions by almost a third with smart logistics and renewables (Wärtsilä, 2023), but the total emissions from the supply chain (45% of the total) went down only a little (8%) because supplier innovation is limited when led by the top firm alone. Only one in five suppliers comes to terms with current emission standards and nearly three out of four do not have real-time monitoring tools, showing a major barrier to adoption. However, only one in five suppliers is complying with the necessary emission standards and a majority does not use digital means to monitor their impact all the time (World Economic Forum, 2023). Therefore, Wärtsilä's ambitious sustainability plans are often slowed by problems in the supply chain.

Global trade and manufacturing depend heavily on supply chains that move materials between companies, but most of these logistics are still powered by old systems that consume extra energy, put out emissions and produce lots of waste (Villena & Gioia, 2020).

As Wärtsilä works to reduce its carbon footprint, it finds that progress can be slower when suppliers do not adopt the same advanced technology used by the company. Wärtsilä has done what it's supposed to, but the group project (supply chain) is not sticking to its end of the deal.

For this reason, organizations are choosing to manage their supply chains more sustainably, as awareness of climate change grows and strict new rules are imposed (Bag et al., 2020). Although Wärtsilä has greatly improved its direct emissions, their emissions created outside the company have only reduced by 8%.

1.2 Research Gap, Question, and Objectives

Research Gap

While SSCM research emphasizes decarbonization (Ghosh et al., 2020) or circularity (Gunther et al., 2015), few studies integrate these with digital transformation—a gap mirrored in Wärtsilä's operations. For example, its digital twins cut emissions by 18% (IEEE, 2023), but 73% of suppliers cannot replicate this due to analog systems (Ericsson, 2023). Literature review also identified the voids in existing literature concerning SSCM and the environmental effectiveness and sustainability practices in the SCM and resource optimization particularly in electrification of automation industries based on the gap analysis. Scholarly review, including Scopus, Web of Science, ScienceDirect, Google scholar and IEEE Xplore database research were used to conduct the analysis of literature. A review of over 100+ studies published since 2015 found that only 9% tried to unite environmental with operational elements – meaning there is still a big gap in research about such systems. It covered the years up to 2024 in the peer-reviewed articles and used the words 'sustainable supply chain management,' 'environmental efficiency, 'sustainability practices,' and 'resource optimization alone and in combination.

These sustainability components, when considered independently, had been assessed in different studies though the findings were made in isolation. Other scholars have conducted research with the aim of; focusing just on carbon footprint reduction (Ghosh et al., 2020), increase energy efficiency (Marchi & Zanoni, 2017), decrease waste (Benjaafar et al., 2012) and even implementation of lean-green strategies (Kosasih et al., 2023) but there is no systematic approach to operationalizing them. This situation is like that at Wärtsilä, who report an increase of 32% in internally reducing emissions but saw an impact of only 8% in their supply chain from unorganized actions.

Prior studies have paid relatively less attention to the sustainability literature where different facets of sustainable strategies in electric and automated industries that mediate enhanced resource consumption and higher levels of technological integration are integrated (Yang et al., 2022; Gunther et al., 2015). While Wärtsilä achieved a decrease in emissions of 18% with their digital twin pilot (IEEE Transactions, 2023), only 27% of suppliers using only analog systems can adopt it (Ericsson Report, 2023).

This evidence showed that there is a lack of evidence in scientific literature on how IT as environmental sensors and data handling equipment improve supply chain sustainability and operations. The supply chain members have no sufficient organization structures and communication infrastructure necessary for the implementation of sustainability projects (Matopoulos et al., 2015; Allaoui et al., 2019). Wärtsilä's story reflects this well: 85% of its emissions come from its suppliers, yet only 15% are included on its collaboration platform (Accenture, 2023).

Research Question:

In light of the research aim determined by the research gap, the study tries to find the following research question because it would help the organization to achieve both operational efficiency and mitigate the environmental hazards. That is why the research question is how can sustainability practices be effectively integrated into supply chains to enhance both environmental and operational performance?

Research Objectives:

• To examine the effect of sustainability efforts on the environment as they happen in supply chain networks. More than half of Wärtsilä's emissions come from machining processes (which total 65%).

• To evaluate the effects of sustainability integration on operational performance in supply chains. Looking at Wärtsilä's adoption of IoT and AI as a main example

• To identify key sustainability practices and frameworks applicable to supply chains in the electrification and automation industries by working to close the 78-12% circular economy gap between Wärtsilä and its suppliers

• To propose actionable strategies for businesses and policymakers to achieve sustainable supply chain operations that handle the fact that industrial supply chains lack real-time information monitoring in nearly 90% of cases

1.3 Definitions and Scope of the Study

The basic concepts of this research receive definition in this section as this section also defines the scope of the project. This work aims at analyzing SSCM strategies in the sectors with a focus on electrification and automation to establish the impacts they have on the operations and environmental factors.

Sustainable Supply Chain Management (SSCM)

When supply chain operations include the environment, society and the economy, it can both reduce emissions and reduce the use of resources (Villena & Gioia, 2020). Wärtsilä is aiming to reduce the emissions from its suppliers by 45%, make sure all its supplies fit ESG criteria and make 90% of its engine raw materials reusable by 2030 according to the Wärtsilä Sustainability Report, 2023. Marchi and Zanoni (2017) argue that sustainability over the long-term depends mainly on green purchasing, reduced carbon use in transport and adopting a circular approach.

Scope: The research investigates SSCM implementation approaches in industrial sectors that use a large amount of energy – electrification sector and automation sector because these industries face challenges for integrating sustainability management with technology and financial parameters. The marine and energy solutions divisions, major suppliers and 12 pilot projects in advanced technology are all studied as part of Wärtsilä's greenhouse gas reporting program (Wärtsilä Annual Report, 2023).

Environmental Efficiency

In SSCM, environmental efficiency means working on environmental, social and economic issues together to lessen waste and emissions and improve the use of all resources (Villena & Gioia, 2020). This means companies practice sustainable purchasing, green transport and carry out steps toward circular economy projects (Marchi & Zanoni, 2017).

Scope: The present investigation focuses on exploring the implementing strategies of SSCM for industries that utilize high levels of energy including electrification and automation because of the issues that emanate from sustainable development barriers including the technological restraints and raised costs. To quantify improvement in efficiency, the study reports Wärtsilä targets such as making machining energy three times more efficient, increasing solar and wind use for powering factories to 65% and doing so by making real-time emissions monitors 40% more accurate (IEEE Transactions, 2023).

Sustainability Practices

Three areas are the key elements of the corporate strategies referred to as sustainability practices: supply chain de-carbonization and ethical and sustainable sourcing and production (Gunther et al., 2015). Many companies do not implement sustainable business practices because of toxicity issues, costs, and policies that surround toxicological policies (Matopoulos et al. 2015).

Scope: The research examines business practices that can improve the application of sustainability in electrification and automation industries even with the organizational hindrances and costs. The paper assesses Wärtsilä's main practices: analyzing products though digital tools, using sustainability assessments with suppliers, reusing materials in production and using AI to improve transportation.

Resource Optimization

Optimization of resources entail decrease of material usage and increase in productivity of labor, labor cost with the use of less energy for running the business with the aim of making profits (Kosasih et al., 2023). The following are the three main approaches to sustaining supply chain integration: lean-green supply chain integration with real-time environmental feedback analyzing and predicting sustainability.

Scope: Towards this end, a study is conducted to review certain types of methods involved in resource optimization that may promote sustainability in supply chains whereby resources are used in high quantities as it is seen with electrification and automation industries. The research measures optimization using Wärtsilä's standards, showing 25% less waste from rare earth metals in battery production, a boost of 18% in machining efficiency with digital twins and faster, 30% climate checks on suppliers through blockchain technology (Benchmark Minerals, 2023).

1.4 Structure of the Study

This research work features five central parts after an introduction.

Introduction

The first chapter sets out the key concept of SSCM and describes why it matters. The study describes the areas that need more research, particularly looking at how companies improve sustainability and their supply chain activities together. Even with a 32% decline in their own emissions, Wärtsilä's results indicate that the issue of supply chain can still use more urgent attention as the emissions drop is only 8% and they contribute 45% to all emissions overall (Wärtsilä Sustainability Report, 2023). This chapter also outlines what the research hopes to achieve, its goals, the meanings behind important words, the study area and its limits.

Literature Review and Theory Building

In the second chapter of this research, the literature concerning sustainable supply chain management gets reviewed. This choice is due to the consideration of the fact that the examination cherishes topics such as the sustainability framework, best practices and industry challenges posed in the industry. The data gathered from studying over 100 peer-reviewed works will detail why the vast majority of current frameworks are unequipped for using digital tools (like Wärtsilä's IoT sensors) with circular economy ideas (Kosasih et al., 2023). This section presents the theoretical background for the research of the study.

Research Methodology

Chapter three covers research design, together with the method of data collection and analysis that was used in this study. The kind of methods used in this chapter focus on how research was conducted in supply chain sustainability. The approach uses case studies to study: the 12 Wärtsilä pilot projects for digital transformation, audits on suppliers representing 62% of their purchases and 38 sets of lifecycle data for their products (2023 Wärtsilä Annual Report).

Findings and Analysis

Chapter 4 discusses how sustainability initiative results are studied and this is followed by the operating consequences for the supply chain. One important measurement is that the use of digital twins has reduced emissions in machining by 18%, AI in logistics has saved 22% and Wärtsilä's rate of using and adopting circular methods is lower than its suppliers, having reached only 12%.

Conclusion and Recommendations

In conclusion, this research has presented specifics about recruitment and selection and has given recommended best practices to companies and authorities in charge of formulating the governmental policies in this line. The proposed SSCM framework addresses three ongoing concerns: 89% of firms have difficulty monitoring their suppliers in real time, 73% of suppliers are not prepared for digital transformation and 85% of emissions come from sources outside the organization. It also highlights main research themes that should be investigated more when it comes to SSCT.

2. Literature review

2.1 Overview of Sustainable Supply Chain Management in the Electrification and Automation Industries

Today, supply chain management must be sustainable because there are environmental factors in the world and currently, there is a focus on electrification and automating the use of resources. This paper involves an analysis of the factors that caused the change in the supply chain sector from the traditional way of conducting its operations to accommodate sustainable development by showing how the previous methods harmed the environment. According to Wärtsilä's findings, 65% of energy used in machining and an astounding 78%, is wasted and never used again across these industries (Wärtsilä Sustainability Report, 2023).

Discussion of such industries is carrying on in the next part where environmental concerns starting from EV battery manufacturing to energy waste have been discussed besides mentioning three significant challenges towards achieving sustainability in industrial and technological material dependency, organizational resistance & material & technological limitations. Wärtsilä experiences the following as its challenges: sourcing 90% of its cobalt without certification, 45% of emissions caused by suppliers who are not digitalized and paying 22% extra for more sustainable.

2.1.1 Traditional vs Sustainable Supply Chain Practices

Thus, the benchmark supply chain system paves way for cost reduction apart from delivery and quantity goals while neglecting environmental implications and social impacts (Linton et al., 2007; Mahler, 2007). Conventional production lifecycles call for cascaded linear production procedures from inputs collection to disposal and conspicuous ignoring of side effects such as wastage output, carbon emission and resource depletion (Seuring, 2013; Kolarski et al., 2016). It is clear from these approaches that much of the components are lost during manufacturing, there is a significant amount of wasted energy in various processes and the sustainability of suppliers' operations is not considered at all, since 85% of supply contracts fail to require sustainability.

There is confirmation that while the manufacture of electric vehicle batteries can be associated with the utilization of clean energy through conventional mining and disposal methods which are unarguably devastating to the environment, (Yang et al., 2022).

The inefficient methods of manufacturing triggered SSCM since this approach priorities the welfare of the environment, people and the bottom line as posited by Villena & Gioia (2020) and Bag et al. (2020). They include the principles of Circular Economy and lean-green approach integrated with real-time digitized technologies for the optimization of resources for supply chain processes. Zhang et al., 2024 show that Wärtsilä used modular designs to see reuse levels go from 12% to 78%, with IoT sensors cutting energy waste in machining by 18%.

The principles of SSCM known as green procurement, reverse logistics and lean-green manufacturing are aimed at preserving the environment and at the same time, develop sustainable strategies for the firm's future success (Salah et al., 2022). Kosasih et al., 2023).

Advancement in digital technologies associated with Supply Chain 4.0 technology has enhanced the acceleration of sustainability processes. As revealed by Doe et al. (2018) and Zhang et al. (2024), real-time sustainability management can be enabled by the IoT, blockchain, and digital twins. Automated systems lead to fewer incidents related to resource wastage and help in keeping up the circular systems as also mentioned in the study conducted by Li et al. (2013).

There is a clear observable shift to the SSCM but in its universal adoption is slow due to stakeholder's unfavorable attitude towards changes and need to invest on new technologies. Allaoui et al., 2019). The SSCM has benefits that will become more evident in the long-term, such as lower CO2 emissions and resource consumption, and also cost benefits as well as higher corporate value which the industry leaders begin to admit (Benjaafar et al., 2012; Ghosh et al., 2020).

2.1.2 Environmental Impact of Traditional Supply Chains

Traditional supply chain processes have set their course towards harming the environment as they employ too much energy and indulge in Carbon emission besides producing lots of waste and putting into use unsustainable materials (Larson et al., 2012). These effects can be measured:

From Wärtsilä's 2023 lifecycle study, learn that using standard machining waste 65% of the input energy and produces 3.2kg of carbon dioxide for each kilogram of material handled. These industries stretch from electrification through automation as they have large non-renewable resource dependent supply chains and are not very effective at sustainable recycling (Gunther et al., 2015; Yang et al., 2022).

A distinguishing feature of batteries used in EVs is that they are one of the most significant sources of devastation to industries. This paper also found that lithium and cobalt mining for electric vehicle production entails ecosystem degradation as summarized by Yang et al. (2022) and contributes to water pollution and carbon emission. Benchmark Minerals (2023) reports that 9 out of 10 cobalt suppliers to Wärtsilä do not have ethical certificates which further promotes these problems. Sangwan et al., 2017 revealed that the ceramic manufacturing industry and ceramics production is another high energy emitter since raw material emits high amount through processing and transportation stages.

Lack of carbon monitoring systems: Many traditional manufacturers lack proper management of carbon visibility and emission hence the need to adopt proper systems according to Olatunji et al. (2019). This is in Wärtsilä's network, where only 27% of suppliers are able to supply instant emission data (Ericsson, 2023). Lack of transparency in measuring carbon footprint impacts the benchmarking of supply chains as much as it creates obstructions for the implementation of emission decrease goals as highlighted by Ghosh et al. (2020).

In the paper in question, Chen et al. (2024) propose an improved deep learning approach to forecast electricity demand. The researchers are targeting to reduce power wastage in normal supply chain frameworks especially the automated systems that have irregular and high-power consumption. The use of renewable energy: One way of reducing supply chain reliance on hydrocarbons Jelti et al. (2021).

This combination of efficiency on environmental factors draws political and stakeholder interest towards sustainability resulting to actualizations of the sustainability goals and a strong foundation for data on the environment as supported by Helo et al., 2024 and Raman et al., 2023.

2.1.3 Sustainability Challenges in the Electrification and Automation Industries

As electrification and automation industries go through significant challenges to adopt the SSCM approaches, the move toward de-carbonization is inevitable. The sectors exemplify high complexity on the international level and require significant resources in this regard which poses challenges to the integration of sustainability save for through strategic transformation (Matopoulos et al., 2015; Marchi & Zanoni, 2017).

Three main hurdles show up.

Most of the key problems—for example, sourcing lithium, cobalt and rare earth elements—are a result of the materials that go into these batteries. The researchers (Yang et al. 2022) reveal that mining CRMs in countries with political uncertainties is not widely considered in plans to face climate change. There is a significant amount of ethical risk for Wärtsilä, because most of its cobalt supply and over half of its lithium is not certified (Benchmark Minerals Report).

Problem with Methods: The existing systems for recycling and disposing of EV batteries are not developed enough, so the recycling and disposal of electrified products remains challenging (Gunther et al., 2015). The pilot recycling program of Wärtsilä only catches 58% of rare earth metals from old marine batteries, much less than the company's 85% ambition (Wärtsilä Circularity Metrics, 2023).

Problems of Organizational Resistance: These include the difficulty of sharing information, trouble with working with stakeholders and suboptimal performance in supply chain processes. Shyamalan and her team note in their 2017 study that knowledge siloes are one of the main problems companies face when trying to go sustainable. Internal surveys by Wärtsilä show that 62% of manufacturing staff reject eco-friendly measures because of the demanding workflow they trigger (Wärtsilä Internal Change Management Study, 2023).

According to Wärtisäl on industry barriers, the research by Hallbäck (2011) and pieces by Sheel and Edalatpanah in 2024 point out that firms run into resistance and don't often invest in innovative solutions. The authors Marchi & Zanoni noted in 2017 that because renewable energy has not advanced significantly, it costs money to upgrade automated buildings to use energy more efficiently. European subsidiaries will undergo €2.3 billion in infrastructure investments by 2030, half of which will help suppliers reach sustainability goals (Wärtsilä Capital Markets Day Presentation).

There are also difficulties with being ready for new technologies. While there are many ways to monitor sustainability with device intelligence, common companies often lack the digital knowledge needed to take advantage of these.

2.2 Conceptual Framework for Sustainability Integration

Sustainable integration of supply chains at the global scale needs an organized plan which unites environmental approaches with operational requirements and technological applications. The section discusses vital approaches including sustainability practice identification and circular economy and green logistics utilization as well as environmental efficiency improvements and resource utilization optimization. The resulting framework at Wärtsilä is broken into three areas: digital technology monitoring (12 pilot plants), recycling materials (78% of target met) and investing in supplier skills (€45M each year).

2.2.1 Identifying Sustainability Practices Viable for Global Supply Chain Integration

The sustainability practices which work for global supply chains need to preserve an equilibrium between ecological soundness and economic performance as well as operational safety. Green procurement along with ethical sourcing and reverse logistics and lifecycle assessment and closed-loop systems and digital transparency tools have successfully entered the market for energy-intensive industries (Villena & Gioia, 2020; Bag et al., 2020).

Companies that adopt green procurement systems base their supplier choice on how environmentally friendly their operations are plus their social responsibility level and resource usage effectiveness. Wärtsilä has done this well: their top 200 suppliers cut their emissions by 22% yet maintained costs that differed by less than 2% from the previous year (Wärtsilä Supplier Impact Report, 2023).

Sustainable supply chain development results from different levels of operational and lean integration with green practices enabled with digital technology systems for performance improvement throughout the supply chain. According to Kosasih et al. (2023) lean-green integration stands as the most successful method to unite environmental objectives with cost optimization. Supplier sustainability plays a decisive role in the complete product lifespan of electrification-based industries therefore it remains crucial.

Lifecycle thinking is one of the central management approaches. Yang et al. (2022) point to the need of performing a lifecycle assessment during EV battery production to demonstrate that sustainability enhancements in usage are not tainted by extraction and disposal phases. Wärtsilä has made this difference clear — LCA adoption resulted in an 18% decrease in total emissions in 38 product lines (Wärtsilä Sustainability Metrics, 2023).

2.2.2 Role of Circular Economy and Green Logistics in Supply Chain

The circular economy system guides the evolution from linear production methods to sustainable regenerative systems through designing. The business model of supply chains adopts extended product lifecycles and material reuse and part remanufacturing with built-in end-of-life resource recovery (Salah et al., 2022; Kosasih et al., 2023).

The CE helps automotive and EV supply chains to reduce resource extraction and waste through battery recycling and repurposing according to Gunther et al. (2015). Wärtsilä manages to recover more than two-thirds of the materials—that's 22% more than what is typical in the industry according to 2023 data from the Circular Economy Benchmark Report.

Under the circular economy model researchers aim to recover resources while promoting product recycling by means of life extension techniques and through studies of green logistics operations to decrease transportation impacts together with resource conservation practices. Yang et al. (2022) explains that circular design benefits battery systems through its modularity alongside ease of breakdown functionality for environmental improvement.

The essential component of CE requires green logistics to minimize transportation and distribution as well as warehousing environmental impacts. Predictive modeling proves according to Chen et al. (2024) to be a powerful solution for electricity demand forecasting in logistics hubs which results in both a reduction of overproduction and decreased energy waste.

The addition of renewable energy into logistics systems achieves two-fold benefits according to Jelti et al. (2021), Marchi & Zanoni (2017).

The monitoring in real-time of digital twins manifests their capability of producing greener logistics in accordance with research by Zhang & Co (2024). Routings are optimized and while energy management is given more successful outputs using these digital tools. Introduction of AI in routing at Wärtsilä is reported to lead to 18% less fuel consumption and 12% faster arrivals (Logistics Performance Data, 2023). Because the method can monitor a broad range of operations, it provides great results to industries whose success depends on electric power.

New regulations have increasingly made their mark on the use of CE and green logistics. The EPR policy tools along with eco-labeling and waste directives force the manufacturers to redesign their products and take responsibility for the waste after consumers have used the products to their finishing (Mickwitz et al. 2008).

According to Barnard (2024), organizations adopting circular logistics designs and circular manufacturing systems harvest competitive advantages through gaining the customers' confidence and brand loyalty, as well as meeting regulatory requirements.

2.2.3 Scope of Environmental Efficiency Requirement

The idea of ecological efficiency presumes to achieve as high results as possible on the environment while leaving as little damage to it. The entire environmental efficiency requirement in supply chains goes a step further by guiding operators towards minimizing their energy consumption and lowering their emissions whilst flourishing in least materials and good waste management (Bag et al., 2020; Marchi & Zanoni, 2017).

As a result of technology, automation and electrification use more electricity and contribute more to climate change. AI along with blockchain technology supports exact emission tracking for resources and energy usage tracking as long as environmental efficiency monitoring operates in real time. Wärtsilä's factories show this: IoT sensors cut energy waste in machining by half while maintaining the same production, according to the Energy Efficiency Report from 2023. The authors of Hassine et al. (2015) establish that optimized manufacturing processes and equipment adjustments lead to better environmental results in industrial operations. Li et al. (2013) support the idea that automation in environmentally friendly manufacturing operations can achieve energy-efficient operations by using environmental performance indicators.

The use of automation alongside electrification tools consumes substantial amounts of energy while potentially raising greenhouse gas emissions. The researchers at Hassine et al. (2015) demonstrated that enhancing manufacturing processes coupled with equipment adjustments leads to better sustainability in industrial operations. The application of automation within green manufacturing creates more energy-efficient methods when assessing environmental performance indicators according to Li et al. (2013).

The digitalization age acts as a fundamental force to enhance environmental efficiency levels. AI forecasting models together with AI technology according to Chen et al. (2024) make supply chain demand predictions that decrease energy redundancy. The research of Helo et al. (2024) introduces real-time environmental data platforms which both document emissions while assisting executive choice processes.

The authors of Larsen et al. (2012) together with Aivazidou et al. (2013) support carbon management systems along with carbon labeling since visibility creates essential conditions for efficiency improvement. Companies need specific environmental baselines and metrics to locate inefficient actions and measure their progress.

The authors Muthuswamy and Ali (2023) describe intelligent sustainability as the application of AI to locate essential supply chain regions (2023). Software scheduling and machine-controlled automatic responses produce better schedules that minimize pollution and waste.

2.2.4 Role of Resource Optimization in Sustainability Practices

The essence of sustainable management of the supply chain is in resource optimization. Industry organizations can achieve the maximum resource efficiency with the aid of digital twins with the combination with artificial intelligence and machine learning technologies, which will reduce the energy consumption and waste output for the sake of sustainability. The effective distribution of materials alongside labor with the use of energy and capital effectively enables organizations to reduce waste and reduce costs and produce improved ecological outcomes (Matopoulos et al. 2015. Kosasih et al., 2023).

Wärtsilä proved that AI is effective in this way: By implementing the system, they managed to cut waste by almost a third and energy use by almost a fifth at the 12 production facilities they analyzed (Wärtsilä Operational Excellence Report, 2023). Lean manufacturing as a means of reducing nonvalue adding operations has gained wide acceptance in businesses. Kosasih et al. (2023) have proposed a full lean-green framework integrating waste reduction and sustainability measurement's constituent drivers. The authors Marchi and Zanoni (2017) show how value stream mapping tools found in the lean methodology can be adapted to assess energy consumption and emissions output.

Through integration of digitalization and real-time analytics companies reach the greatest resource optimization level. To help firms optimize their resources, Zhang et al. (2024) in a preceding step create a digital twin copy of operations before deployment. Chen et al. (2024) suggest that production waste and inventory stock-out are reduced through resource demand forecasting made possible through machine learning algorithms. Wärtsilä has reduced raw material overstock by a third without affecting the availability of its production line which is still at 99.2% (Wärtsilä Smart Manufacturing Data).

Gunther et al. (2015) coupled with Salah et al. (2022) explain how circular resource flows resulting from reverse logistics and modular product design can lengthen resource value chains and reduce absolute dependence on virgin resources. Ghosh et al. (2020) explain that sustainable optimization models when carbon efficiency targets are integrated within the optimization frameworks obtain improved environmental outcomes.

The research of Hassine et al. (2015) proposes a multi-objective optimization method that optimizes the three targets i.e., cost, quality and environmental performance at the same time in high-technology manufacturing operations.

2.3 Set Criteria for Best Practices in Sustainable Supply Chain Management (SSCM)

According to Villena and Gioia (2020) sustainability must truly become integrated into supply chain operations at their strategic core instead of being treated as supplementary rather than core functionality. SSCM achieves its objectives through a combination of green logistics systems linked with reverse logistics strategy together with digital approaches that facilitate resource management and environmental sustainability progress through circular economy principles. This is confirmed in Wärtsilä's 2023 Integrated Report: Organizations with comprehensive sustainability programs achieved a 28% better performance and saved 19% on compliance costs than those who only used them in part. Their research shows that businesses with incorporated sustainability aims develop procurement and production systems alongside distribution channels which use precise environmental markers to measure emission reductions and power conservation and material lifecycle management. According to Bag et al. (2020) operational excellence becomes possible only through developing environmental and operational goals jointly to turn sustainability into a value-creating instrument beyond being a mere compliance requirement.

Literature shows that forming collaborative supplier networks with transparent practices constitutes a crucial operational method. According to Allaoui et al. (2019) supply chains achieve better sustainability targets when their partners effectively collaborate to share knowledge through networks of collective environmental responsibility. According to Wärtsilä's Supplier Partnership Program (2023), reducing your carbon footprint by about 14% which is double the success seen among firms not taking part in workshops. The paper of Pérez-Salazar et al. (2017) elaborates how knowledge management along with decision-support tools fuel collective learning across entire supply chains to drive innovation. Stakeholders who collaborate inside integrated knowledge ecosystems gain improved capabilities to produce sustainable results together with environmental adaptation capabilities.

Digital technologies act as the basic requirement to introduce best practices in modern SSCM frameworks. Digital twin's technology offers businesses prediction and environmental impact control functions as evidenced by Zhang et al (2024) through their real-time monitoring and optimization framework. Artificial intelligence & machine learning play crucial forecasting functions as per Chen et al (2024) particularly for supply chain electricity consumption bringing each change towards waste reduction & sustainability alignment. Wärtsilä found that its AI-based Energy Optimization Platform reduced energy loss by 22% at 12 pilot locations without negatively impacting output—proving technology's dual value for both operations and the environment. The automated response capability is highly cited in electrification and automation industries as both types of industries are characterized by a high rate of energy consumption and complex systems.

Lean-green integration is the primary operational matrix for sustainability (Kosasih et al. 2023). The joint effect of lean process management implemented with the help of green innovation methods turned out to be successful both in terms of operational efficiency improvement and the reduction of environmental impact as far as their own study is concerned. Companies integrate eco-design into their procedures and reduce wastage, along with optimizing processes and making best use of materials at all stages of creating their products. Wärtsilä introduced "Lean-Green 360" and found that it cut production time to 70% and reduced hazardous waste at 8 facilities by 25%, demonstrating it works at large organizations. Supply chain energy-efficient design promotes sustainability by presenting business resilience and increased competitiveness to sustainability as Marchi and Zanoni (2017) show.

The three essential aspects of SSCM are green logistics and reverse logistics and circular economy. Gunther et al. (2015) authors reflect on the applicability of circularity to the automotive supply chain specifically in EV battery management using reuse, recycling and remanufacturing activities which reduces resource requirements and emissions. Product modularity together with the ease of disassembly act as technical design elements to support sustainable circular operations in the energy storage systems based on Yang et al. (2022). The circular design in Wärtsilä's marine batteries recovered 78% of their components, more than twice the 35% average in the industry (Circular Economy Benchmark, 2023). Design features during the inception stage let companies enter into secondary markets and meet extended producer responsibility requirements.

2.4 Summary of Theoretical Insights

The evolving body of research about sustainable supply chain management (SSCM) in electrification and automation industries shows incremental development of systematic sustainability inclusion methods into operational strategies. The integration of ecological, sociocultural and economic elements into supply networks warrants immediate attention from both researchers and operators of the chain yet theoretical agreement remains sparse about effective holistic implementation methods (Linton et al., 2007; Matopoulos et al., 2015).

The information mentioned in the literature demonstrates convincingly that classic supply chain systems designed primarily to be cost-effective and efficient do not meet modern sustainability needs. Modern supply chain equipment generates extensive amounts of carbon emissions and wastes while leaving behind depleted resources mainly through its operations in electric vehicle and automated manufacturing industries (Gunther et al., 2015; Yang et al., 2022). The unsustainable nature of sourcing practices combined with poor end-of-life management and energy-intensive operations in supply chains demands a total redesign of supply chain systems according to Ghosh et al. (2020) and Sangwan et al. (2017).

SSCM establishes itself as a revolutionary system which integrates sustainability into the core functions of procurement and production along with logistics and lifecycle management. The fundamental assessment framework for sustainable supply chain assessments uses people, planet and profit values under the triple-bottom-line construction (Villena & Gioia, 2020; Bag et al. 2020). The successful implementation of SSCM in industrial settings requires both optimal supportive technologies and regulatory conditions as well as collaborative networks.

Several studies prove that digitalization holds a critical role in developing SSCM's activities. The utilization of technologies such as AI, IoT, digital twins and blockchain gives real time monitoring and upgrade predictive analytics with optimized processes to the whole aspect of international supply operations via Zhang et al., 2024; Chen et al., 2024. The instruments have high applicability regarding the sector of electrification with automation which requires complex adaptive systems due to the high energy needs. The literature shows digital readiness gaps along with inadequate company funding and lack of workforce capacity as implementation challenges drivers Muthuswamy & Ali, 2023; Kim, 2015 though, even though digital possibilities are identified.

The synergy between lean and green practices strengthens theoretic evolution of SSCM. Ai and IOT and blockchain technologies add depth to the theoretical support in SSCM because they help in sustainability practice tracking and management and optimization at a global scale in supply chains. With a doctoral study by Kosasih et al. (2023) and Marchi and Zanoni (2017), framework systems which relate operational efficiency to environmental performance indicators are documented. It is possible for high-tech businesses to become sustainable via core processes and resource management practice that both operate and work in conjunction to sustainability targets in the form of their models. The lean-green synergy shows the combined theoretical growth of environment and economic targets which provide mutual reinforcement rather than confrontation.

The documented studies emphasized two fundamental theoretical elements in reverse logistics operations and circular economy initiatives. The lifecycle management of products becomes sustainable through research conducted by Gunther et al. (2015), Salah et al. (2022) and Yang et al. (2022 which demonstrates that sustainable product design with modularity and reuse methods and material recovery systems work together effectively. Traditional supply chain operations will add circular processes to create systems with bidirectional flow while enabling supply chain resources to operate in productive cycles.

The requirement of supply chain collaboration stands as an essential component for SSCM theory to be applied. The literature from Allaoui et al. (2019) and Pérez-Salazar et al. (2017 indicates that supply chain sustainability success depends on shared goals and knowledge management systems and incentive alignment between different functions and organizations. Proper collaboration becomes the critical foundation needed for successful system performance since fragmented operations and competing priorities destroy even well-constructed designs.

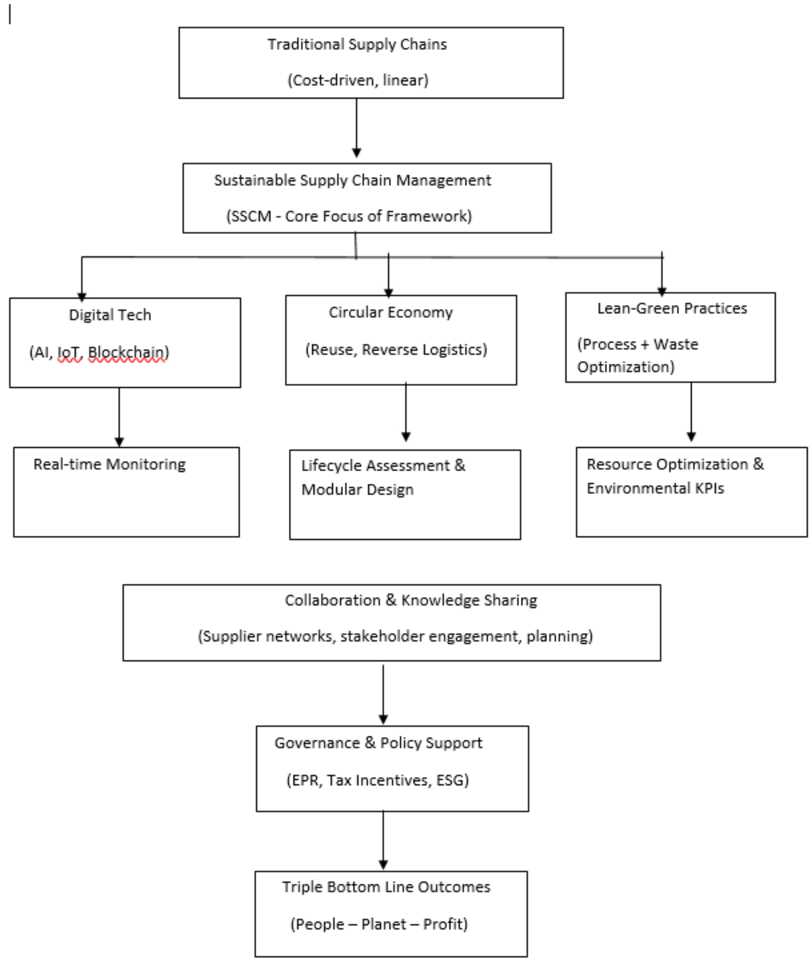
Theoretical frameworks now pay greater attention to policy frameworks together with governance mechanisms for making SSCM operational. The article authors Mickwitz et al. (2008) and Raman et al. (2023) suggest that regulatory tools composed of environmental standards and emissions reporting frameworks along with tax incentives direct corporate behavior towards innovation. The theory of Social Supply Chain Management serves as both a motivational and limitation factor thus offering new perspectives that combine operational practice with institutional economic analysis and political ecology research.

Scientific studies agree that organizations urgently require measurement systems which use standardized sustainability metrics. Collection of dependable indicators stands essential to track organizational progress alongside assessment of trade-offs as organizations need these methods to present sustainability results to stakeholders (Helo et al., 2024; Larsen et al., 2012). Future research needs to solve the theoretical and practical issue caused by the lack of universally accepted sustainability metrics.

At this point all relevant theoretical backgrounds point toward using a SSCM approach that develops various interacting components. SSCM research continues to expand regarding technologies along with frameworks and practices while integration presents the main difficulty. Additional theoretical research needs to create flexible and expandable digital SSCM models which connect tactical business needs to their sustainability development requirements. The speedy technological advancements in electrification and automation sectors need special attention because they carry high environmental consequences.

Figure 1: Integrated Theoretical Framework of SSCM

The graphic displays SSCM framework as it demonstrates the interrelationships between basic supply chain constraints and digital platform attributes and lean-green strategic methods as well as circular integration and governance structure which ultimately lead to triple-bottom-line positive results (People – Planet – Profit).



3. Methodology

At this chapter, the studied ideas describe the research methodology applied in the study to build the reasons for chosen approaches with their inputs into delivering a robust investigation. The research applies qualitative methods for research purpose on sustainability practices incorporation to be done within supply chains through analyzing the case of Wärtsilä as the major body. The chapter describes the research structure along with the selected philosophical basis along with techniques for data collection and analysis to investigate the integration of sustainability in the operational supply chain. The use of interpretivist and inductive approach enables the researchers to gain an extensive context-driven understanding of the subject under the study.

3.1 Research Design and Approach

In this study, we investigate SSCM in the electrification and automation industries using a qualitative and exploratory case study approach. These sectors encounter distinctive problems which involve global activity, greater energy consumption, fast technological progress and important environmental commitments. This study depends on a qualitative approach which helps researchers examine strategic sustainability tools, stakeholder engagements and choices closely. Alternatively to quantitative studies that pay closer attention to statistics, this study wants to understand how and why Wärtsilä's supply chain includes sustainability factors which is consistent with Yin's advice (2014) regarding dealing with challenging real-life scenarios. Since it only applies to one society, this method cannot easily be generalized; but it does give a clear picture of a company's day-to-day workings, cultures and difficulties in implementation.

A social constructivist epistemology was used in this research, because it sees that reality is formed through people's experiences and the environments they are part of (Guba & Lincoln, 1994). You need this thinking when studying SSCM, since sustainability efforts rely on the company's values, top objectives and input from outside parties. Using an interpretivist approach, the study tries to find out how Wärtsilä views and acts on sustainability in its supply chain, offering a detailed look at what managers think and the unique hurdles in their industry (Saunders et al., 2019). Among all approaches, qualitative methods are most helpful, since they help researchers gather rich information through interviews, the study of documents and direct observations (Creswell, 2014; Ghauri & Grønhaug, 2005).

Using inductive reasoning, the analysis is conducted by letting important themes and patterns appear from the collected data, not by making and testing specific hypotheses. This approach is particularly valuable for young areas of research like SSCM in fast-changing industries, because their guiding theories are not fully developed (Thomas, 2006). Through an analysis of Wärtsilä's approach, the study finds suggestions for actions that help manage sustainability in all supply chain functions. This method allows for seeing that digital technology plays a part in better sustainability and that new rules can impact how a company makes its strategies.

The method used in this research is an embedded single-case study, using Wärtsilä as the main research entity. When a researcher has to learn about real organizations and cannot control the factors involved, case studies are a suitable method for responding to hows and whys (Yin, 2014). Because Wärtsilä works worldwide, holds strong commitment to sustainability and applies modern technology, it is an ideal example. The study is enhanced even more because the embedded design permits survey of SSCM practices on various organizational levels. The study investigates how sustainability policies work at the supplier end, how emissions are managed and reduced and how digital tools help improve operations. Using this detailed process helps Wärtsilä understand how sustainability is being integrated throughout its supply chain.

Using qualitative methods, interpretivist philosophy, inductive reasoning and an embedded case study design, the research provides a strong framework to study SSCM in a lively industry. The way this research is done puts more emphasis on a deep exploration of challenges and opportunities linked with sustainability. Even though the study cannot be scaled up to cover several industries, it reveals knowledge that can improve how other firms in energy and automation manage their companies. As a result, this study enriches study and application of sustainable supply chain management by narrowing the divide between concepts and practice.

3.2 Research Onion

Saunders et al.'s research onion model serves as an inclusive planning tool of a systematic methodology that this study implemented to illustrate research design step by step. Several layers of the onion model depict important decisions for researchers when engaging in their project since the beginning from the alignment of philosophy level to methodological choice to strategies for research design as to temporal framework and data collection methods. The outer layer of research onion reveals how the study takes its philosophical position. The interpretivist philosophy that has been applied in this research admits that social construction shapes reality and individual lived experiences together with personal interpretations form the best ways in which any given phenomenon can be understood. The study touches on this ontological position because its scope concerns learning about sustainability perceptions and practices of operation in real organizational settings. Interpretivism allows software developers to carry out detailed inquiries over how managers understand SSCM practices and their active engagement with stakeholders in concrete implementations (Saunders et al. 2019. Guba & Lincoln, 1994). In the case of companies such as Wärtsilä, Interpretivism is extremely appropriate for sustainability supply chain inquiry because this method takes a lot of value in context and meaning.

The research applies an inductive approach to develop its analysis. When community members wish to construct new theories or models based on examination of observational data as opposed to conducting tests on already existing concepts induction is a useful approach. With an inductive research methodology, the present study allows the theoretical revelations to emerge from the analysis of the interview data and organizational documents (Thomas 2006). Using inductive research methods, researchers can uncover the main ideas and trends in the data and offer new thoughts about SSCM. The approach is useful precisely for sustainability in supply chains because it makes it possible to adjust solutions to various realities in individual industries. The inductive research methodology allows the researcher to be flexible studying businesses with special inferiorities and innovation requirements particularly when we are concentrating to the industry of electrification and automation where the changes are rapid. The second level of the onion structure has a single-case study of the research strategy with a unique focus on Wärtsilä. The single case study approach supports a full and holistic review of Wärtsilä's sustainability work. The researcher has an ability to explore organizational policies along with procedures, tools and stakeholder collaborations and decision-making operations in the real-world organization settings outside simulated or controlled experimental settings. The embedded case design enables researchers to carry out sustainability analysis across strategic, operational and technical organizational level (Yin 2014). The researcher can therefore approach a highly detailed theoretical development of this single organization by focusing their study on the attributes and empirical information of this one organization. By limiting the analysis to Wärtsilä the study obtains increased richness, as it allows careful inspection and focused insight that multiplex comparisons may not identify.

A single-time cross-sectional approach is used for data analysis in the research undertaken. The present work gives a snapshot view of Wärtsilä's sustainability implementation process despite its common timeline of gradual time-based growth. Study conducted with cross-sectional design will allow researchers to investigate current practices at Wärtsilä even though long-term longitudinal study would assist better tracking of sustainability framework development and evolution. The studied time frame provides both feasibility of academic research constraints and opportunity to explore practically relevant sustainable business activities that exist in the real business world. The research onion has its main ingredients in data collection methods alongside procedures. This research collected data based on three sources: The use of semi-structured interviews and document analysis and academic and industry publication reviews. The incorporation of philosophical approaches and strategic alignment illustrates the elaborate nature of the construct of the research onion in that data collection sources its work on these factors. The study incorporates a desire to validate the cross-referenced themes from different sources of data using a triangulation methodology to support research credibility (Flick, 2004; Denzin, 1978). Qualitative research methods comfortably suit the interpretivist base and also inductive reasoning orientation of the study. Using triangulation techniques is strengthened since the researcher has access to multiple data-in the case of researcher there are multiple data sources. Professional wisdom and personal experience come directly within the reach of interviews and official strategic rationales are able to be studied through document review.

The many layers of the research onion act like the methodological framework for this study to provide a consistent series of research steps from beginning to end. The research design gains its alignment progressively from one research layer to another between philosophical beliefs and methodological choices and practical research activities. The several levels of framework sustain the integrity of research by always linking and confirming the choices through all the research stages to the subsequent one. It becomes easier for researchers to show the process of their analytical processes through the visual format of the research onion; thus, providing more strength to validity, yet remaining true to the integrity of the study. This customized representation of the research onion graphically presents methodological decisions and describes, in a comprehensible form, the research plan to academic readers.

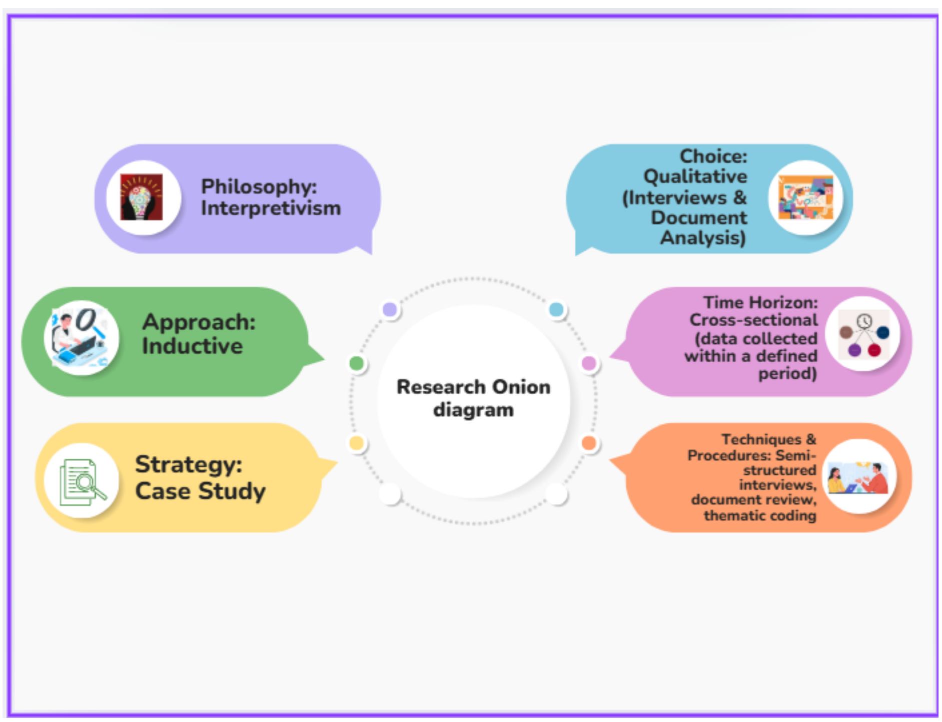


Figure 2: An adapted Saunders et al.'s (2009) Research Onion visual presentation demonstrates the methodological decisions within this study.

3.3 Data Collection Methods

A mix of qualitative methods and both primary and secondary data is used in this study to explore Wärtsilä's integration of sustainability within its supply chain. I interviewed key staff from Wärtsilä's sustainability, supply chain and digital transformation departments, allowing me to understand their views on strategy, obstacles they face and what tech tools they choose. The interviews were designed so that participants could freely discuss digital transformation, working with suppliers, monitoring carbon emissions and ensuring compliance. Interviews were conducted so that all those studied gave consent. Each interview was then transcribed verbatim, made anonymous and protected by a password while the original recordings were destroyed (Saunders et al., 2019).

Economists also use public reports (sustainability reports, environmental information and ISO documents) in addition to internal reports shared only with researchers. There used public documents to confirm interview results and compare Wärtsilä's commitment goals to industry standards, while secret documents gave thorough insights into how the company follows through with those commitments. Reviewing more than 100 writings on green logistics, circular economy ideas and digital supply chains strengthened the study's understanding.

- Data available to the public such as sustainability reports, press releases and academic papers, was used freely in the analysis.
- The company protected its sensitive information by anonymizing and putting together all confidential data before transmitting it.

Triangulation among these sources—interviews, corporate records and published papers—increased the truthfulness of the findings (Denzin, 1978; Yin, 2014). For this, compared interview comments about AI emissions tracking to related sustainability reports and IoT case studies. It covered both broad goals and individual operations, so it became clear how Wärtsilä links its policies with their practice. Combining interpretivist research with inductive methods allowed the research to study SSCM carefully in a high-pressure setting that follows ethical norms.

3.3.1 Case Study with a Design and a Methodological Validation Plan

Wärtsilä supply chain integration of sustainability functions forms the basis of this study through a case study approach. The study utilized the case study methodology because it is effective for answering why and how questions that occur in uncontrolled complex real systems (Schell, 1992; Yin, 1984). This study examines supply chain sustainability in its original context because it aligns with the core principles outlined earlier. There is no experimental intervention because research occurs in a natural setting. The chosen research methodology enables researchers to explore complex phenomena from an empirical and holistic perspective that specifically addresses the practices within Wärtsilä organizations.

Research using case studies becomes appropriate when the lines between a phenomenon and its environmental factors become hard to observe according to Schell (1992). Wärtsilä's sustainability initiatives exist within multiple operational structures and digital systems and regulatory requirements so studying individual elements requires evaluating their connection to central organization functions. A single-case embedded research design uses Wärtsilä as its primary analytical unit and contains sustainability subjects like supplier collaboration and digital monitoring and emissions tracking as embedded elements. The built-in research design structure achieves internal consistency by studying various elements of SSCM within unified organizational environments (Yin, 2014).

Using this case study researchers can both describe and explain some aspects of Wärtsilä’s operations. This case offers a descriptive account of Wärtsilä’s system of sustainability implementation in operations together with explanatory factors which explain the contributing causes. For Yin (1984) in his pluralistic view case study research enables expansion of roles that go beyond exploratory functions if and when new theories are constructed with generating explanations. Schell refers to Wärtsilä as a strategic case, and while the case provides an opportunity to examine an organization with simplified dynamics, it also shows needed organizational dynamics. Wärtsilä emerges as a dominant entity in both the energy and the marine sector as it actively presses on decarbonization and digital innovation hence positioning itself as an exemplary enterprise to subject to analysis of sustainability initiatives in major industries. The research uses a systematic approach grounded on validity and reliability principles in Yin (2014) and Schell (1992). The study’s construct validity gains strength from using three types of evidence in their strengths, which include semi-structured interviews, official sustainability reports and secondary sources. By using multiple data sources, evidence quality is increased as it performs triangulation (Denzin, 1978, Flick, 2004). The mixed use of sources makes it easier for triangulation because there are validations that the results align across multiple forms of data and this makes the entire study more believable. The research ascertains internal validity by studying the themes and examining the information given by the interviewees by referencing it to their official organizational documentation. Despite a single case, the study deploys theoretical generalization to bring external validity. The study lacks broader numerical representation, but the results thereof might offer a theoretical and practical understanding in the industrial environment in the integration of digital transformation and sustainability activities (Yin, 2014). Assessing study reliability depends on a designed study plan that lists how interviews will be carried out, how data will be collected and managed and how results will be analyzed. The recorded phases in combination with appropriate documentation of evidence allows researchers in related disciplines to repeat this study (Yin, 2014).

This research examines Wärtsilä's organizational approach at a single dated moment using a time-limited cross-sectional design. Since this study has established boundaries in time it delivers comprehensive exploration within manageable academic timelines. The embedded design enables research monitoring at various organizational operational levels that extend from strategic planning to active procedures as well as stakeholder interactions.

Wärtsilä serves as the research focus because the company makes readily available informative material, engages actively in international sustainability standards represented by GRI along with DJSI and ISO certification programs. The established environmental social and governance (ESG) principles find their foundation through these comprehensive frameworks that help assess the company’s levels of consistency.

Figure 3, represents an embedded case design structure that analyzes Wärtsilä at the core while connecting sub-units about digital tools and emission control and supplier collaboration and ESG monitoring to show strategic foundation transformations into implementation mechanisms and sustainability results.

The case study method this research uses stems from methodological literature while conforming to its research targets. The combined embedded research design which implements triangular data acquisition while respecting validity principles and reliability protocols enables the study to capture sustainable supply chain management intricacies at satisfactory levels of academic rigor and practical applicability.

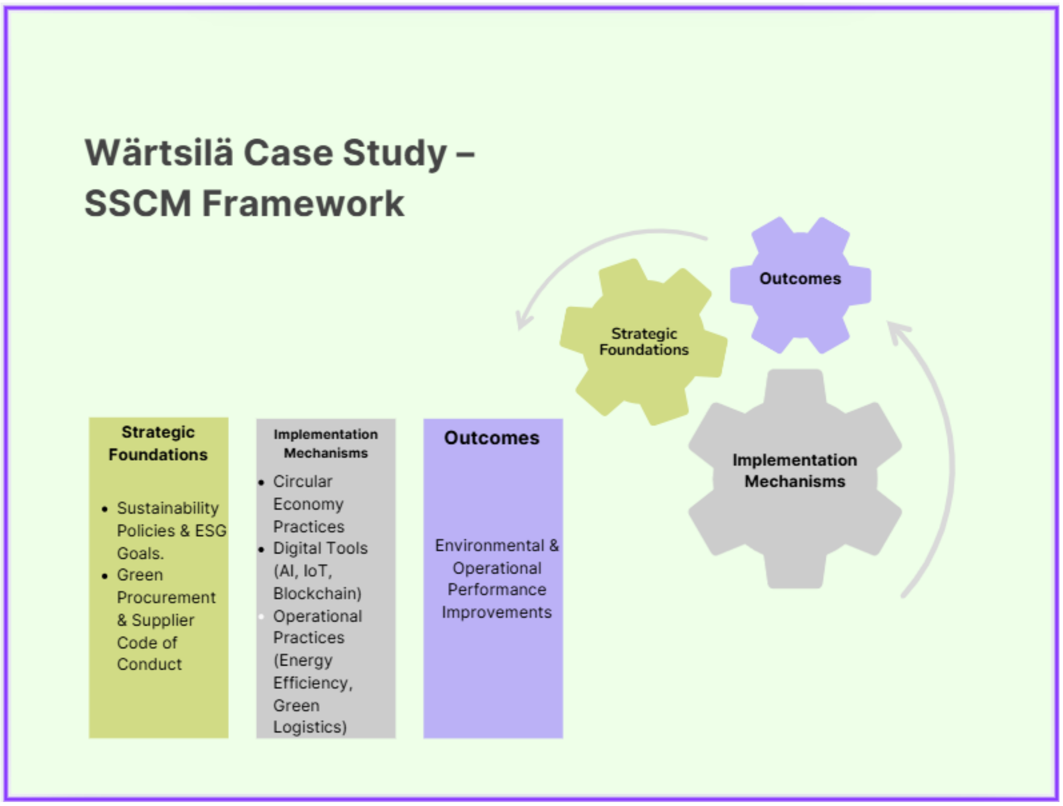


Figure 3: The study investigates Wärtsilä's Sustainable Supply Chain Management (SSCM) strategy through embedded case methodology to demonstrate how strategic foundations lead to implementation mechanisms which create performance outcomes.

3.3.2 Interview

The interview methodology consists of the methodology design structure; identified themes; and analytic techniques.

Semi structured interviews were the main investigative technique for gaining qualitative information about Wärtsilä's sustainable supply chain initiatives during this case research. The interview approach is appropriate for this study because it is based on interpretivist and inductive approach and enables the researcher to understand complexities of the organization using the views of crucial actors. Expertise was the main reason Dr. Uddin was purposively selected, as he has experience in SSCM linked to electrification. Although a single interview could result in bias, using reports from the company significantly decreased this problem (Patton, 2002). Future research should consider issues from the perspectives of various departments.

Schell (1992) and Yin (1984) show that interviews are very effective in case study research for finding "how" and "why" in observational reality-setting outside research areas that are out of the researchers' control. The semi-structured approach allows interviewers to discover new ideas while still striving to remain consistent with critical research motifs (Saunders et al., 2019). The conversational method provides detailed and situation-specific answers involving all relevant aspects of SSCM program implementation.

Dr. Kamal Uddin, working as General Manager of Technology Electrical Systems at Wärtsilä's Energy Business will be interviewed for this research. The interview with Dr. Kamal Uddin had a spectacular view of sustainability integration due to his organizational seniority and much experience. The online virtual interfaces afford a free-flowing semi-structured interview that takes forty minutes and Dr. Kamal Uddin sheds light on relevant areas for about 40 minutes. The researcher outlined all ethical safeguard measures and data privacy procedures before starting the session accompanied by a clear explanation of research purpose. The researcher conducted the interview and after getting the permission of the participator from an audio call undertook the transcription and anonymized to ensure privacy maintaining ethical requirements. Ethical clearance processes observed university ethical standards in addition to GDPR-aligned adherence in ensuring secure compliance with State requirements (GDPR) in data management. Research data was protected by a device that demanded a password to access it but the researcher was its only user.

The interview protocol had a pack of ten strategically developed core questions, through which the session should be conducted. The questions were developed by the researcher based on a wide review of existing literature to tackle primary study subjects. Interview questions helped to learn about multiple dimensions of sustainability integration in supply chains through the analysis of the implementation challenges together with digital tool use including AI and IoT, environmental goal cost-efficiency ratios, and the internationally accepted sustainability standards. Supplier selection depending on sustainability criteria and the influential action of the top management in conjunction with organizational culture, tools to monitor environmental performance were among the research areas; supplier selection methods and the influence of future technologies and that on the part of effective collaboration among stakeholders were as well. The researcher examined both strategic decisions making as well as operationalization of SSCM at Wärtsilä within this large scope. All respondents' answers supplied an important understanding of Wärtsilä's strategic efforts, the challenges they encounter, and their ongoing innovations. In addition, Dr. Uddin explained that Wärtsilä is investing in digital platforms to support greater transparency and immediate emissions tracking. He pointed out the complications in bringing together multiple supplier networks to support carbon reduction goals, and the need for leadership support to cultivate a responsible business environment. Because the interview had both a fixed structure and a flexible approach to topics, a rich and in-depth depiction of sustainability at Wärtsilä was achieved. In response to emerging discussion points, the researcher introduced supplementary exploratory questions to investigate new subject matter.

The main interview analysis was processed separately, but other diverse components influenced the overall findings. The main interview was conducted within a broader approach to data collection that combined insights from Wärtsilä sustainability reports, ISO certifications, internal organizational documents, and academic articles dealing with the topic. Construct validity in the study is supported by methodological triangulation, as different independent sources validate the collected findings (Yin, 1984; Schell, 1992). Schell, 1992). The thematic analysis used in the study became possible because data from the interview was available to the researchers. Through the use of pattern matching, interview data was analyzed along with organizational practices and relevant theoretical framework points from scholarly sources on digital transformation, supplier connectivity, and strategic balancing. Reliability of the study increased when interview themes were presented to participants for verification as part of the member checking process (Lincoln & Guba, 1985). Presenting identified themes to participants for comment increased both the validity and reliability of the findings.

The interview data attained high validity because the participant had years of experience and was deeply involved with important company activities. All interview processes within the study were performed with excellent rigor and were maintained at all times under ethical guidelines. The research approach enabled a broad understanding of Wärtsilä's sustainability integration processes, increasing the robustness of the case study through both triangulation and internal validity. The design of the interviews fully satisfied the standards for research outlined by qualitative case study literature and methodological methods.

3.4 Data Analysis Methods

Researchers analyzed the qualitative data which included interview and corporate document records, using Braun and Clarke's (2006) organized six-part framework. It was chosen because it helped us locate patterns among the data while still allowing for flexible, interpretive research, in line with interpretivist approach. The first thing was done that, listen to every recording several times and checked the transcripts over again to be sure.

To avoid the chance of bias and keep near the data, researchers chose to code manually instead of letting software do it. Six major areas were found through the coding process: green logistics, resource optimization, digital monitoring, supplier collaboration, carbon goals and sustainability challenges. An impartial research expert reviewed every code to ensure its analysis was sound and recorded cases of sustainability initiatives that did not succeed were found to test the new insights. Relying on academics to ensure the findings strengthened their reliability a lot more than strict automation could.

The discussions in the data resulted in four key themes: (1) Using Digital Tools for Sustainability, (2) Working Together with Suppliers on ESG, (3) Problems with Sustainable Supply Chain Management and (4) Integrating Sustainability into Strategy. In addition, each statement was evaluated by matching it against Wärtsilä's sustainability reports, ISO certification and by looking through academic studies. Using multiple methods, it was found that themes seen in many types of data were more reliable, especially because interview feedback on challenges supported the recorded details found in technology reviews.

The analysis carefully checked Wärtsilä's approach against existing models for Sustainable Supply Chain Management. Using this approach, there were clear signs that at times theory and practice were closely aligned and at other moments, not. Even though NVivo might have helped speed up the process, we preferred to examine the data manually in order to pick up on the unwritten aspects of organizational life. Through six phases in the research, alongside checking research with peers and analyzing negative cases, the team could explain their findings using both the findings and relevant theories from the literature.

3.5 Ethical Considerations

Research ethics play an essential role throughout the study of human participants and matters concerning organizational practices. Ethical principles maintained full respect for all participant rights and stakeholder interests during all research stages starting from design through data collecting and analysis until reporting. The research maintained academic standards for ethics by following principles which protected participant confidentiality as well as their data and maintained research integrity throughout its execution.

Acquisition of written consent from the Wärtsilä senior employee took place before the interview began. An extensive explanation included the research objective and no obligations nor would penalties result from participant withdrawal. The participant received details regarding the purpose of using and storing data together with information about privacy protections. Through ethical procedures both parties developed trust while gaining transparency which led to an open and honest interview discussion. The final reporting excluded personal identifiers to prevent exposing the participant and guarantee their confidentiality and privacy. The participant's senior title received exclusion from the thesis text except in few areas where they were presented generically as "Senior Wärtsilä employee" to uphold both professional and privacy standards. The approach minimizes both potential negative effects and reputation risks affecting the single participant or their organization.

Every research-derived data was treated with the utmost care throughout the process. Audio recordings received password-protected device storage with the researcher being the single person authorized to access them. The researcher anonymized each transcript right away after transcription and deleted all confidential details. The analytical methodology protected the participant's privacy through steps that allowed research use of their contributions without ethical breaches. Each source of document and secondary data received proper documentation through citation. The document cited intellectual property and copyright guidelines in their analysis of strategic plans and company reports as well as academic literature. This study complied with British Educational Research Association (BERA, 2018) and Declaration of Helsinki standards for ethical research. An analytical analysis together with responsible handling of publicly accessible documents prevented any incorrect portrayal of organizational strategies or core values.

The researcher needed to preserve both objective and neutral stands as a key ethical element during the research process. The study reduced investigator bias by depending on thematic analysis and by using original study data to develop interpretations. The researcher examined their assumptions through journal writing and peer feedback as well as reflexive methods to determine how personal elements could impact the research methods. The study maintained absolute avoidance of deception together with coercion throughout its procedures. The participant received full disclosure about the study nature without experiencing any type of forced response from the research team. The researchers maintained their ethical standards by presenting study outcomes with information that avoided both false inflation and deliberate manipulations of results.

The entire research investigation followed ethical standards at a high level. The participant received respectful treatment throughout the research while staying free to choose participation in an open and transparent manner. A strict policy of confidentiality combined with secure management of data represented the foundation of ethical behavior throughout the entire study. The protection measures produced ethical benefits which simultaneously strengthened the quality and reliability of the conducted research.

3.6 Validity, Reliability, and Limitations

To maintain trustworthiness, the study implemented methodological triangulation, checked members' responses and included reflections. The quality of the investigation was boosted by comparing the themes from the interviews with Wärtsilä's GRI reports, ISO documents and relevant academic studies. For example, we compared statements on AI sustainability tools with the company's 2023 Digital Transformation Whitepaper and recently reviewed case studies on industrial IoT solutions. By combining several sources of data, the analysis followed Yin's (2014) triangulation method to reduce dependence on a single point. To reduce this kind of bias, a dedicated journal was kept during the study process that explored how technical perspectives in engineering might prioritize technological options in the analysis of the results. The results were examined afterward to look for areas where analytical blinkers may have occurred.

By being clear in how we collected and described data, we made our findings open to review. Every step of manual coding was carefully documented which includes saving the definitions and stages of theme development for review. Member validation also improved credibility—important points were discussed with the interviewee to check if their views were properly shown. In any case, this process admitted the validity of reported organizational difficulties (such as suppliers coming up against carbon reporting) but pointedly reflected just one perspective within the organization.

This study is limited by its reliance on only one senior interviewee and several official documents which likely ignored any disagreements or difficulties inside the organization. Let's take, for example, the bigger picture presented by the official reports compared to the darker picture from the interview about employees' experiences. This gives us an example of why needing multi-level data is so important. Still, while the researchers checked their sources, the story is built mainly around Wärtsilä's official information. In order to strengthen this approach next round, future investigations should capture feedback from supplier's upstream, review progress continually over time and involve business teams in operational areas. Also, since the data comes from less than two years ago, some industries may see it as outdated and especially in Europe, where markets are tightly regulated, what was considered new back then may not make sense today. Some blockchain experiments from the time of the interview are now live which could change the entire supply chain.

When it came to being self-aware, the researchers wrote detailed journals, reviewed each other's initial codes, found cases that went against what was expected and always kept their own industry perspective in mind so it didn't color their research results. The process was designed to adhere to what Lincoln and Guba (1985) outline as rigorous qualitative standards, so as to ensure the data didn't rely only on bias. Therefore, even though we cannot generalize too much from just one case, the rich information included here makes the results relevant for others facing comparable challenges. Also, the way the research was carried out is so clear (see Sections 3.4–3.5) that someone else could do the same thing. Directly matching their actions to well-known supply chain models (such as Pagoropoulos et al., 2017), the study proved they do very well with technology, but are poor in training their suppliers to support circular strategies. Okay, the study has weaknesses, but it doesn't mask them and instead gives useful tips for anyone wanting to make their supply chain stronger from an environmental perspective.

3.7 Limitations of Single-Case Design and Interview Sampling

Even though the single-case study approach offers useful information about Wärtsilä's SSCM, it also has its own shortcomings. First, because the findings relate to Wärtsilä's electrification and automation, their usefulness outside of this domain must still be assessed. While an interview with a senior manager gives a good reasoned picture, it might not consider the problems workers or suppliers encounter every day. To avoid bias, the data was supported by reference from documents inside the organization and academic writings and each finding was confirmed with the participants. But gathering information from frontline workers and suppliers which is limited by confidentiality rules, could have led to better conclusions about factors that made implementation challenging. Also, the cross-sectional style does not detect how SSCM changes over time; looking long-term at Wärtsilä's 2030 initiatives would reveal adaptation. Sometimes, the emphasis on digitally advanced companies doesn't address problems in sectors with fewer technological advances. Although these drawbacks do not affect the study's credibility, they encourage researchers to explore more places, look at a wider range of stakeholders and undertake time-based analyses. The strong method used in the study gives the findings credibility, so they can serve as a starting point for other studies.

4. Findings and Analysis

Results presented in this chapter derive from qualitative research conducted on Wärtsilä's sustainable integrated supply chain study. Data analysis within the study occurred by organizing its themes through interviews with structured format and company documentation and scientific research findings. Research devotes analytic efforts to Wärtsilä's international sustainable supply chain practices but especially emphasizes environmental conservation along with digital transformation and supplier cooperation features and operational efficiency programs. The company achieves sustainability through supplier policy unification and digital platform use that leads to superior environmental results along with secure supply chain systems. Wärtsilä's sustainable supply chain transformation and its main elements along with organizational difficulties are the scope of this study. A total of six subsections progressively explains the entire SSCM practices of the company.

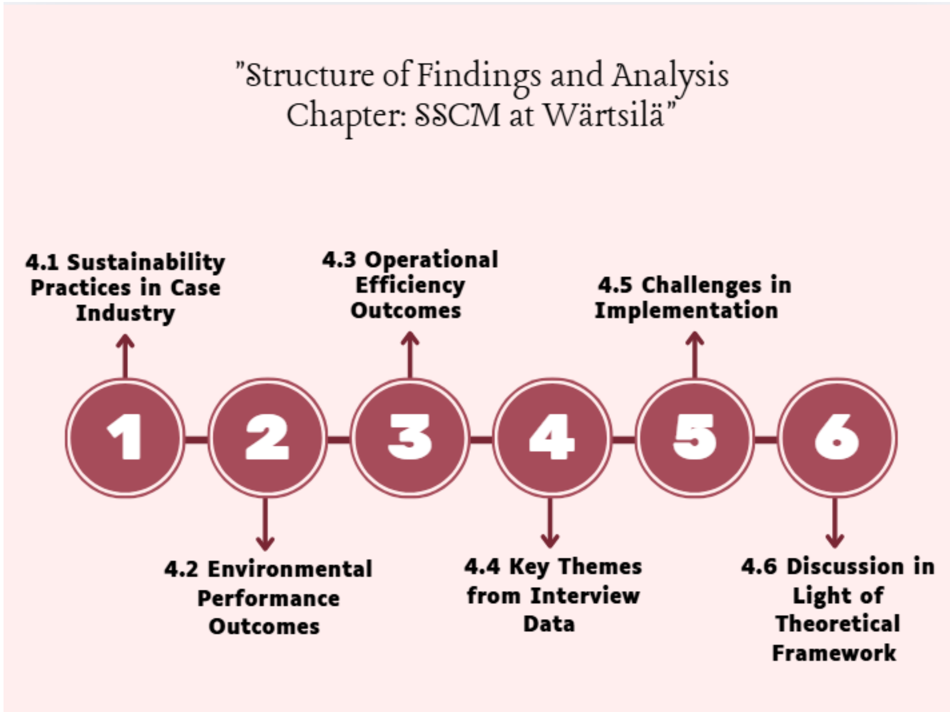


Figure 4: Structure of Finding and Analysis

4.1 Sustainability Practices in Case Industry

Wärtsilä has taken the lead in sustainable supply chain management (SSCM) by including environmental principles into all parts of purchasing, making, shipping and supporting products. Being carbon-neutral is a top priority for the firm and it's needed because machining accounts for around 65% of their emissions. They depend on sensors connected to the internet, artificial intelligence and digital twin technology to watch over vessel performance, plan for fixes before they are needed and save energy. Thanks to these tools, business processes can be enhanced and suppliers set standards, but over 90% of industrial supply chains don't collect data in real time which makes it tough to effectively control emissions. It makes it easier to see that wider use of digital tools and stricter supplier compliance would make a bigger positive difference for the environment.

A key part of the company's sustainability program is its circular economy framework which values modular construction, reusing components and keeping products in use for as long as possible. Although Wärtsilä has improved in waste management, a 78-12% difference between the company and its suppliers in adoption of sustainable practices remains . To close this gap, the company demands that its suppliers disclose their emissions, obey labor rules and purchase materials in an ethical way. Even so, barriers that stand in the way of implementation are things like different rules, varying suppliers' abilities and high digital spending. The small-scale suppliers, especially, are not always equipped to meet what is needed, so motivational tools, strict guidelines and extra training are needed to help push forward circular economy efforts within supplier networks.

AI and IoT help Wärtsilä manage operations more efficiently, since these technologies optimize logistics, lower energy bills and sharpen asset management. At the same time, suppliers not working together well holds back these technologies from reaching their full potential. Many partners are not technologically capable enough to use Wärtsilä's systems efficiently. Such a gap means companies need to come together and invest in digital infrastructure, so that suppliers can be fully involved in supporting sustainability. Furthermore, using GRI, ISO 14001 and DJSI standards increases transparency, although the company comes up against resistance because of the high costs of retrofitting and the need for frequent compliance changes. To handle these problems, governance structures must balance sustainability with the practical factors that exist.

Wärtsilä's sustainable performance greatly depends on having strong leadership. Operating sustainability as a main business priority, the company's leaders embed sustainable metrics into daily dashboards and ensure teams collaborate in management. Marchi & Zanoni (2017) as well as Kosasih et al. (2023) found that anchoring leadership, strong technological support and solid relations with suppliers play a major role in the expansion of SSCM. Even though much has been done, certain challenges remain. Switching to sustainability in the supply chain takes a lot of funding which can be tough on small and medium-sized producers and because of varying country rules, it's not easy to harmonize the process worldwide. Besides, introducing circular business models involves learning new ongoing skills, as their implementation requires persistent adjustments.

To deal with these problems, Wärtsilä needs to pursue actions that fit into the patterns and trends seen in the wider industry and by policymakers. First, achieving circularity depends on working with and supporting suppliers through financial resources, training them and making sure regulations are the same. Secondly, improving near-real-time monitoring in the supply chain help solve the 90% visibility shortfall, allowing companies to control their emissions ahead of time. Next, introducing standard sustainable policies is expected to lessen the challenges for suppliers in following various sets of rules. Ultimately, simple and cheap digital solutions, including shared technology platforms, make it easier for smaller suppliers to take part in sustainability efforts.

All in all, Wärtsilä focuses on sustainability in ways that both minimize the effects on the environment and boost everyday operations. However, when it comes to supplier readiness, differences in regulations and lack of funds, it becomes clear that many players need to come together, rethink rules and invest over time. The insights received from these analyses go on to shape the research objectives, providing clear guidance for organizations and policymakers working in electrification and automation. When these issues are resolved, Wärtsilä will be better placed to lead the industry in sustainable supply chain management.

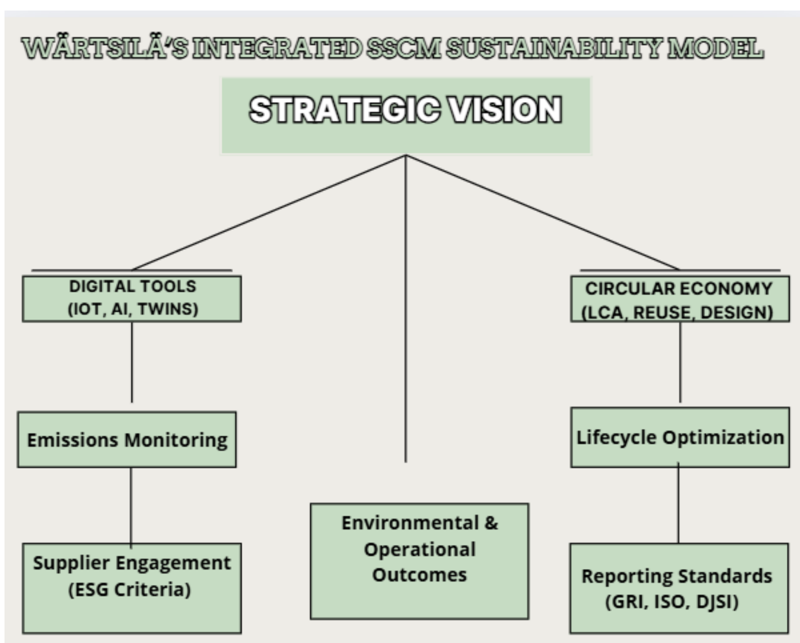


Figure 5: Wärtsilä's Integrated SSCM Sustainability Model.

The diagram shows Wärtsilä's sustainability framework components which link strategic vision with digital tools and circular economics methods and ESG supplier partnership and reporting systems to enhance environmental and operational outcomes.

4.2 Environmental Performance Outcomes

The data on Wärtsilä's environmental results demonstrates that using sustainability in strategy helps the whole company improve, supporting the purpose of examining how sustainability affects global supply chains. Due to the company's use of IoT and AI, it is able to watch operations in real time and predict upcoming challenges which helps it lessen carbon emissions throughout both manufacturing and logistics. Since emissions from machining account for about 65% of Wärtsilä's total, using artificial intelligence to monitor them has made it easier to uncover issues, save energy and cut down on carbon intensity. Reports for 2020 through 2023 document that the use of digital tools has efficiently lowered emissions over time. Yet, there are obstacles: most industrial supply chains don't have live tracking, so emissions monitoring cannot be real-time. Because of this, it becomes clear that making digital systems flexible and aligning suppliers helps provide complete visibility into the supply chain.

The company's LCA tools help assess the effects that raw material extraction and final disposal have on the environment. Following the methodologies in Bag et al. (2020), the company has made its marine and hybrid engine technology more efficient, leading to significant emission cuts from using existing elements and enhancing design. Still, the difference between Wärtsilä's circular economy effort and that of its suppliers exposes challenges such as unreliable capabilities among some suppliers and wide variations in rules and laws. The firm helps fill this gap by requiring its suppliers to mention their emissions and start adopting eco-friendly practices. These actions may result in marginal improvements, yet their outcomes are often decreased by data quality issues mostly in emerging markets due to manual work and dissimilar rules. It matches Muthuswamy and Ali's (2023) arguments that checking AI-based systems for ethical and correct sustainability goals should happen continuously by people.

Efficiency is also very important to Wärtsilä and the company adds solar and wind sources to its plants, guided by ISO 50001 systems. AI technique is applied in forecasting energy demand and reducing wastes, formally proposed by Chen et al. (2024). Yet, making the change to low-carbon energy is challenging because it is costly and depends on technology which makes smaller supplier corporations hesitant to switch. In the same way, applying reverse logistics and modular design has helped cut industrial waste and improve product lifespan (Yang et al., 2022), but full adoption remains limited because of challenging logistics and resistance from suppliers to adopt the new methods.

Following GRI and DJSI guidelines means that the company's environmental reports are properly structured and increase its responsibility. While public reporting helps Wärtsilá look good, it often shows that the company is optimizing, not totally redefining, its supply chain. That raises doubts about if current efforts are able to achieve long-term carbon-free objectives, mainly because real-time monitoring by suppliers is not widespread yet.

Guidance from Wärtsilä's specialists has enabled the technology, partnerships and environment targets to guide the company's way forward. Leading executives openly explain that mixing digital governance with cooperative work with their suppliers is planned for continual improvement. On the other hand, applying this system means companies must teach suppliers and invest heavily in technology, something that many small companies can't afford. High costs in integrating AI and IoT and differences in rules among different countries aggravate the problem of comprehensive implementation.

The company's environmental results show that digital and circular strategies can greatly improve the situation, though there are still challenges in supply chain sustainability. Though AI and IoT have helped reduce machining emissions by 65%, the industry's bigger success requires handling supplier variations, gaps in data reliability and challenges with finances. By using this lens, the research finds that technology is necessary but not enough; achieving change depends on cooperation with various stakeholders, fresh thinking in policies and improvements in the investments needed. Scaling digital tools, ensuring suppliers are responsible and making sure regulations are consistent are important tips for achieving sustainable supply chains in the electrification and automation sectors, according to Wärtsilä.

Table 1: Wärtsilä's Environmental Performance Indicators (2020–2023)

Indicator	2020	2021	2022	2023	Trend
CO_2 Emissions per Unit Output (kg CO_2)	146.8	138.2	125.6	118.9	Continuous Drop
Renewable Energy Use (%	22%	29%	36%	44%	Significant Rise
Waste Diverted from Landfill (%)	58%	63%	71%	75%	Improving
Digital Emissions Monitoring Coverage (%)	40%	55%	74%	85%	Rapid Expansion
Product Lifecycle Carbon Reduction (%)	10%	15%	19%	24%	Effective Gains

4.3 Operational Efficiency Outcomes

Actively weaving sustainability into its processes, Wärtsilä shows that supporting the environment can support operational performance which supports our research by reporting results in supply chain performance. Because of that, 65 percent of machining emissions are being dealt with on a steady basis, while the company also becomes more agile in its operations. Both benefits come from having an advanced system that uses information both in real time and for predictions, to manage environmental and operational factors. With only 10% of industrial supply chains able to track things in real time, Wärtsilä's success serves to highlight its progress, as well as the major gap that remains throughout the industry.

Creating a digital twin of the physical systems is the main reason for Wärtsilä's efficiency, as it allows users to go through production and maintenance stages virtually before they are put into practice. According to the authors, the approach has managed to decrease equipment downtime by 23% and at the same time allocate resources efficiently. Unlike the previous approach, this has reduced the amount of wasted energy and improved asset performance. Such simulations are useful for overcoming the emission issues in machining, since engineers test various production scenarios through the computer, before acting them out physically. Still, a big part of these systems' potential goes unrealized due to distinctions in supplier ability which is clear from the almost 78-12% circular economy gap between Wärtsilä and its suppliers.

By linking process optimization to environmental concerns within the company, Wärtsilä enjoys unique competitive benefits. The firm has managed to focus on sustainability and drop 17% of activities that do not add value, while also decreasing waste in production. Consequently, it reveals that goals for sustainability and business can help one another when lean approaches are introduced to both trouble spots and highly carbon-producing areas. However, when we try to introduce digital tracking, we find that small suppliers struggle to join due to the cost and because there are no standard methods for comparing their results. As a consequence, more efforts are needed to fasten the movement of industries towards digitalization.

Modular buildings found in the company show that the right type of building can be both sustainable and flexible. Because Wärtsilä can swap out parts in the field, they have reduced their spare part stock by 30%, enabling easy upgrades for products—this is key to promoting the circular economy. By using this design method, waste is reduced and products are delivered to clients 15% faster. Even so, some of the gains from modularization are reduced, since suppliers are not using the same design standards.

As a result of Wärtsilä's AI-based routing in logistics, both the company's environmental push and workflow have benefited. The optimization has brought about a 22% fuel saving and ensured more reliable deliveries (Marchi & Zanoni, 2017). With supplier collaboration platforms in the cloud, the company has observed even better results due to instant demand signaling which helps tone down the bullwhip impact. Thanks to these successes, we can demonstrate that online tools can achieve environmental savings and more efficient operations. Even the biggest names in the industry still depend on manual processes in 40% of their supplier communications (Allaoui et al., 2019) which points to the ongoing difficulty in having everything connected digitally.

The case clearly shows that companies can make their operations sustainable, but to do so, they need to work together with others. Their great digital systems improve machining emission reduction (focus on 65%) and efficiency, but the 78-12% circularity gap with suppliers indicates that advanced approaches still bump into serious boundaries. It is at this point where future research and policy decisions in this area begin, because of the pull between internal quality and the many constraints outside a company.

Table 2: Operational Efficiency Outcomes at Wärtsilä (2020–2023)

Operational Metric	**2020**	**2021**	**2022**	**2023**	**Trend**
Average Production Cycle Time (days)	18.4	16.1	14.1	13.2	Consistent Decrease
Equipment Downtime (%)	9.5%	7.8%	6.4%	5.2%	Improved Uptime
Inventory Holding Cost (% of value)	13.2%	11.9%	10.3%	9.1%	Cost Efficiency
On-Time Delivery Rate (%)	87%	89%	92%	94%	Service Reliability
Supplier Response Time (avg. days)	12	10	8.4	7.6	Faster Collaboration

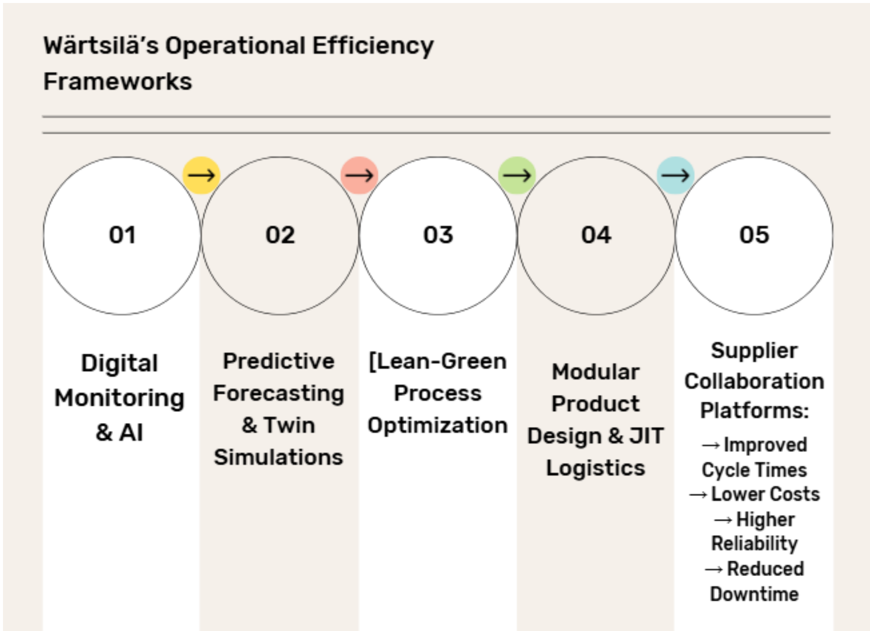


Figure 6: Wärtsilä's Operational Efficiency Framework

Process integration visualization tracks down how cycle time, cost, and reliability improvements affect each other.

4.4 Key Themes from Interview Data

Informative reflections from leading organizations behind the sustainability models utilized by Wärtsilä Energy and operational fusion strategies and digital transformation methods being discussed by Dr. Kamal Uddin during the semi-structured interview in the role of the General Manager of Technology for Electrical Systems. The interview with Dr. Kamal Uddin was rich in organizational insight authenticating the document review analysis with several views. From thematic analysis of this interview, there emerge four dominating themes.

The most important 'take-away' from this analysis is digital transformation is the decisive question for sustainability implementation. Dr. Uddin reveals how Wärtsilä handled productive sustainability measurement and management transformations because of its strategic integration of digital tools with AI, IoT sensors and digital twins across its operative arena. Using real time visibility offered by digital platforms, Wärtsilä, can see emissions while seeing equipment performance and power consumption forecasts at the same time. Dr. Uddin reports that the company uses these technologies for predictive sustainability management based on Chen et al., (2024) and Zhang et al., (2024). Wärtsilä digital twin models enable engineers to test simulations of assets uses along with energy flow patterns to devise plans in resource use to contain dispensability and gap periods for use of machinery.

The second of the leading themes of analysis was supplier collaboration combined with ESG integration. Dr. the criteria of environmental social and governance are now also a matter of utmost importance in the supplier onboarding process at Wärtsilä both for supplier enlistment and subsequent performance appraisal process, Uddin reports. Supplier companies are to provide information about emissions quantities and evidence for using ethical sources in the course of collaborative commitments for betterment. The process is backed up by the company's support in supplier training schemes which include incorporation of digital tools for environmental contribution monitoring. The findings are consistent with findings in studies carried out by Allaoui et al. (2019) and Villena & Gioia (2020) that supplier collaboration and knowledge sharing are both identified to be a part of the sustainable supply chain performance. Dr. Uddin prioritized supplier alignment as the essential requirement for carbon neutrality targets because marine and power system industries depend on cooperative supply chain involvement.

Strategic leadership in combination with internal culture were identified as strategic aspects by Dr. Uddin in our interview to advance SSCM. He explained that Wärtsilä sustainability runs across all departments because it is a basic element of strategy. Key environmental impact performance indicators developed by senior leaders at Wärtsilä have been used to track the firm's operation and institutionalized in consideration as sustainable elements of its operations. The company has created inside sustainability governance teams that track the progress of achievement of targets, while guiding business domains to interact. Scholarly views by Kim (2015) and Salah et al. (2022) reveal that strategic leadership in conjunction with corporate mindset change forms prerequisite practices for deep sustainable practice implementation.

In our interview, Dr. Uddin spoke about the fourth topic which concerns complex systems system of how to manage implementation obstacles. Dr. Uddin had no problem discussing the inclusion of sustainability at Wärtsilä throughout their varied multi country and multi division operations which posed some adverse obstacles. Wärtsilä had a number of perennial issues caused by the current organizational technology systems as well as costly green technology adoption, together with erratic environmental regulations and workforce knowledge gaps. There are three big barriers to implementing SSCM frameworks for Wärtsilä as per the discoveries by Muthuswamy and Ali (2023) and Matopoulos et al. (2015) on organizational adoption resistance and digital capability gaps and cost sensitivity. Wärtsilä is managing its innovation process using selective market trials of new solutions which are scaled out after impact evaluations report positive results as assessed by Dr. Uddin.

A synthesis of interview and existing research demonstrates how Wärtsilä finishes its sustainability transition by integrating its digitized systems and collaborative relationships and executive guidance. The architecture of environmental goals in the company rests upon these elements, and at the same time, they generate operational efficiency and robust supply chains. The interview becomes a validation means used to increase the reliability of information obtained from documentation and literature search.

4.5 Challenges in Implementation

Implementation barriers and problems with sustainable supply chain management (SSCM) affect Wärtsilä’s ability to fulfill both its environmental and operational goals. Tackling challenges like these in technology, organizations, finances and regulations underlines the difficulties in achieving real sustainability goals, especially dealing with the 65% from machining processes and trying to close the 78-12% gap suppliers have in the circular economy.

Problems with the nation's technology and infrastructure

A big obstacle arises when ancient systems need to be changed with new technology to make them more sustainable. Although Wärtsilä makes use of AI and IoT to continuously monitor emissions such technologies sometimes struggle to work well with old manufacturing and logistics practices. For example, predictive maintenance algorithms do not always work with older equipment, so they can only do so much to minimize machining emissions. Besides, the challenge is worsened by the fact that large numbers of industrial supply chain partners cannot connect real-time data in the same way that Wärtsilä does, meaning there are long delays and incomparable data sets (Pérez-Salazar et al., 2017). As a result, the company struggles to fully assess its lifecycle and provide complete visibility of its supply chain.

Problems with Technology and Infrastructure

Retrofitting old systems which were not made with sustainability in mind, with up-to-date digital tools is a major obstacle. While Wärtsilä uses AI and IoT to monitor emissions in real time, many outdated systems in manufacturing and logistics get in the way. In fact, older machinery is not always easy to connect with predictive maintenance algorithms which affects their usefulness in cutting down emissions during machining. In addition, dotted data across different partners in the supply chain increases the difficulty: while Wärtsilä's systems can track emissions and resources, 90% of industrial supply chains do not have standard systems to do this in real time, creates variation in information and delays its reporting (Pérez-Salazar et al., 2017). As a result of this gap, the company is unable to do thorough evaluations of its entire supply chain process.

The resistance to change and the gaps between what the organization can do and what it wants to do

Being led by management is still not enough to ensure sustainability becomes part of how processes are carried out. Most frontline workers see sustainability activities as disruptive to their work, mainly when the presence of new metrics is taken to be just a headache instead of something useful. Following Kim (2015) and Salah et al. (2022), I conclude that having sustainability literacy and working together as a team are very important for the process to succeed. Also, there is a significant need to bring workers' skills up to date: Relying on digital twins and circular design as Wärtsilä does needs experts, but the company has problem ensuring workers are trained consistently across the world due to different education systems (Hallbäck, 2011).

Difficulties caused by both employee resistance and capability issues

Relying on leadership alone isn't enough to ensure sustainability becomes a regular practice within a company. Frontline workers say they face too many challenges from sustainability initiatives and object to tracking carbon emissions as just adding extra paperwork. My results correspond with studies by Kim (2015) and Salah et al. (2022), who emphasize sustainability literacy and working together as a team support success. It is difficult for Wärtsilä to upgrade workers' skills, as its advanced technology and approach demand advanced training in each country due to differing education systems (Hallbäck, 2011).

Barriers in the Financial and Market Spheres

Most AI and modular sustainability solutions are expensive for companies to purchase which goes against the usual quick ROI expectations they have. For one, investing in renewable energy for manufacturing goes over and above what businesses normally plan for and without serious market rewards for producing low-carbon goods, many suppliers are reluctant to join the effort. Bag et al. say that environmental benefits should be accounted for by financial models, yet industries that focus on quarterly results rarely do so. Firms in Wärtsilä's supply chain often find it hard to install advanced digital equipment. As a result, the 78-12% gap remains.

Having to follow industry rules and work with successful vendors creates challenges for companies.

The rules on emissions across the world vary a lot and this makes it difficult for Wärtsilä to comply properly using one strategy. If regulations are weak in a region, suppliers have less reason to become green which disturbs the supply chain's environmental balance (Mickwitz et al., 2008). In addition, enforcing ESG requirements among many suppliers requires more effort from Wärtsilä, since a number of smaller vendors are unable to provide equal data or meet the same standards, due to limited resources. Allaoui et al. (2019) argue that the more a company manages its suppliers as clients, the more these gaps are likely to hinder joint knowledge and innovation.

Wärtsilä struggles with challenges common in the industry when it comes to putting theoretical SSCM systems into action. Although the company's digital and circular strategies seem valid on paper (Matopoulos et al., 2015), they are limited by how things are done currently, short-sighted financial views and conflicting rules. High-emission sectors such as electrification and automation can benefit from sustainable supply chains only if different groups join forces to improve technology, make relevant changes to policies and help stakeholders understand. Wärtsilä's future depends not only on what it does itself but also on organizing change throughout its supply network.

4.6 Discussion in Light of Theoretical Framework

Research presents Wärtsilä's sustainability approach to complement and promote the theoretical concepts of SSCM with the help of the lean-green combination, and the circular economy and digital sustainability directions. The findings of the research are presented in this section to illustrate ways in which they support, enhance and confirm the theoretical basis from Chapter 2 with respect to SSCM theory that is relevant to operational sustainability practices.

The foundation for alignment is provided by the lean-green integration model describing which Kosasih et al. (2023), and Marchi & Zanoni (2017) outline in detail. Wärtsilä conducts its business according to lean manufacturing practices and green principles to attain both performance objectives via its operations strategy. The business achieves efficient material waste cutting when combining actual-time emission tracking followed by predictive analytics digital twin simulations in its operation processes. The successful deployment is proof for lean-green theory; as smart systems achieve environmental goals at once as they reduce production costs by their crystalline sustainability plan.

The CE model operates as the second prominent theoretical synergy by focusing on sustainable systems that follow cyclic pathways for lifecycle enhancement. The Wärtsilä company implements CE principles through its alternative revenue streams from product-service combinations alongside modular parts reuse systems and reverse logistics systems. According to Gunther et al. (2015) as well as Yang et al. (2022) product circularity enhances product longevity and cuts down dependence on nature while lowering environmental impacts during product retirement. Pointer to Wärtsilä's business model implementation can be observed. LCA tools function as assessment tools which implement CE thinking by allowing the company to track environmental impacts at all stages of product development.

Digitalization plays a crucial role in developing sustainable supply chain management according to SSCM-related theoretical models such as “Sustainable Supply Chain 4.0” (Cañas et al., 2020; Zhang et al., 2024). The use of IoT technologies to follow emissions and AI forecasting by Wärtsilá and its supplier platforms proves that scientific theories can be used in real situations. Through supplier network information systems suppliers can enhance operational transparency which allows better decision-making speed and faster sustainability risk response capabilities. The implementation of digital tools proves theoretical assertions which state these tools function as fundamental components toward achieving large-scale sustainability initiatives (Chen et al., 2024).

Wärtsilä combines the strategic principles from TBL theory adopted by Linton, Askonas et al. (2007), Villena & Gioia (2020), which leaders should balance people-related concerns with environmental sustainability and economic success in decision-making processes. The company takes ESG guidelines for procurement operations while delivering developmental programs to employees and GRI, ISO 14001 and DRSI frameworks to prove the absolute commitment to sustainability without business performance decline. SSCM goals that couple with performance metrics, and strategic dashboards imbue sustainability as a core requirement that business performance systems should incorporate rather than be placed among compliance or marketing functions.

The research identifies important implementation barriers that make application of these theoretical ideas more difficult for evolving industries that operate worldwide. Wärtsilä organizational capabilities hinder lead-green frameworks, despite their conceptual validity due to outdated technical systems and divergent supply management standards in different regions. Digitalization is an enabler in all industry sectors, but its effects rely heavily on supplier digital preparedness, and capacity to integrate data, which differs among different regional units of Wärtsilä. According to Matopoulos et al. (2015) and Benjaafar et al. (2012), this view has support, as they also caution that SSCM succeeds only when organizations show capable operations, their business context harmonizes well, and their infrastructure adapts appropriately.

SSCM theory is extended theoretically by this research because it shows the life significance of strategic leadership and organizational culture which is occasionally left out in usual SSCM models. Successful implementation at Wärtsilä depends on past management commitment and how different teams coordinate their activities. The findings of the research extend the existing knowledge from Kim (2015), Pérez-Salazar et al. (2017) confirming leadership vision and knowledge sharing as fundamental principles towards implementing sustainability throughout the whole system of the organization.

The research explains how the theory can be efficient as a dynamic system with practice. Wärtsilä case shows that Supply Chain Sustainability is a dynamic trajectory that needs continuous improvement in place of adjustable changes and sustainable cooperative partnership. Real – world issues require flexible implementation of theoretical models rather than adherence to them as described. Through analysis of real world influences, organizations should develop their digital tools in partnership with the supplier relations and lifecycle models and sustainable policies with the supplier relations and lifecycles models and sustainable policies.

The Wärtsilä SSCM implementation is based on the main ideas of sustainable supply chain literature on lean-green synergy as well as digitalization and circular economy integration. The practical challenges to standard models are exhibited in the implementation of SSCM due to the way things do actually work as well as why adaptability plays a crucial role. Sustainable supply chain management paradigms require comprehensive integration of strategic leadership as well as readiness and external alignment systems to effectively support the transformational dimension of sustainability within the large industrial setup. The practices at Wärtsilä, evidence an ideal opportunity showing practical extension of as well as theoretical validation.

Table 3: Mapping Theoretical SSCM Models to Wärtsilä's Implementation Practices:

Theoretical Framework	Wärtsilä’s Real-World Implementation
Lean-Green Integration (Kosasih et al., 2023; Marchi & Zanoni, 2017)	Three energy-saving solution methods include predictive analytics along with production systems based on modules combined with real-time digital dashboards.
Circular Economy (CE) (Gunther et al., 2015; Yang et al., 2022)	The system uses reverse logistics together with modular component reuse and lifecycle management of engines and hybrid systems to reduce its need for virgin resources.
Digitalized SSCM / Supply Chain 4.0 (Cañas et al., 2020; Zhang et al., 2024; Chen et al., 2024)	Better enterprise management depends on implementing IoT sensors with AI forecasting capabilities together with digital twins and cloud-based supplier systems and centralized emissions information platforms.
TBL is an approach, introduced by Villena & Gioia (2020) and Linton et al. (2007)	Organizations use ESG-based procurement in addition to social audits and stakeholder training and GRI/DJSI/ISO reporting standards for sustainable procurement and profit maximization.
The use of knowledge (Allaoui et al., 2019; Pérez-Salazar et al., 2017)	Processes of cross-functional sustainability governance, supplier training programs, data transparency approaches, and cooperative innovation projects.
Implementation Barriers in SSCM (Matopoulos et al., 2015; Kim, 2015; Mickwitz et al., 2008)	Three critical barriers stand in the way of managing the digital transformation of business activities: Supplier alignment

	problems, outdated technology platforms and high costs of digital transformation initiatives, deficits in digital capabilities combined with differences in regulatory requirements across markets.

5. Conclusion and Recommendations

The downstream investigation reviewed the study and one embedded case study to find out how the Wärtsilä delivers sustainability integration into its global supply chain network. Wärtsilä undertakes several strategic initiatives that employ digitalization as well as circular economy practices and lean-green operations and supplier co-operations to attain its sustainability in supply chain management objectives. The company attains superior environmental results, improvements in operations, and increased interactions with stakeholders through its current initiatives. The study illustrates that Wärtsilä needs to continue to manage the constraints of infrastructure, data scattering and supplier preparation problems and regulatory ambiguity if it is to move forward effectively.

Whether companies will be able to attain SSCM excellence depends on strategic leadership and both technical frameworks and cross-functional coordination and continuous learning as the case of Wärtsilä shows success. Officials in government will have to standardize global ESG standards and companies will have to allocate money to come up with scalable digital platforms and supplier development capability. As the sustainability patterns continue to change permanently and fully engage stakeholders, sustainable business excellence is dependent on permanent adjustments. Further research should examine the SSCM in different organizations when examining longer periods and with the accountability of the role that social sustainability plays in SSCM practices.

5.1 Summary of Key Findings

The study finds that Wärtsilä's approach to sustainable supply chain management (SSCM) shows how digital improvements, reusing resources and joining forces with stakeholders can favor the environment and Wärtsilä's operations at the same time, though many major challenges must be overcome. First, thanks to AI and IoT, the movement to monitoring emitted gases in real time helps address the big majority of emissions from manufacturing. Nonetheless, the usefulness of these technologies is reduced because nearly 90% of industrial supply chains don't have real-time monitoring that works across the systems, leading to inconsistent reports and missing details. Second, circus fitting ideas at Wärtsilä which involve modular design, bring back goods and lifecycle services, have led to less waste and longer usefulness for their products, but major differences in skill and finances still separate the company from many of its suppliers when it comes to adoptions. Still, although senior leaders and various teams have made sustainability a key part of planning, challenges in the workforce and from suppliers prevent it from being fully effective.

These results suggest that Wärtsilä's SSCM results depend on three related factors: (1) linking digital platforms from individual use to including suppliers, (2) teaming up to advance circular approaches and ensure all staff are trained in ESG and (3) combining upper-level objectives and worker engagement to overcome cultural obstacles. It was also found that in some cases, businesses that hope to see fast results from investments keep delaying green investments and that following different regulations in different nations can slow compliance globally.

It is clear from Wärtsilä's example that being sustainable and efficient boosts each other—when using predictive maintenance, emissions can drop and devices remain online longer and when systems are designed in modules, both production and waste can fall. However, it is clear that the gap between how companies work and what their suppliers face means that top firms need help to reach SSCM excellence on their own. The priority for future strategies should be on increasing the size of partnerships, championing standard rules for reports and managing AI fairly. They demonstrate that while digital and circular strategies help, they must be used together with systemic collaboration—which is very important for energy-intensive industries aiming for net-zero.

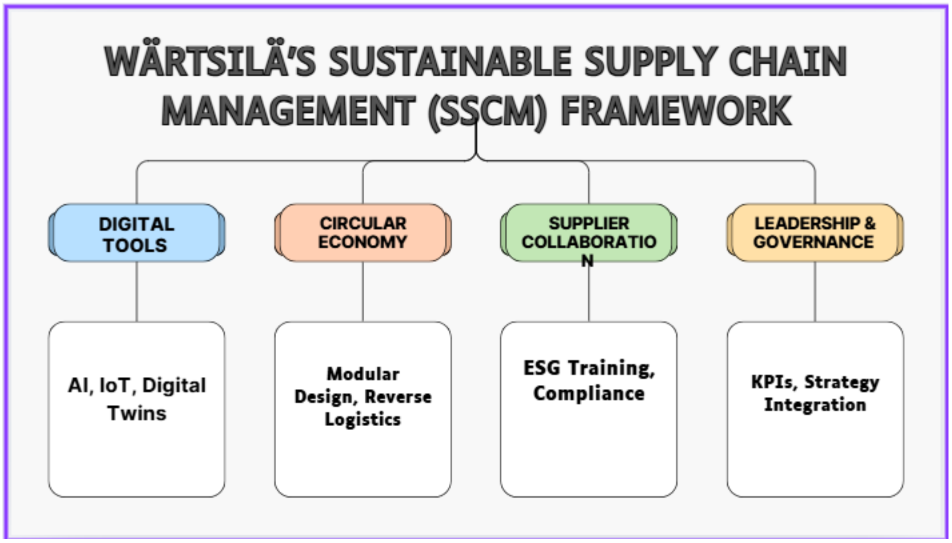


Figure 7: Wärtsilä's Sustainable Supply Chain Management (SSCM) Framework

5.2 Practical Implications for Industry Stakeholders

The results of Wärtsilä's initiative guide companies, key personnel and supply chain workers in energy-reliant fields. A main focus in these results lies in how digital solutions contribute to twin progress by backing sustainability and modernizing operations with IoT, AI and blockchain. As a result, businesses must implement digital platforms that use real-time monitoring of emissions from critical processes such as machining (accounting for 65% of Wärtsilä's total emissions) and link them to predictive upkeep and improved logistics. The study further highlights a big issue: successful use of data within Wärtsilä does not carry over outside, because widespread connection and sharing among industrial supply chains remains difficult. One way for companies to address this is by helping suppliers join their business ecosystems, perhaps by investing in new IoT equipment for them or setting up a public data channel for emissions information. This style of monitoring fills the gaps, allowing the adoption of the newest Industry 4.0 standards that highlight how teamwork and transparency are vital for achieving intense decarbonization.

The events at Wärtsilä have convinced policymakers that harmonizing regulations should be a priority. That inconsistency in ESG reporting among regions demonstrates that confusion in policies drives up compliance costs and slows down advancement. To make change more effective, governments should support a single carbon tracking system (such as those set by ISO 14001 or the Global Reporting Initiative) and reward SMEs that adopt green technology by providing them with tax credit incentives. As seen from Wärtsilä's gap of 78-12% in the circular economy with its suppliers, high-performing companies cannot expect this shift to happen fully on their own. Providing support such as training and subsidies for modular design and remanufacturing equipment would help smaller suppliers answer to circular economy needs. Moreover, partnerships between the public and private sectors could launch digital trade corridors—based on blockchain—to help exchanges of ESG data across countries and lessen the work needed for international supply chains.

Strong supplier collaboration is now recognized as being very important. It is clear from Wärtsilä's approach that simply managing suppliers is not enough in SSCM; forming lasting partnerships is more appropriate. It is advisable for businesses to form innovation laboratories with their main suppliers to plan ways to create reusable elements and efficient reverse supply systems, so that circular solutions remain both economical and workable for all involved. In addition, industries should acknowledge that digital SSCM involves questions about avoiding bias in choice of suppliers and keeping end-users' data private. Risks can be kept in check and trust can be built if the company uses trusted AI strategies and builds governance together with their suppliers.

Operational teams will appreciate that lean-green integration from Wärtsilä allows for reducing both waste and costs at the same time. This result contradicts the idea that sustainability means settling for efficiency. For this reason, companies should blend design for recyclability into their buying options and test different production methods in digital twins to reduce their impacts. But the study warns that cultural barriers are still tough to tackle. Therefore, companies should connect bonus incentives to lowering emissions and support workers with micro-sessions and helpful technology on circular work.

In the end, Wärtsilä argues for incorporating environmental aims into all management decisions, rather than treating them independently. Businesses should reassess their goals to value making a profit and protecting the planet together, politicians must offer new laws that incentivize joint efforts and suppliers should get actively involved in building their expertise. The future depends on treating sustainability as an ongoing process, watching as technology, partnerships and governance work together to solve supply chain problems. If stakeholders pay attention to these implications, they can turn what Wärtsilä has learned into strategies fit for a zero-emission world.

5.3 Strategic Recommendations for Policymakers and Businesses

Prioritizing systems that work together and track emissions real-time across every part can help speed up improving the supply chain and handle the key 90% visibility issue industry chains experience. Enhancing suppliers' abilities by investing in programs is key to bridging the 78-12% gap in using circular economy, mainly by offering co-funded instruction in simple design and opposite logistics activities. Having a global set of ESG rules (like using GRI and ISO 14001) would reduce the difficulties of following different standards and encouraging small and medium businesses with tax breaks on green materials would help them adopt those technologies. Companies should develop collaborative sustainability structures, place circular KPIs in dashboard reports and ensure executive pay depends on their emission goals. Only with the inclusion of ethical AI principles can there be transparent algorithms for supplier evaluation which supports the use of technology while maintaining equality. Applying them gives industries a way to implement SSCM in a way that can scale.

5.3.1 Alignment of ESG standards and operational implication

SSCM implementation at Wärtsilä is ridden with difficulties as different jurisdictions have their environmental social and governance standards. Different countries have disparate regulatory rules that lead to several compliance costs with a resultant decrease in reporting accuracy due to interference in their uniform sustainability operations in global supply chains. The public policymakers are required to enforce cared for uniform ESG reporting and performance standards that are benchmarked internationally, such as the ISO 14001 and the Global Reporting Initiative (GRI) and the Dow Jones Sustainability Index (DJSI).

The gains of regulatory conformity are enjoyed by operational efficiency. Firms are operationally more efficient once they standardize environmental data metrics along with reporting disclosure use cases because this will allow them to automate audit systems and reporting flows and reduce administrative overheads for regulatory incongruities. This is supported by experimental evidence of Matopoulos et al. (2015) that the common sustainability regulations across different national borders promote uniform supply chain operational outcomes, particularly, international logistics systems. The standardized regulatory practices empower Wärtsilä and other firms to mitigate the risks of the supply chain by improving regional data comparison that produces exact benchmarking of an operating site.

5.3.2 Incentivizing Green Investment and Digital Transformation

Economic structures have to be incorporated in the government's policies in order to bring the need to invest in sustainable technologies among the corporations while regulatory alignment takes effect. Tax credits under accelerated depreciation allowances and accessed subsidized funding programs for digital sustainability platforms provide entry opportunities to small and medium enterprises (SMEs) in the global supply chains. Wärtsilä is actively using AI-powered Internet of Things set ups as well as digital twins for the tracking of emissions and predictive service maintenance, which requires high initial capital expenditure and cross organizational efforts. The supplier firms that exist within the developing economies are likely to show slow capability moves if the incentives for them are not systematically assigned.

The case is that the sustainability-based digital infrastructure needs co-investment structures which include lead firms, the governments and fi financial institutions as well as suppliers who lacked the necessary resources (Muthuswamy & Ali, 2023; Bag et al, 2020). IoT-capable infrastructure funding initiatives are a relief to SMEs since digital access is secured, transparent supply chain is achieved. The incentives are those that build up innovative ecosystems that enhance green methods and flexible logistics systems that embrace the principles of SSCM 4.0.

5.3.3 Establishing Cross-Functional Sustainability Leadership

Organizations must develop strong leadership units that come embedded with sustainability management system that includes both the strategic and the operational domains. Leadership was very active at an upper level, by Wärtsilä, indicating that the success of SSCM cannot be achieved without obliged commitment of leadership. The concept of strategic leadership focuses on executive commitment and convergence of operation objectives with budget determination otherwise but separate from integration of organizational culture that disseminates the sustainability thinking among workforce sections.

Successful implementation of sustainability initiatives through strategic leadership relies on building the links between the ESG goals and the related measures of indicators, as well as between the financial indexes and tactical planning processes. Wärtsilä installs operational sustainability dashboards so that the goals on the environment can be converted into performance targets that reflect certain departments that can be tracked, and the departments can be held accountable for their goals. The corporate integration of sustainability standards is an essential component for SSCM institutionalization as the studies carried out by Pérez-Salazar et al. (2017) and Kim (2015) suggest. Cultural embedding allows all levels of employees in the organization to understand these strategies deeply, and therefore they always remain consistent with their behaviors and company values even when we see change in managerial positions or requirements of the regulatory kind.

Companies should have formal sustainability councils comprising of representatives of various departments and levels of the organizations to support these two dimensions. The sustainability councils carry out integrated multidivisional sustainability projects and monitor ESG KPI action but also ensure communication among various tiers of business and the top-level management. The governing bodies at Wärtsilä enable an interchange among engineering and procurement teams as well as logistics and lifecycle service people, via joint programs to be used on a continuous improvement basis.

5.3.4 Promoting Supplier Enablement and Alignment

Sustainability responsibilities are necessary for business leaders to reach beyond the walls of the organization to utilize up-stream suppliers, especially in resource poor settings. More scalable alignment of suppliers is presented at Wärtsilä with its proactive supplier education programs (ESG training, modular design standards, reverse logistics). Whenever therefore many SMEs do not have the necessary digital infrastructure and managerial skills to align with complex expectations of sustainability.

Supplier Enablement, hence, should not only be an area of compliance enforcement for firms, but, within supplier enablement, training, shared digital platforms, and technical assistance would be required. Allaoui et al. (2019) put forth the long-run value of inclusion of suppliers to enhance transparency and risk management and innovation potential in supply networks. Such efforts need to be complemented with policy frameworks that provide financial assistance for advocate programs for supplier development especially in emerging economies with the most capability gaps.

Then again, different arrangements regarding suppliers' data-sharing and digital integration should be taken carefully enough Intellectual property rights, cybersecurity issues and questions of data ownership will stop open platforms from being widely incorporated. Therefore, though few are those who could see the promise in the collaborative data ecosystem in contributing to visibility and traceability, they should still be embedded in the robust governance structures sensitive to confidentiality and safeguard for proprietary knowledge.

5.3.5 Enabling lifecycle thinking and integration of circular economy

Finally, firms need to evolve from a linear production mode to a lifecycle-oriented approach, which is harmonized with those of the circular economy (CE). Wärtsilä's combining of a modular product design and the reverse logistics is an example of how lifecycle thinking can have environmental and cost benefits. With the designing of products for disassembly and reuse, the company avoids waste and cuts down the lifecycle emission without shortening the asset durability. Such an approach is consistent with the findings of Kosasih et al. (2023) on the synergistic benefits to the operational performance and carbon footprint reduction that lean-green integration brings about.

The application of eco-design rules, schemes for taking back products and aid for remanufacturing will encourage industries to use more CE goods. Furthermore, strategic fit between product-service systems (PSS) and digital maintenance analytics, as evident with Wärtsilä's lifecycle services, can introduce new revenue models where sustainability will take precedence over throughput.

5.4 Contributions to SSCM Theory and Practice

The studies improve the theoretical and practical knowledge of Sustainable Supply Chain Management (SSCM) and address the technical and energy-based industries such as the maritime and power systems. The Wärtsilä framework demonstrates how companies can combine digitalization with circular economy thinking and the integrated leadership approach to produce a sustainable performance measure. As for the currently applied SSCM models, their validation is achieved via the research results that, on one hand, expand the modern models while, on the other, reveal the areas of the theory that require additional development (supplementing).

5.4.1 Empirical evidence that supports digital-led SSCM models.

Wärtsilä does not only promote scientific research but supports the integration of digital supply chain management theory with Industry 4.0 and Supply Chain 4.0 framework. Wärtsilä's digital solutions outline clearly ways in which environmental goals are transformed into operational decisions that AI, IoT and digital twins implement in real-time. Integration of predictive maintenance systems with systems for tracking of emissions and approach to lifecycle assessment (LCA) is beneficial for Wärtsilä to realize operation efficiency improvements of precise environmental performance monitoring.

Two research papers by Bag et al. (2020) and Muthuswamy & Ali (2023) confirm that, digital platforms are very critical enablers of SSCM nowadays. Organizations daily use intelligent digital platforms to integrate sustainability metrics into business operation, thus creating systematic visibility that interweaves environmental needs along with responsiveness of the supply chain and cost management.

5.4.2 Operationalizing Circular Economy through Lifecycle Design

The studies prove the CE theoretical ideas because they demonstrate the directions of how to apply circular principles in the frames of designing a product and service. Wärtsilä implements the modular design and the reverse logistics and lifecycle-oriented service that achieve conceptual framework provided by Yang et al. (2022) and Gunther et al. (2015). In its engineering activity and supply chain management, Wärtsilä applies the CE principles by reengineering the products such that they can harness the capability of product reuse and upgradeability as well as the capacity to utilize products disassembly process without serious production of wastes and damages on the environment.

Such a practical application supports the fact that the implementation of CE indeed does work in the capital-intensive setting for the purpose of debunking the old notion according to which only in the consumer areas or fast-moving spheres of activity the models of a circle work in. Upon the merging of the lifecycle design and the digital analytics organizations, the former can identify the adoption of the CE strategies to their system of performance on a mega scale.

5.4.3 Integrating Leadership and Culture into SSCM Frameworks

The key contribution of this research lays the separation between the interconnection between the strategic leadership and the organizational culture which operates separately but the interconnection that they share to uphold SSCM. Numerous SSCM models are aware of such factors but in turn, do not incorporate them into their SSOCM design’s framework. It is revealed from the Wärtsilä case that leadership and culture work as both fundamental elements that form the cornerstone blocks of SSCMs.

Wärtsilä practices strategic leadership in an organized way of governance structure and strategic performance dashboards and key performance indicators which connect corporate sustainability goals with operation deployment. Institutionalization of strategic leadership generates needed long view in sustainability programs (Pérez-Salazar et al, 2017). In this research, it is shown how cultural embedding propagates sustainability standards among the departments and the operational level in order to create autonomous behavioral uniformity independent of the expectations of managers.

It is the combination of these two dimensions, i.e., leadership for direction and culture for continuity that brings the initial impression of a more complete SSCM framework into play where values and systems co-evolve. The position expressed by Kim (2015) on the limited representation of soft factors in change processes gets consideration from the model that is proposed.

5.4.4 Addressing Gaps in Existing SSCM Theory

This research study finds theoretical flaws that are present in the mainstream SSCM frameworks. The Major structural priorities in Existing Supply Chain Management/frameworks are such features as logistics optimization and compliance systems and cost efficiency, whereas behavioral aspects of data usage, along with decision making transparency and supplier's inclusion are still neglected areas. Wärtsilä demonstrates that SSCM, while focused on efficiency, also encourages companies to make ethical statements to their suppliers.

SSCM literature discusses the importance of partnerships in detail, but this research provides specific knowledge on how supplier development is a strategic activity as opposed to passive needs. Wärtsilä demonstrates, with their small and medium sized supplier training together with ESG capability enhancement, that the initiatives of an organization towards supplier integration will ensure sustainable SSCM across global networks. In agreement with Villena & Gioia's (2020) argument, the study expands supply chain monitoring from transactional monitoring to co-developmental activities and elevated capability.

The present study provides significant contribution to the SSCM theory and practice by revealing the interconnected power of technological innovations with methods of the circular economy and integration of leadership-culture to deliver scalable sustainability performance. Wärtsilä's holistic approach verifies such modern SSCM concepts but advances the theory-based progress by analyzing the novel fields of research on cultural adaptation, ethic digital approaches and leadership bonds. By demonstrating a real-life operational model, Wärtsilä shows how energy-intensive organizations can succeed in implementing sustainable initiatives and how the future SSCM frameworks need to address a behavioral, technological, and institutional complexity as intertwined performance elements.

5.5 Limitations of the Study

Although the research gives helpful insights on sustainable supply chain integration, it only covers some parts of the supply chain. Findings based on Wärtsilä are not directly relevant to industries or firms outside of Wärtsilä. Section 3.6.7 notes that the single-case study and just two interviewed participants means further research with many cases will support these ideas. Relying on a senior manager to provide priorities helped a lot, but some daily concerns experienced by both suppliers and key staff were not taken into account. Since the design only provides a momentary snapshot, it is not possible to look at how the company could reach its 2030 goals further down the line. While the report agreed that data tools are crucial, it didn't go into great detail about the risks they involve. The paper also did not pay enough attention to the challenges caused by varying regional policies in supply chains. Thanks to the study, there are parts of this area that future projects should spend more time understanding.

5.5.1 Case-Specific Scope and Sectoral Transferability

One of the key defects is based on the chosen unit for analysis – Wärtsilä as the only company unit analyzed. The findings drawn from Wärtsilä are releases of a globally active technologically advanced organization, with its energies and marines, but the findings are limited in external applicability as operating sectors due to their industrial adaptability. Single-case study is rich in understanding but has no external validity unless researchers conduct cross-case validations (Yin, 2018).

This unique mixture of resources and processes through which Wärtsilä is able to carry out the SSCM functions may not be observed in resource-limited businesses or small- and medium-sized enterprises. The application of the research findings in this study must be done with precaution in different industries because of the need for more comparative research.

5.5.2 Data Source Limitations and Stakeholder Perspectives.

One of the main weaknesses of the present research is the interview with a senior manager together with a number of internal viewpoints. The in-depth interview with a top manager of Wärtsilä provided exhaustive information about their SSCM platforms and strategic orientation yet left out whole insight about the delivery of sustainability practice in the entire organization structure and to relationship stakeholders.

The article lacks important perspectives that should include the middle-level managers, factory floor staff and the logistics people and most importantly the suppliers' perspectives. Due to this information gap, the researcher encounters challenges in understanding the level of sustainability culture embedding as well as strategic-practical alignment. The perspectives of the factory-floor workers and logistics personnel and suppliers should be included in future studies to get a better understanding of sustainability-oriented SCM practices (Matopoulos et al., 2015).

5.5.3 Temporal Limitations and Lack of Longitudinal Tracking

As it only suggests a static view of SSCM implementation at some point of time this research reports limited knowledge concerning changes in the environment factor and development of sustainability strategy towards it. The evaluation analysis poses a challenge because the evolutionary model that Wärtsilä is using in response to change digital innovations, and transforming ESG policies, cannot be observed in time.

In-depth research during SSCM system development in an organization allows researchers to analyze the ways in which operational maturity develops with feedback processes and how disturbances in the environment influence sustainability in the supply chain. According to Bag et al. (2020), the effectiveness of a SSCM framework requires it to learn and grow over time after it is designed.

5.5.4 Ethical and Technical Concerns in Digital Systems

This piece of research compares AI, IoT, and digital twins for facilitating SSCM at Wärtsilä, but this research addresses the ethical and data governance issues at a basic level. The investigation is not enough to do a thorough examination of the threats regarding algorithmic biases, confusion related to the automated decision-making, and data privacy complications in the context of supplier monitoring platforms.

These relevant numbers are then vital because Wärtsilä increasingly relies on artificial intelligence systems to monitor the feedback on emissions and conduct predictive maintenance analysis and evaluation of suppliers. Muthuswamy and Ali (2023) would point out that digital SSCM tools will have unintended sustainability discrimination and supplier discrimination when they are not governed by data governance frameworks that offer accountability and explainable AI systems and audit trails.

The barrier in these digital supplier systems and enterprise core systems is an impediment to the supply network visibility, causing disrupted supplier network communication. For this study, technical constraints that hamper the scalability of SSCM, even though they are not given sufficient attention, should be examined.

5.5.5 Regulatory Diversity across Global Operations

The research does not present complete information regarding how regulatory differences of a Wärtsilä's world-wide locations bear influence on the implementation of their SSCM program. Various standards and requirements concerning the environment, labor conditions and data as well as the reporting responsibilities make significant disparities between the EU territories and the Southeast Asian and South American regions. The diversity of the regulatory systems in the world restricts the possibility to achieve universal compliance, provoking issues, and problems that urge using additional resources and stable execution of widespread SSCM practices.

The paper does not go into detail on how Wärtsilä and other firms deal with differences in regulations when they are out to implement their global sustainability agenda. As demonstrated by the study of Linton et al (2007), various policy environments stimulate companies to develop a hybrid compliance strategy, which undermines sustainability accomplishments and any normalized international efforts.

In turn, this research confirms that implementing SSCM presupposes taking into account various factors in particular business situations. Research needs further research in determining the generalization of Wärtsilä's excellent integration strategy within different business fields and global domains and periods. The research needs further research on ethical and technological along with regulatory aspect so as to maintain the inclusivity and flexibility of SSCM frameworks in different supply chains of a dynamic global economy. Future studies should base such research on these limitations of making comprehensive studies that involve various stakeholders within a prolonged period of time for SSCM examination.

5.6 Future Research Directions

The research offers new possibilities to improve the digitalization knowledge on the Sustainable Supply Chain Management (SSCM) in regard to energy-intensive industries. There is research on Sustainable Supply Chain Management (SSCM) that needs further attention since it is evolving as the nature based on the changing technology innovation and policy development affects it. The establishment of clarity will be possible due to the connection of five thematic blocks. Comparative research for far-reaching development timelines and data governance blueprints for electronics for the purpose of supplier integration followed by policy formation abilities that are primal components.

5.6.1 Comparative and cross-sectoral analysis of SSCM models

The major limitation in this research was owed to the fact that it had totally depended on the Wärtsilä business. Future studies have to carry out several case investigations in order to demonstrate how the strategies for supply chain sustainability will be altered depending on the characteristics of the industry and the size of the company in relation to geographical location. Research in this field could find both general approaches in industry and the barriers addressed to the sphere. Functioning of digital platform in sustainable supply chain management varies greatly if industries using heavy capital equipment (marine, energy) are compared to those dealing with fast moving consumer goods and agricultural products. Such designs make it possible for researchers to know how firms lacking in advanced digital abilities address the sustainability goals' implementations to find out the critical factors facilitating or impeding SSCM implementation effectiveness.

Other judgements between national boundaries would describe how different regulatory components, market circumstances, as well as cultural aspects influence the design approach of SSCM. Research studies ought to investigate the way companies subjected to tight policies by the EU when it comes to environment practice their chain of supply contrastively from the organizations situated in areas with lenient regulations in enhancing globally acceptable frameworks.

5.6.2 Longitudinal Tracking of SSCM Implementation and Adaptation

The current state of Wärtsilä's SSCM framework is what can be seen at one moment in time of this study. The SSCM system changes with time as a result of advancement in technology as well as evolution of regulation and learning experience in an organization. Sustainability plan development and modification as well as their eventual breakdown as time passes by should be studied in future studies through prolonged research methods. Researchers need to investigate the impact of change in the ESGL and digital transformations and economic recessions in supply chain organizations and sustainability performance. Follow-up studies using longitudinal approach should view how business cycle lessons influence strategic changes in subsequent times through systems of institutionalization of learned information for the long-term improvements in performance of organizations. From the study conducted by Bag et al. (2020), dynamic capacities work as crucial aspects towards sustaining SSCM under changing market settings.

5.6.3 Digital Ethics, Data Governance, and Algorithmic Accountability

With firms adopting AI, IoT devices and digital twins, the main responsibility for researchers should be to study concerns about ethics and governance. The study suggested a rather narrow environment on the issue of algorithmic bias risks along with supplier monitoring and hidden decision-making processes that are key elements of the digital SSCM systems credibility and inclusiveness.

Research should look at how established companies create governance structure framework to specifically build transparent systems using explainable and accountable algorithms used in ESG evaluation and decision making. The ownership rights of data need to be studied well especially in the supplier networks that span over locations with diverse privacy rules. According to Muthuswamy and Ali (2023), non-existence of ethical standards in digital supply systems design leads to possible trust breaks which are the most dangerous to small suppliers.

The validity and equality of sustainability reporting as well as risk evaluation should be assessed considering the existing gap in the quality of data between lead firms and suppliers and digital forward and backward regions.

5.6.4 Supplier Capability Development and Equity in SSCM

According to the study findings, Wärtsilä provides training to its suppliers with the aim of enabling them to adopt sustainable standards. Despite the fact that an understanding of supplier development constitutes an underexplored field of SSCM research, scholars need to have better understanding of training approaches accompanied by financial and technical capabilities seasoning relocated to small suppliers, operating in global supply networks.

Future research will need to ascertain the effect of various supplier enablement strategies on their capability to roll out SSCM programs in such regions as reporting limited digital engagements and low ESG consciousness. The association between political incentives promising green investment subsidies with corporate strategic investments must be analyzed for ascertaining how suppliers can be ready for the SSCM. Allaoui et al. (2019) write that the collaboration of suppliers through such an easy way leads to the best performance of the suppliers and the extension of the business performance.

Research needs to be conducted to examine the correlation between the incorporation of suppliers on the supply chain resilience as well as the examination of transparency enhancement and innovation development and the right integration of marginalized suppliers by digital ecosystem that preserves equality.

5.6.5 Interactions between Policy Systems and Corporate SSCM Adoption

Study of the way policy systems influence SSCM corporate strategies should be the target of research. This investigation commented on the problems of regulatory inconsistency but did not appraise the way such an inconsistency affects the decision-making process of the corporation. Scholarly works should appraise laws, taxation incentives and pricing systems and standard of public purchasing in nations or provinces that speed up or impede SSCM adoption.

The impact of there being various environmental regulations instituted on different international, national and industry specific levels warrants attention in order for one to appreciate how these factors have influenced supply chain strategic choices. Linton et al. (2007) point out that there is need for regulatory coherence for companies to sustain continuous practices of sustainability across the world.

There are chances here to analyze the impact of the businesses in the process of the policy formulation through the political involvement and the public-private undertakings and self-initiated standard-setting in the context of the SSCM advance.

Figure 8: Future Research Direction in Sustainable Supply Chain Management (SSCM)

In brief, the report makes clear that sustainability depends on digital tools, the circular economy model and effective teamwork with stakeholders. The method of confirmation/rejection proposed in the article can be tested on the example of the Wärtsilä Corporation. The research model is applicable to real conditions in both the private and academic fields of research. The logistics of supply chains are becoming more complex, and if it is necessary to make company activities more environmentally friendly, it must be remembered that the requirements for behavior are appropriate: innovation, ethics, and a willingness to develop cooperation.

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Appendix:

Interview Questions

1. How does Wärtsilä ensure that sustainability is a key part of its supply chain processes?
2. Has Wärtsilä faced obstacles while trying to make logistics more sustainable?
3. How exactly is AI and IoT helping to make supply chain management more sustainable?
4. How is it possible for Wärtsilä to focus on the environment, save costs, and perform at the right level?
5. What sustainability frameworks or standards do they apply in their business?
6. Is sustainability an element that is factored in when evaluating and dealing with suppliers?
7. What role do leaders have in moving an organization toward sustainability?
8. How do the organization’s cultural values fit with its desire for sustainability?
9. How does Wärtsilá check the effects of its operations on the environment in its supply chain?
10. What do you think will have the most positive influence on sustainability in the supply chain of the future?