CHALMERS
UNIVERSITY OF TECHNOLOGY

Environmentally sustainable and resilient inbound logistics flows

Master's thesis in Supply Chain Management

NATHALIE KUCHARSKI
SOFIA SJULIN

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

Environmentally sustainable and resilient inbound logistics flows

NATHALIE KUCHARSKI
SOFIA SJULIN

Department of Technology Management and Economics
Division of Supply & Operations Management
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025

Environmentally sustainable and resilient inbound logistics flows
NATHALIE KUCHARSKI
SOFIA SJULIN

Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31-772 1000

Gothenburg, Sweden 2025

Environmentally sustainable and resilient inbound logistics flows

NATHALIE KUCHARSKI
SOFIA SJULIN

Department of Technology Management and Economics
Chalmers University of Technology

Abstract

The European Union has set a target to be climate neutral with net zero greenhouse gas emissions by 2050. This target has accelerated the demand for electric vehicles, with a corresponding increase for battery cells. Today, electric vehicle producers in Europe are relying on Asian battery suppliers, which impacts costs, resilience, and environmental sustainability. The European Union is making significant investments to expand their own battery production capacity. This study investigates how inbound logistics design can support both environmental sustainability and resilience, focusing on material supply to a European battery cell production facility.

A structured risk identification and assessment method was used to determine risks for three different transportation modes: road, rail, and sea. The analysis shows that long-sea transportation presents the highest risk values, followed by rail. The mode-specific risks were then translated into flow-specific risks, where three European flows and one Asian flow were analyzed. The Asian flow presents the highest risks. In addition, European sourcing reduces transportation costs on average with 43%. However, there are exceptions where certain materials result in comparable or even slightly higher costs compared to Asian suppliers. Overall, when selecting an European supplier, the logistics costs are lower. However, in the context of battery cell production, there is a high reliance on Asian suppliers, making it difficult to create a supply chain based only on Europe. A Delphi study was conducted to investigate the views of transportation providers on the future of environmentally sustainable transportation. This study included participants from European, Asian, and global transportation providers. The findings show that achieving zero emission transportation is a complex task that requires collaboration of stakeholders. Barriers such as infrastructure limitations, fuel availability, customer demand, and the lack of a strong regulatory framework hinder widespread adoption. In addition, many differences were identified in the current state of transportation providers within Europe and between Europe and Asia. Furthermore, discussions regarding which transportation solutions will be part of 2050 are discussed, and a clear split in opinions emerged regarding the role of fossil fuels in 2050.

Keywords: environmentally sustainable logistics, resilient supply chains, risk management, decarbonization strategies

Acknowledgments

Writing this thesis has been both challenging and rewarding, and we will thank all those who supported us along the way.

We would like to begin by expressing our appreciation to our supervisor and examiner at Chalmers University of Technology, Ceren Altuntas Vural, for her invaluable feedback, encouragement, and guidance throughout the entire process. Her dedication and support were essential in enabling us to successfully complete this master's thesis.

We are also very grateful to our supervisors at the case company, for their invaluable guidance and for providing the necessary resources that made this thesis possible. In addition, their assistance in connecting us with key contacts for the interviews, along with their daily support and expert insights, was crucial to progress in this quality of our research.

We would also like to thank all the interviewees and stakeholders. Your time and contributions have been very valuable, as this thesis would not have been possible without your support.

Finally, we thank Clara Odqvist and Ellen Yllfors for their commitment, time, and valuable feedback when opposing our master thesis.

Nathalie Kucharski & Sofia Sjulin, Gothenburg, June 25, 2025

Contents

List of Figures

List of Tables

1
Introduction

The transportation sector is a major contributor to European Unions' (EUs) total greenhouse gas emissions, accounting for 25% of the total emissions [46]. The European Commission has established a goal of reducing transport-related greenhouse gas emissions by 90% by 2050 [46]. Electric vehicle (EV) is one of the key technologies used to decarbonize the transportation sector [62]. Therefore, the EV market is growing rapidly and is expected to continue to increase in the coming years [33]. With the increased demand for EVs there is a corresponding increase in the demand for batteries. The demand for the most widely used battery, the lithium-ion battery, increased by 65% between 2021 and 2022 [68]. This highlights the critical role batteries play in supporting the emission reduction goals.

Numerous European EV producers are highly dependent on battery makers in Asia. Today, Asia, particularly China, leads and dominates the global production and sales of electric trucks [68]. The EU is making significant investments in expanding their battery production capacity to reduce its reliance on Asian suppliers. Europe is predicted to account for approximately 25-30% of global battery cell production in the future [33].

An important aspect of establishing new battery production in Europe is the design of logistics processes. The process of acquiring and transporting raw materials, components, or products to the manufacturing plant are key activities in the first stage of logistics, known as inbound logistics operations [82]. Currently, Asia, particularly China, dominates both cell components and material processing used for battery cell production [41]. This heavy reliance on Asian suppliers not only impacts costs and supply chain resilience but also raises concerns about environmental sustainability, as long-distance transportation contributes significantly to greenhouse gas emissions. Green logistics aims to minimize the environmental externalities of logistics, including transportation, warehousing and inventories [34].

With growing uncertainties and increasing supply chain disruptions, resilience is a topic that has received more attention [114]. According to Kasilingam [80], traditional logistics management has primary focused on achieving high levels of customer service at the lowest possible total cost. However, the evolving global landscape characterized by geopolitical tensions, environmental risks, and instability in transportation requires a re-evaluation of the design of inbound logistics.

1.1 Purpose

The purpose of this research is to investigate the interplay between the design parameters of sustainable and resilient inbound logistics flows. The phenomenon will be investigated within the context of a European battery cell production facility.

1.2 Research Questions

The purpose is addressed through two research questions:

1. How do transportation risks and costs impact the inbound logistics design when sourcing EV battery components from Asian versus European suppliers?

2. What are the joint perspectives of European and Asian transportation providers on the potential of a fossil-free long-haul transportation solution for European supply chains?

1.3 Limitations

This research is time constrained due to restricted duration of this study and will therefore be limited to investigate specific parts of the supply chain. This research will only consider the inbound logistics. Therefore the outbound logistics will not be investigated. Additionally, this research is limited to a single case analysis with the focus on battery cell inbound materials.

2
Frame of Reference

This chapter presents the fundamental concepts that frame this research. The main concepts covered within the frame of reference are logistics management and inbound logistics, risk management in logistics, and environmentally sustainable logistics design. The frame of reference is structured into three main sections. The first section provides a comprehensive overview of inbound logistics design to build a foundational understanding of how logistics systems can be structured for improved efficiency. The second section focuses on risk management, outlining how various risks can be identified, categorized and managed using established theoretical strategies. The final section discusses environmentally sustainable logistics and explores different decarbonization strategies, highlighting the key drivers and challenges associated with the transformation towards fossil-free transportation.

2.1 Logistics Management & Inbound Logistics

Logistics management is one part of the supply chain that includes managing the transportation and storage of material from the supplier to the point of consumption [144]. Further, Kasilingam [80] provides another explanation of logistic management as the bridge between production, markets, and suppliers. Logistic management includes a variety of important functions, such as inventory control, storage, selection of the warehouse and plant location, facility layout, and transportation [80]. Providing high customer service at a low total cost is the primary objective of logistics management [80].

Logistics management can according to Kasilingam [80] be divided into three distinct parts: inbound logistics, intra-facility logistics, and outbound logistics. The relationship between these three parts is presented in Figure 1. Inbound logistics is defined as, "material handling, transportation, receipt, and warehousing of raw materials, parts, and supplies, and their distribution to manufacturing as they are needed in the production process", [101]. Inbound logistics include all activities needed to secure a stable and timely flow of materials to manufacturing, assembly or point of sale [144].

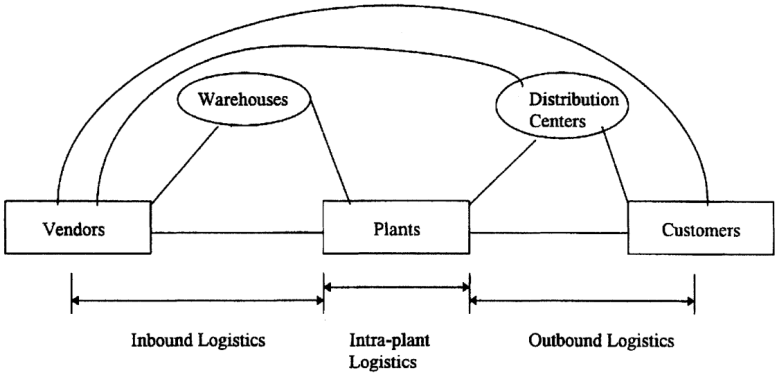

Figure 1: Functions within logistics supply chain [80]

2.1.1 Inbound Logistics Design

According to Kasilingam [80] purchasing, inventory control, facility location and layout, and transportation are the key logistics functions and activities. Furthermore, according to Zijm et al. [144], transportation costs, handling costs, inventory costs, and service level agreements are the main factors that affect the design of inbound logistics systems.

Zijm et al. [144] distinguish between two different delivery concepts: Direct delivery and consolidation hub. The concept of direct delivery is delivery directly from the supplier to the point of consumption. Eliminating the intermediate step, such as warehousing, shown in Figure 1. The widely used approaches in direct delivery are just-in-time (JIT) and just-in-sequence (JIS), which are strategies aiming to reduce inventory by having deliveries very close in time to the point of consumption. JIT and JIS thus require good organization, coordination, and a reliable inbound logistic. The concept of using a consolidation hub implies delivery to a storage facility, before further transportation to the manufacturing plant. Furthermore, Kasilingam [80] stated that transportation decisions are closely related to inventory. In order to maintain a low inventory effectively, faster transport modes must be used.

Other closely interrelated logistics concepts include facility location, mode of transportation, and carrier selection [80]. Although some locations offer lower acquisition costs, they often come with higher transportation costs. A common example is the production of goods in developing countries, where raw materials and labor are cheaper, but the products must then be shipped to consumers in developed countries. This scenario highlights a trade-off between cost-effective manufacturing and increased expenses related to transportation and storage [80]. To effectively evaluate such trade-offs, firms often use the concept of Total Cost of Ownership (TCO) [130]. TCO encompasses all costs related to a purchase from a specific supplier. TCO includes not only the purchase price, but also costs related to ordering, receiving, storing, transportation, quality issues, and warranties [130]. By adopting a TCO perspective, companies can make more informed logistics and sourcing decisions. Transportation represent the largest portion of total logistics costs, accounting for approximately 40% of overall logistics costs and 2.88% of total sales [80].

2.1.2 Inventory Strategies

Balancing the demand and supply of material flows is a highly complex task. Several uncertainties in the supply chain make this task difficult, particularly the uncertainty of quantity and time [78]. Jonsson and Mattson [78] mention that these uncertainties can be avoided and managed by buffer strategies, primarily through safety stocks and safety lead times. Safety stock refers to maintaining inventory levels above expected demand to manage variability. Similarly, safety lead time involves scheduling material deliveries earlier than required to mitigate delays. Both buffering mechanisms lead to larger inventory levels, commonly referred to as safety stocks. These safety stocks are used to ensure the continuous flow of material and operations. [78].

Sodhi and Tang [128] explain that the value of the product has an important impact on the positioning of capacity and inventory. An example demonstrates that lower value products can be imported from overseas, thereby aligning the strategy with the value of the product [128]. However, when high-value products were shipped oversea, it was seen to be more appropriate to use fast air transportation to delay related risks and limit inventory costs [128].

In addition, Sodhi and Tang [128] stated that there are three main factors that influence inventory decisions: *1. The value of the product, 2. Its rate of obsolescence, and 3. Uncertainty of demand or supply.* Additionally, Chung et al.[28] states that lead-time uncertainty, supply or demand uncertainty, forecast errors, lot sizing, replenishment frequency, commonality and resource utilization are factors affecting the size of the safety stock. Additionally, Chung et al. [28] noted that increasing buffer stocks is a common strategy used by companies to mitigate delivery uncertainty. When a company reduces its delivery uncertainty, they can enhance flexibility, reduction of buffer stocks, all resulting in cost savings. Lead time plays a crucial role in this context, as it has a significant impact on delivery uncertainty [28].

2.2 Supply Chain Risk Management

In recent years, the topic of logistics and supply chain risk management has gained increasing popularity, with numerous studies dedicated to providing critical reviews on the subject [27]. Supply chain risk management (SCRM) aims to strengthen the resilience of the supply chain [113]. Ho et al. [61] defines SCRM as, “an inter-organisational collaborative endeavor utilising quantitative and qualitative risk management methodologies to identify, evaluate, mitigate and monitor unexpected macro and micro level events or conditions, which might adversely impact any part of a supply chain”. The European Central Bank [9] stated that companies are increasingly shifting their focus towards building a resilient supply chain, prioritizing this over the traditional emphasis on cost reduction. SCRM includes the interaction

of two key concepts, supply chain management and risk management.

De Oliviera et al. [113] presents a generic SCRM model that provides a structured four-step approach to managing risks across the supply chain. The four core stages are: *1. Risk identification, 2. Risk evaluation, 3. Risk mitigation, and 4. Risk monitoring.* Identifying risks is an important step to increase the efficiency of the following risk management steps [113]. In addition, at this stage, supply chain risks are typically categorized to help clarify who should be responsible for managing them and how each category should be addressed. In addition, details on risk categorization are provided in section 2.2.1. In the second step, risk evaluation, the main objective is to establish a shared understanding of the relative importance and prioritization of identified risks [128]. Probability, frequency, and potential impact of the risk are common factors used to determine the importance of a risk. In this step risk assessment methods such as a Failure Mode Effect Analysis can be used [113]. The third step, risk mitigation, aims to adapt appropriate strategies for each risk category to decrease the impact of the risk incident [128]. Risk mitigation strategies will be further discussed in Section 2.2.4. The last step, risk monitoring, involves assessing how effectively the implemented risk mitigation strategies are performing. Also, making necessary adjustments or enhancements if they fail to achieve the intended supply chain outcomes [132].

2.2.1 Risk definition and risk categorization

Defining and categorizing risks is a critical component of SCRM. March and Shapira [90] present one of the first definitions of supply chain risks, describing them as, "variation in the distribution of possible supply chain outcomes, their likelihood, and their subjective values".

Categorizing risks is complex, as there is no standardized approach, and each organization has its own unique methods for categorizing risks based on the specific context [128]. Furthermore, supply chain risks are difficult to categorize, as a disruption in one area can have significant effects on other parts of the supply chain [128]. Therefore, this chapter provides an overview of various approaches to categorizing risks. Min et al. [99] categorized supply chain risks into three parts, demand-side, supply-side, and catastrophic. Yang et al. [143] categorized supply chain risks as supply disruptions, demand ruptures/surges, and transportation ruptures. Sodhi and Tang [128] explained that supply chain risks can also be categorized into two fundamental parts: normal risks and abnormal risks. Normal risks are routine and predictable risks that can frequently occur in everyday operations, such as transportation delays due to weather conditions [128]. Abnormal risks are rare and unpredictable, making them more difficult to plan for. Examples of abnormal risks are natural disasters and geopolitical risks [128]. Kaewfak et al. [79] further categorized risks within intermodal transportation into 5 parts: freight-damage risk, infrastructure risk, operational risk, security risk, and environmental risk.

2.2.2 Transportation Disruptions

Wilson [138] defined disruptions as, "an event that interrupts the material flows in the supply chain, resulting in an abrupt cessation of the movement of goods". Transportation disruptions occur when the flow of goods is temporarily stopped. Albertzeth et al. [6] defined transportation disruptions as, "a delay or unavailability of the transportation infrastructure which makes it impossible to move goods either inbound or outbound". Transportation disruption is just one aspect of the broader concept of supply chain disruptions, which also includes issues related to supply, demand, facilities, freight breaches, and communication failures [6]. In addition, transportation disruptions are the result of several sources such as: natural disasters, labor disputes, terrorist activities, and infrastructure failures [138]. Transportation disruptions usually lead to goods not arriving on time and therefore have an big affect on the service level [6]. Furthermore, according to Giunipero and Eltantawy [52], transportation disruptions can negatively impact the entire supply chain by leading to late deliveries and thus delay production.

2.2.3 Risks in Global Supply Chains

Global supply chains are part of a complex network, involving numerous actors working together [133]. This complexity leads to a higher exposure to various risks. An increase in complexity in the transportation of goods in global supply chains usually requires multimodal transportation, as relying on a single mode is inefficient for such long distances [67]. Li and Yang [115] explain that such multimodal transportation networks include numerous transportation links and transshipment nodes which may increase the risk of delays. Furthermore, the transhipment nodes involve handling processes that can lead to node transhipment delays [115].

When it comes to supply chain risk management within global supply chains it is especially important to investigate sea transportation as it accounts for over 80% of global trade [85] and is constrained by strategic passages [107]. Wen et al. [137] state that the Asia-Europe maritime logistics network is the world's busiest and most crucial shipping routes. With the network consisting of 54 seaports in total [137]. The Suez canal is one main corridor that connects Asia and Europe [107], with approximately 50 ships passing through each day [134]. This transportation corridor has historically been the source of major supply chain disruptions. The blockage in the Suez canal in March 2021 is one example, additional logistical challenges associated with this corridor is its limited capacity [120]. Thus, the Suez Canal has become a bottleneck, causing congestion and delays [120]. Liang et al. [85] identify additional risks such as heavy maritime traffic, frequent accidents, and extreme weather conditions, particularly typhoons in regions like Japan and South Korea. In addition, increasing geopolitical tensions and attacks on vessels have further heightened maritime risks.

Globalization of companies results in a more geographically extended supply chain with increased vulnerability and potential supply chain risks [99]. Min et al. [99] stated that offshoring from low-cost countries (LCCs) increases hidden costs such

as traffic congestion, communication difficulties, and a high rate of damage or loss during transit. Furthermore, Ferreira and Prokopets [50] reinforce this claim, stating that "the perceived cost savings from offshoring from LCCs such as China were not as large as we often thought when all costs were considered". Despite European companies offering lower political risks, higher logistics efficiency, and a business-friendly environment, these advantages are often overlooked in offshoring decisions [99]. Min et al.'s findings indicate that offshoring to high-income countries (HICs) becomes more attractive compared to LCCs when supply chain risks are included in the decision making process. The European Central Bank [9] observes a trend where companies are increasingly opting to source from within the EU. However, they note that this shift is likely to result in higher prices, although these are expected decrease slightly in the next five years.

European Central Bank [9] state that geopolitical risks is the main factor that influences the decision of companies to relocate production to the EU. Jawadi et al. [73] defines geopolitical risks as, "potential political, economic, military, and social hazards that arise from wars, terrorist actions, and tensions between states that disrupt the usual, peaceful conduct of international relations". Wan et al. [134] state that the shipping supply chain is exposed to many external risks, such as terrorist attacks, extreme weather, natural disasters, exchange rate fluctuations, political risks, and accidents.

2.2.4 Risk mitigating strategies

Resilience is the ability of a company to withstand and recover from challenges [114]. The goal of a supply chain design is usually to reach resilience [6]. Ho et al. [61] explained that risk mitigating strategies are used to minimize the probability of risks accruing and reduce their negative impact.

Sodhi et al. [128] distinguished between two key terms related to supply chain risks: prevention and response. Prevention involves proactive measures taken before a risk event occurs, while response refers to the actions implemented after the event to mitigate its impact. In correlation with this Yang et al. [143] states two different supply chain risk mitigation strategies: proactive and reactive. This research is limited to prevention efforts and proactive strategies. According to Sodhi [128] increasing inventory and building a redundant supply base are the two primary proactive strategies.

Enhancing the resilience of a supply chain involves strengthening its structure through redundancy, capacity expansion, and strategic inventory management to mitigate disruptions and ensure stability [143]. However, these types of strategies have been shown to be costly. Holding inventory that may become obsolete for rare disruption events, that may not occur, is not efficient. [128]. Despite this inventory being necessary, however, different aspects need to be taken into consideration.

2.3 Environmentally Sustainable Logistics Design

Environmentally sustainable logistics design is a strategic approach that aims to reduce the environmental impact of logistics operations while optimizing resource efficiency [12, 92]. According to Blanco and Sheffi [12], this reduction in environmental impact includes minimizing the consumption of non-renewable energy sources, air emissions and greenhouse gas emissions. Seroka-Stolka et al. [126] means that environmentally sustainable logistics is defined as *"a set of supply chain management practices and strategies that reduce the ecological and energy footprints of the distribution of goods"*. There are a wide range of operations that contribute to making logistics processes more environmentally friendly while ensuring an efficient and effective flow of goods. These operations traditionally include transportation, storage, handling, waste management, loading, and unloading operations [12, 126, 140]. By optimizing and developing these logistics operations, it is possible to reduce the environmental impact of logistics operations and work toward an environmentally sustainable logistics design.

The transportation sector has an significant contribution to CO_2 emissions [12]. Blanco and Sheffi [12] state that the transportation is responsible for about 90% of freight and logistics activities emissions, and the transportation sector account for 23% of total emissions worldwide [140]. This research will primarily focus on environmentally sustainable logistics in relation to transportation activities and their role in achieving fossil-free operations while minimizing environmental impact.

According to a research by Vyacheslavovna Larina et al. [84], various perspectives on environmentally sustainable transportation are presented by multiple authors. Despite the different viewpoints, the authors share a common understanding of environmentally sustainable transportation as a system that is energy efficient, has low emissions, is socially responsible and economically supportive. Vyacheslavovna Larina et al. also emphasize that it is not easy to reach such system, as it requires coordinated changes across multiple sectors.

Vyacheslavovna Larina et al. [84] describe how investments by various transport carriers' are driving the shift to green transportation. To support this transformation, a range of decarbonization strategies can be implemented to reduce emissions within the transport sector. However, this shift also presents significant challenges, that have arisen from underlying drivers. In this section, the decarbonization strategies, key drivers and challenges related to achieving fossil-free transportation are discussed.

2.3.1 Decarbonization strategies

The International Transport Forum (ITF) has developed a Transport Climate Action Directory with five decarbonization measurements to help decision makers turn their decarbonization ambitions into action [69]. The five measurements serve as a set of options for companies to reduce their transportation emissions within their

specific context [70] that includes: *1. Improved design, operations and planning of transport systems, 2. Low-carbon fuels and energy vectors, 3. Electrification, 4. Mode shift and demand management and 5. Innovation and up-scaling.* In this research, the decarbonization measurements will be referred to as decarbonization strategies.

2.3.1.1 Improved design, operations and planning of transport systems

The first strategy that can be used to reduce transportation emissions is to improve the design, operations and planning of transportation systems. By allocating resources to route planning and optimization, it is possible to reduce fuel consumption and increase vehicle utilization [74]. Optimization of routes will minimize the distance traveled and thus reduce fuel consumption [74]. Ahmad et al. [5] also agree that planning of transportation will reduce emissions. Ahmad et al. mention that the fill rate of the vehicle is an important factor for decarbonization. The authors [5] explain that optimizing vehicle loading by matching shipment size to vehicle capacity enables high volume utilization, resulting in fewer trips and reduced emissions.

2.3.1.2 Low-carbon fuels and energy vectors

The use of alternative energy sources such as biofuels, hydrogen and liquid natural gas (LNG) has grown significantly over the past decades [135]. According to The International Energy Agency (IEA) [66] there are different alternative fuels for heavy trucks in the future, the shares of those are shown in figure 2. Continuously, the IEA [64] expect bioenergy, hydrogen, and hydrogen-based fuels to increase significantly in maritime shipping and aviation, rising from less than 1% of current energy consumption to nearly 15% by 2030 and 80% by 2050. The IEA [64] also believe that ammonia will become the primary fuel for maritime shipping, supplemented by biofuels, hydrogen, methanol, elerctricity and fossil fuels.

One biofuel that is frequently discussed in many articles is Hydrotreated Vegetable Oil (HVO). HVO are compatible with most diesel engines [13, 32, 121, 139], allowing diesel vehicles to operate with a fuel blend containing up to 30% HVO without requiring any technical adjustments of the vehicle [13]. Other studies mention that pure 100% HVO (HVO100) can be used in modern diesel engines without the need for modifications [32, 108]. Bohl, d'Ambrosio et al., and Roque [13, 32, 121] therefore describe that HVO is a biofuel that significantly has reduced transportation emissions. Boonrod et al. and Hor et al. [16, 63] state that fossil CO_2 emissions can be reduced by 90% by using HVO.

Hydrogen (H_2) is an environmentally sustainable fuel option that can reduce transportation emissions near 100% [2, 112]. The alternative fuel H_2 can be used in vehicles that are supported with a fuel cell, instead of traditional combustion engines, to generate electricity for propulsion [97], or in internal combustion engines (ICE) [21]. Another discussed low-carbon fuel is LNG that can be used to decar-

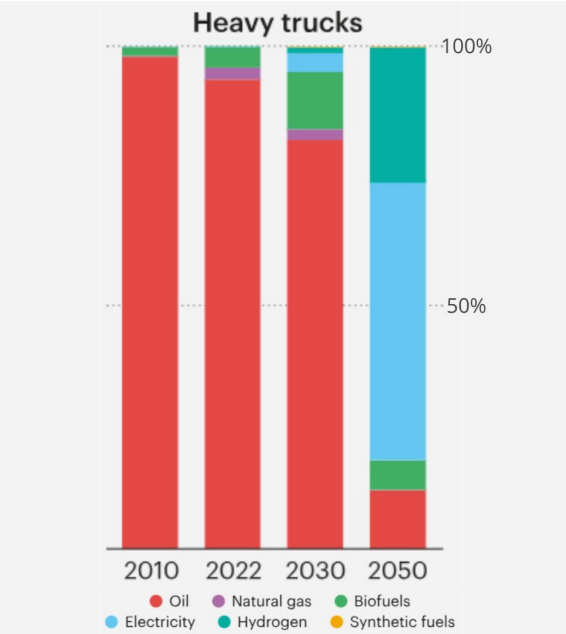

Figure 2: The fuel shares of heavy trucks energy consumption between year 2010 and 2050 [66].

bonize transportation, particularly in sea and road transportation [23]. LNG can decrease CO_2 emissions with 20-30 %. However, bio LNG presents an even more sustainable solution that can decrease GHG emissions with 93% or even close to net-zero depending on the origin [31, 136].

Due to alternative fuels, the type of energy vectors also have to be considered in relation to decarbonization. There are different options for energy sourcing such as small hydro power, wind power, ocean energy, solar technology and bio energy [117]. By sourcing energy from sources such as these examples it is possible to reduce emissions and work towards decarbonized transportation solutions [117]. A report by the International Renewable Energy Agency (IRENA) [72] states that sourcing energy from renewable sources can decarbonize carbon emissions with 90%.

2.3.1.3 Electrification

The electrification of transportation modes is growing rapidly and is a key option that is expected to reduce emissions in the transportation sector [55]. Today, electrification is mostly adapted for land transportation. Due to the weight of batteries, it is challenging implementing this solution to other transport modes such as ships [109]. Guno et al. [55] state that EVs present an opportunity for the transportation sector to transition to zero emissions. Both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) are viable solutions, contributing to decarbonization [35]. BEVs offer zero tailpipe emissions, making them a significant option for reduce transportation-relates GHG emissions [4]. However, the environmental benefits of BEVs are highly dependent on the source of electricity used for charging. Renewable energy sources can significantly reduce GHG emissions, but

electricity sourced from fossil fuels significantly decrease the environmental benefits of BEVS [4, 94]. PHEV can also reduce GHG emissions, but the extent depends on the electricity and fuel use [11].

2.3.1.4 Mode shift and Demand mangemnet

The fourth strategy suggested by ITF [69] is mode shift and demand management. Modal shift is known as a fundamental approach to lower transportation emissions [7]. This strategy should be used to shift from high-emission transport modes, such as road transportation, to more sustainable options like rail that can significantly reduce emissions. According to Anagnostopoulos [7], rail transportation is one of the most environmentally friendly transportation modes and pollutes significantly less emissions compared to road and air transportation. In addition to mode shift, demand management also plays a crucial role in reducing transportation emissions. This could be done by implementing shared mobility solutions. This makes it possible to carry out transportation with the latest technologies and the opportunity to combine different modes of sustainable transportation [26].

2.3.1.5 Innovation

Innovation and up-scaling is the last strategy proposed by ITF [69]. Companies can invest in research and development (R&D) to drive technological advancements towards sustainable transportation. Nilsson et al. [106] state that it is important to have a long-term perspective on benefits of innovations and look beyond financial benefits and understand the innovations value in a broader sense. Therefore R&D support emerging technologies towards more sustainable transportation alternatives [59]. Another strategy towards decarbonization is to scale up projects of cutting-edge solutions that can accelerate decarbonization of transportation. The up-scaling will drive the transformation forwards, some of those drivers of the decarbonization are mentioned in next section.

2.3.2 Drivers for environmentally sustainable transportation

The transformation to fossil-free alternatives is driven by several key factors that are presented in this section. According to a study developed by BCG and the Europeans Federation for transport and environment (T&E) [18], the main factors driving the decarbonization of especially trucks include regulations, infrastructure development, total cost of ownership and Original Equipment Manufacturers (OEMs) commitments.

Different studies [51, 92, 119] highlight the transportation sector's significant environmental impact, which in turn pushes companies to adopt more sustainable solutions. Similarly, Farla et al. and Enerdata [49, 95] emphasize that regulations and government policies shape industry standards and their way of thinking in decision making processes, towards the shift of sustainability. Regions and countries across Asia and Europe have established diverse sustainability policies and targets,

shaping the incentives for carriers to adopt to green transportation. The following are some key policies and regulations driving this shift forward.

Europe has been at the forefront of environmentally sustainable transportation, implementing policies and regulations aimed to becoming the first continent to achieve climate neutrality by 2050 [42]. Central to this ambition is the European Green Deal that is a legally binding target of net-zero greenhouse gas emissions by 2050 [42]. The European Commission, through its Fit for 55 package, has introduced policy proposals to reduce net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels [45]. These targets demonstrate the EU's commitment to leading the environmentally sustainable transition, shaping policies that drive the sustainable progress and global environmental benefits [44]. EU do also have several financial initiatives to support the environmentally sustainable transition in transportation. The connecting Europe facility is an EU funding that supports the development of high performing and sustainable networks in transportation to enhance infrastructure development of different transportation modes and energy sources [43].

While Europe has taken a regulatory-driven approach to achieving climate neutrality, Asia's environmentally sustainable transportation transformation is characterized by a combination of government incentives for regional emission standards. Several key policies and regulations that are driving this shift in countries such as China, Japan, India and South Korea, each setting their goals within different time frames. China has implemented a comprehensive set of regulations, policies and financial support to promote sustainable transportation. The Chinese government has outlined its commitment to achieve carbon neutrality 2060 [141] and a peak in its carbon dioxide before 2030 [71]. Japan is also a country in Asia that aims to achieve net-zero greenhouse gas emissions from international shipping by 2050 [100]. Ministry of Land, Infrastructure, Transport and Tourism (MLIT) states that Japan, alongside a group of other countries, will jointly propose to the International Maritime Organization (IMO) that this target should be established as a common level of ambition for the global shipping sector [100]. Similar to Japan and Europe, the European Parlimentary Research Service [47] mentions that the president of South Korea declared that the country aims to reach carbon neutrality by 2050.

Technological advancements also play a crucial role in the transformation toward fossil-free transportation [59, 102]. New transport solutions not only reduce emissions, but also serve as innovative alternatives for the transport sector [68]. As these technologies get attention among consumers and industry stakeholders, it creates a strategic advantage for companies to adopt them. Adapting to innovations enable companies to remain competitive, meet evolving consumer expectations and be seen as leaders in sustainability and innovation [93].

At the same time, increasing social awareness is driving the change in this transformation. According to McKinnon [92], the evolution of regulations and technologies contributes to a growing public demand for sustainable solutions. McKinnon [92] further explains that minimizing environmental impact strengthens a company's

brand image and helps meet customer requirements. These factors such as technologial advancement, customer expectations, regulatory shifts and other benefits are key drivers for companies to move towards lower emissions in the transportation sector.

2.3.3 Barriers for environmentally sustainable transportation

Despite these drivers, some challenges will remain when carriers develop their strategies for environmentally sustainable transportation solutions. Some of the main challenges that are discussed in certain researches are the costs, regulatory uncertainties, infrastructure and technological advancements.

Cost is a significant challenge across all mentioned decarbonization strategies. Several studies [1, 48, 88] highlight that the investment and operational cost of zero-emission vehicles (ZEVs) and more environmentally friendly solutions are significantly higher compared to conventional diesel modes. This poses a major challenge for hauliers seeking to transform to more sustainable alternatives. Therefore, there is uncertainty from the carriers' perspective on when or if an investment will result in a return [122].

Regulatory uncertainties are also key challenges that must be addressed in all five decarbonization strategies. Regulatory uncertainties lower the pace of decarbonization [76, 56]. The most sustainable alternative to transportation varies significantly depending on location, technological advancements and social acceptance [53, 96]. Bonin Roca et al. and Habermacher et al. [14, 58] argue that unclear or frequently changing policies make investments in sustainable technologies riskier due to unpredictability of future regulations.

2.3.3.1 Electrification

Electrification is an essential strategy to achieve net zero emissions. Sikandar et al. [1] state that electrification presents challenges beyond cost including infrastructure, adoption, energy transition, awareness, and market related challenges. Gruno et al. [55] highlights that a transformation to 100% electric transport is not a cost optimal solution in accordance to high investment costs on infrastructure. Today's infrastructure is not balanced to handle a large amount of EV for the transportation sector, one of the challenge is therefore to optimize innovative energy storage systems [55, 123]. As a result, the current infrastructure slow down the transformation towards electrified transportation and is a difficult challenge to overcome [1]. The charging infrastructure in Europe has grown significantly the recent years [103]. However, most of the current public chargers are designed for smaller vehicles and the challenge therefore lies in expanding the large-capacity charging infrastructure. Monteforte et al. [103] state that the current chargers require longer charging time compared to other fuels.

Another technological challenge associated with electrification is the capacity of batteries [1]. The capacity affects range, charging time and overall vehicle performance [57]. The limited range remains a challenge, particularly for long-haul transportation, as current technologies do not meet these demands [83, 98]. This requires more frequent charging stops, which can significantly increase overall travel time and reduce convenience for users.

2.3.3.2 Low carbon fuels or energy vectors

The shift towards low carbon fuels or energy vectors makes infrastructure a crucial challenge to overcome. Using low carbon fuels requires development of refueling stations for alternative fuels such as hydrogen and bio fuels [142]. Similar challenges exist for energy vectors, as the infrastructure of charging stations must provide energy from environmentally sustainable resources [110, 142]. Additionally, ensuring the availability of such fuels and energy at the required time and location is a critical challenge [110, 142]. Advancements in technology according using low carbon fuels present another challenge, as improving efficiency and production costs are essential for feasibility [60].

Qian et al. [118] state that electrification is the most promising technology to decarbonize land transportation in China. The development of electrified transportation solutions is in the forefront in China. However, coal remains the primary source of energy in China [71], which is a significant challenge to the environmental sustainability of electrification. Similar concerns exist in other Asian regions and parts of mainly eastern Europe, where electricity can still depend on fossil fuel sources [39, 124]. However, Samar [124] also mentions that the EU member has steadily increased the use of renewable energy over the past two decades.

2.3.3.3 Mode Shift

Transitioning to sustainable modes like rail contains of significant political decisions and costs of upgraded infrastructure [30]. Today, rail transportation can only be used for some specific routes, since the rail infrastructure is limited [30]. Cruz et al. [30] state that this situation leads to congestion on operations and safety problems, further complicating the transformation to low-carbon fuel solutions. Nelldal and Andersson [105] argue that technological solutions alone are insufficient to reduce total greenhouse gas emissions from transportation. Instead, they emphasize that significant emission reduction requires a shift in transportation modes, particularly mode shift towards rail, which is more energy efficient [105].

2.3.3.4 R&D investements and Improved design, operations and planning of transport systems

Aside from the high initial costs associated to investments of R&D and upscaling projects, technological challenges will remain. It is a challenge to upscale environmental sustainable transportation projects, since many of them still are in early stages of development and therefore require advancements in performance [8]

A challenge associated with improving the design, operations, and planning of transport systems towards decarbonization, stated by Faissal et al. [75], is to balance efficiency and environmental sustainability. This requires coordination of lead times, fill rates, trip minimization and other operational priorities, making it a complex and challenging task [24]. The infrastructure is also limited to certain possible routes that can hinder possible optimization efforts [20].

2.3.4 Fossil-free transportation

Previous studies on fossil-free transportation in the near future generally fall into two perspectives: those who believe it is achievable and those who are skeptical. Critics who argue that full transformation is unrealistic believe that current challenges are too large, without significant changes, achieving fossil-free transportation will not be possible in the near future [38, 104]. Many companies are not interested or have the capacity to invest in the transition to fossil-free transportation [81, 129]. As a result, the lack of engagement from key industry stakeholders slows down the progress, which makes full transformation unrealistic. To overcome sustainable transportation adoption barriers, the challenges described in section 2.3.3 have to be effectively addressed in a large scale.

Despite critics of the transformation, there are several optimistic perspectives that are actively driving the change toward decarbonization and net-zero emission targets in the transportation sector. Enerdata [40] state that it is not a matter of "if", but "when" the transition toward electric trucks will be done. Similarly, another study by the International Energy Agency (IEA) [66] also supports the transformation of road transportation, predicting a major shift to electricity, hydrogen and biofuels as primary fuel sources, while significantly reducing emissions in the process. The IEA [64] also notes that decarbonization is feasible beyond land-based transportation. Emissions from shipping will be significantly reduced by using fuels such as ammonia, hydrogen and biofuels. Moreover, the IEA [65] expect that nearly 90% of the global electricity will be produced by renewable energy sources such as solar, wind, hydro and bioenergy.

3
Methodology

This chapter outlines the methods used to address the research objectives of the study. It begins by presenting the research design and the contextual background of the case. This is followed by a detailed explanation of the data collection and analysis methods. The chapter concludes with a discussion on the quality of the method and the ethical considerations used.

3.1 Research Design

For this research, a single case study has been selected as the research design. Bell et al. [10] describe that a case study analyzes a single case in detail within a real-world context. The authors [10] describe a case to most commonly be an organization. Therefore, the single case study is widely used in business research since it allows deeper knowledge for the specific case. Compared to other research designs, a single case study focuses on a specific and limited situation. Mariotto et al. [91] explain that a critique of a single case study is that the research findings may lack the ability to be applicable to other situations and cases. Another criticism is that the validity and reliability of this kind of study can be difficult to ensure because the research is based on one case. However, Dubois et al. and Mariotto et al. [37, 91] explained that this type of study does not necessarily imply that the findings are limited in value. They state that when analyzing a complex structure it is better suited to do a deeper examination of a single case rather than attempting to investigating multiple ones. Mariotto et al. [91] continued to argue that investigation of a single case offers new perspectives to a challenge compared to existing theories and can therefore be useful for future studies. The single case study also allows for the use of various data collection methods, making the design flexible and more suitable for the single case.

3.1.1 Case Selection and context

The case company in this research is a European automotive company that is currently building a new battery cell production plant in Northern Europe. This case study focuses on the design of the inbound logistics system for the new facility. This case analyzes the potential setup of inbound logistics, based on a limited sample of potential suppliers, as the factory is not built or operating. This study investigates two alternative inbound logistics systems for the flow of 15 inbound materials to this plant, one potential supplier in Asia and one in Europe. Table 1 provides an

overview of the inbound materials and the potential supplier locations. Some of the potential suppliers are considered as 'dummy suppliers', meaning they do not currently exist in the specified European country, but are expected to be viable options in the future. This setup provides the foundation for addressing the research questions.

Table 1: 15 inbound materials to the battery cell production, and their supplier location in Europe and Asia

Material nr	Location	Country
M1	Europe	Finland
	Asia	South Korea
M2	Europe	Netherlands
	Asia	South Korea
M3	Europe	Belgium
	Asia	Japan
M4	Europe	Sweden
	Asia	South Korea
M5	Europe	Germany
	Asia	Japan
M6	Europe	Germany
	Asia	South Korea
M7	Europe	Sweden
	Asia	China
M8	Europe	Hungary
	Asia	South Korea
M9	Europe	Hungary
	Asia	South Korea
M10	Europe	Hungary
	Asia	China
M11	Europe	Sweden
	Asia	China
M12	Europe	Germany
	Asia	South Korea
M13	Europe	Sweden
	Asia	China
M14	Europe	Sweden
	Asia	China
M15	Europe	Poland
	Asia	China

Figure 3 illustrates the entire value chain for battery production, from raw material extraction to the final assembly of the battery pack. This thesis investigates inbound materials for battery cell manufacturing.

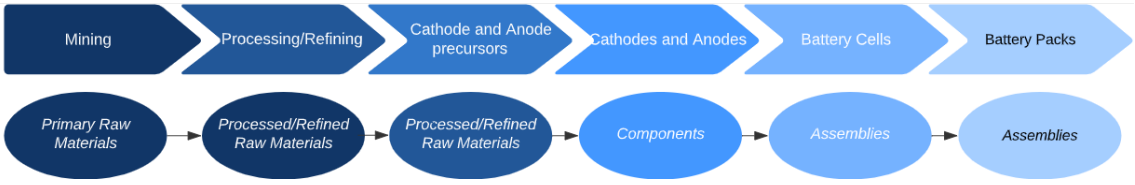

Figure 3: Value chain for battery production [87]

Battery production relies on several critical minerals and raw materials [116]. With increased demand for batteries, there is a corresponding increase of materials. Among the key inputs for battery cell production are cathode and anode active materials [116]. According to the European Commission [87] China is and will remain the major supplier of battery grade raw materials through 2030, despite increasing diversification in the global supply landscape. The supply of battery grade raw materials is currently highly concentrated, with China dominating global processing capacity in most critical inputs [87]. Figure 4 presents the current share of the top three countries for processing materials for battery production.

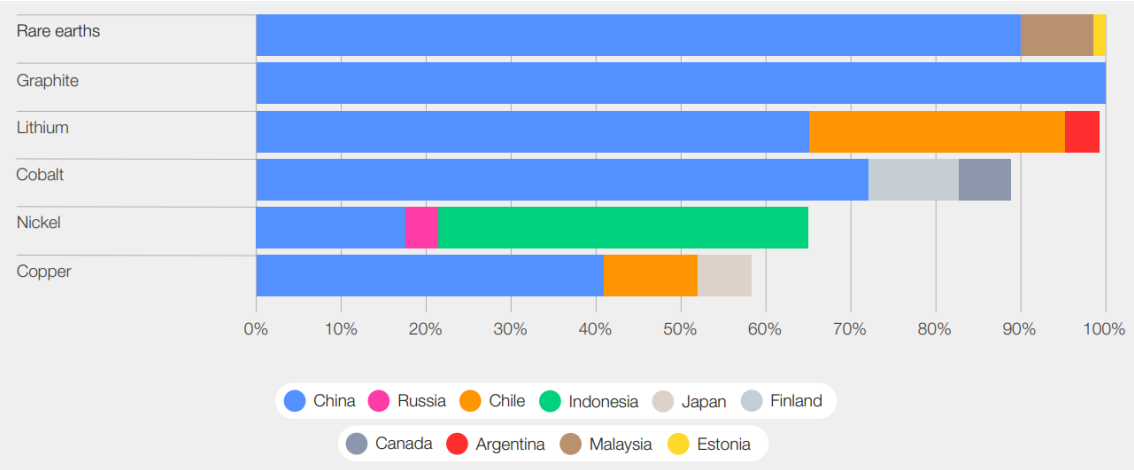

Figure 4: Processing material market share of the top three countries in 2022 [116]

Due to this, minerals and critical materials used for battery production travel long distances before reaching the end product [116]. However, the European Commission stated, "The EU is expected to expand its production base for battery raw materials and components over 2022-2030, and improve its current position and global share. However, dependencies and bottlenecks in the supply chain will remain creating vulnerabilities" [87]. Figure 5 shows a prediction made by the European Commission regarding processed raw materials and battery cells year 2030, for China and the European Union.

Country	Cobalt (Refined Co)	Graphite (Anode precursors from natural graphite+synthetic graphite)	Lithium (Refined Li)	Manganese (HP EMM+HP MSM)	Nickel (NiSO4)	Cells
	51%	87%	34%	56%	59%	65%
	7%	3%	4%	14%	8%	14%

Figure 5: 2030 projection on battery grade processed raw materials and battery cells [87]

3.2 Data Collection

This research is based on two data categories, primary and secondary data. The difference between the two lies in the source and collection method. Primary data is collected by the researcher, usually through interviews, and specific to the research being conducted [10]. Secondary data are existing information conducted by other organizations or researchers [10]. This chapter will further explain primary and secondary data collection methods used in this research. Data collection for each research question is done in parallel, presented in Figure 6 and will be further discussed in this chapter.

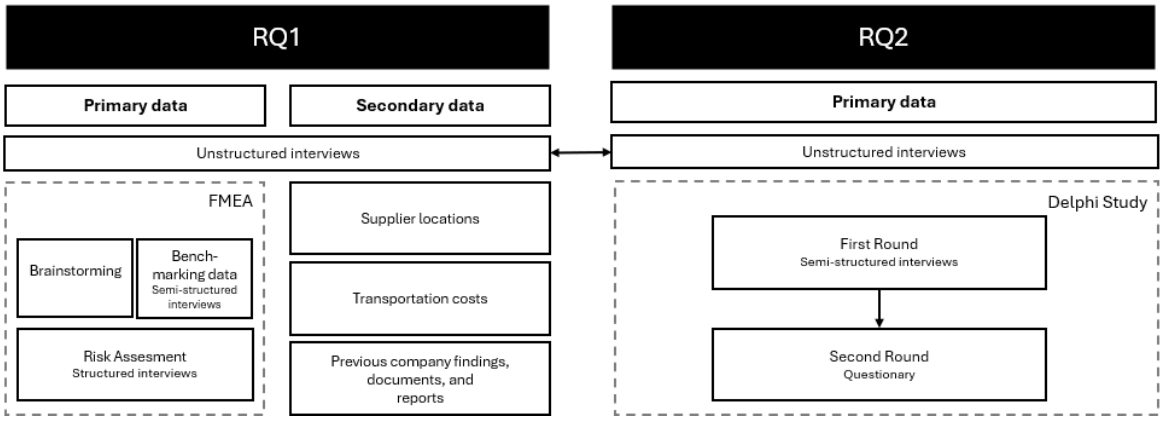

Figure 6: Data Collection Methodology

3.2.1 Primary Data & Sampling

Primary data are defined as the data collected by the researcher to carry out the analysis [10, 3]. Primary data is often collected through various methods, such as interviews, observations, and experiments. Since primary data are collected in real time directly from the researcher, the data are typically more accurate and relevant compared to secondary data [10]. Figure 6 summarizes the data collection performed in this thesis. In this research, multiple data collection sessions were carried out to fulfill the data needs of different studies that helped to answer the research questions. First, regardless of the RQ or the different studies, unstructured interviews led the way through the whole data analysis process. Unstructured interviews were used to elaborate on the research problem, understand the context, gather information about the potential data sources, elaborate on the secondary data sources and iterate between preliminary results and the forthcoming research steps. In parallel to these unstructured interviews, two parallel studies were conducted with separate samples and data collection episodes. The first study was an FMEA where semi-structured and structured interviews were used to collect data. The second study was a Delphi study where semi-structured interviews as well as a structured questionnaire were used to collect data. The purpose, the data collection processes and the samples of these studies are elaborated further below.

Through various interviews and questionnaires, several respondents have provided valuable data to answer the research questions in this thesis. Bell et al. [10] argue that due to research time constraints, it is generally not possible to collect data from an entire population. Sapra [125], state that a sample size too small than required can lead to faulty conclusions. On the contrary, a sample size too large than required can consume unnecessary and expensive resources. To ensure that the findings are relevant and representative of a larger population, it is crucial to carefully select the respondents and the sample size [125]. Therefore, a properly selected sample strengthens the reliability and accuracy of the study, which in turn makes it possible for the results to be applicable beyond just the selected respondents [10]. A purposive sampling method was used to collect the primary data for this study. Bell et al. [10] state that purposive sampling is used to gather respondents in a strategic way

so that they are relevant to the research question being posed. The respondents for the primary data are presented in Tables 2, 3, 4, and 5 are further described below.

Unstructured interviews were used to gain a primary understanding of the topics covered in this research and to further discuss and clarify the secondary data. This approach enabled discussion to gain a deeper understanding of the case company's view on the research topics and the secondary data. An unstructured interview is described, according to Bell et al. [10], as a methodology used when the interviewer only asks a single amount of questions and after that the interviewee is allowed to respond freely. The interviewer in turn responds to parts that seem to be worth following up on. Both Bell et al. and Chauhan [10, 25] state that unstructured interviews are similar to a conversation between the interviewer and the interviewee and therefore can cover parts that a structured interview might miss. Therefore, it was appropriate to take advantage of unstructured interviews by having interviews similar to discussions with the company's employees who were involved in the research and part of creating and maintaining the collected secondary data. A purposive sampling method was used for the unstructured interviews, where two company employees with key knowledge in the studied area were part of these interviews. All unstructured interviews are presented in Table 2.

Table 2: Unstructured interviews with employees at the case company with knowledge about the secondary database

Date	Time Duration (min)	Contribution to Research Problem
20-Jan	90	Identified key data structures and variables in the secondary database relevant to transportation flow analysis
22-Jan	30	Clarified limitations and assumptions of the database that affect data interpretation
23-Jan	60	Defined scope of data analysis in alignment with company and academic expectations
13-Feb	60	Gained an explanation of the sustainability assessment applied in the case company
14-Feb	30	Discussed the overall purpose and scope of the study in accordance to the research objectives
17-Feb	45	Explored the structure and components of transportation cost calculations, contributing to the understanding of cost variability in inbound logistics
21-Feb	60	Facilitated access to external carrier data, enabling further investigation into lead time variability and cost differences

24-Mar	30	Identified and validated key inbound transportation routes to be included in the discussion
27-Mar	30	Clarified constraints and characteristics specific to sea transportation, supporting lead time variability estimation and risk assessment
9-Apr	30	Outlined the data and qualitative input required for the second Delphi round, refining the criteria for expert judgment on transportation risks
24-Apr	45	Provided insight into cost elements in transport scenarios
25-Apr	30	Validated assumptions used in transportation cost modeling based on internal company practices
5-May	10	Brief follow-up to confirm assumptions and details related to transportation cost inputs used in the analysis

3.2.1.1 Primary Data Collection for the FMEA

FMEA is a structured approach used to identify potential failures in products and processes and to address these failures before they lead to actual problems [15]. According to Dev et al. [36] a successful FMEA enables one to identify potential failures based on experiences of similar processes and identify system, product, or process problems before they occur. The authors [36] further explained that identification of such failures makes it possible to design processes in a different way and minimize risks. Therefore, the use of FMEA can reduce the costs and time needed to improve the quality of a project [36]. The objective of using FMEA in this study is to understand the potential risks within transportation to derive insights regarding the appropriate buffer levels needed to mitigate disruptions during manufacturing. In this study, Process FMEA (PFMEA) was used. Carlsson [22] states that PFMEA is commonly used for shipping, incoming parts and the transportation of materials. PFMEA are performed in order to make sure that assembly operations are reliable, and to decrease the risks from potential disruptions that could impact quality, safety, or productivity.

The two main data collection parts of the FMEA were: *1. Identification of potential failure modes and 2. Evaluation of the failure modes.* In order to identify potential failure modes, brainstorming meetings were held, along with meetings to benchmark risks based on experiences of an existing manufacturing plant in Northern Europe. Brainstorming is used to generate ideas, and increase the quality of the results [22]. Generating a great amount of ideas is the main objective of brainstorming [15]. When conducting a brainstorming session ”yes” and ”no” questions should be avoided, instead probing questions were used [22]. Carlson [22] provides the following examples on probing questions that were used for the brainstorming:

1. How would you describe the current situation regarding...?
2. What has been done in the past regarding...?

3. What has worked/not worked regarding...?

Benchmarking is defined as *"A method of measuring and improving our organizational performance by comparing ourselves with the best"* [131]. In this research, benchmarking was used to gather data on delays experienced by a factory near the one being investigated in this research. The data collected consisted of weekly explanations for their transportation delays. This data was collected through *semi-structured interviews*. Bell et al. [10] stated that semi-structured interviews offer flexibility, allowing the researcher to remain open to various types of relevant information while still following a general predefined frame.

For the Asian flow, the focus was on identifying risks related to road transportation in Asia, port handling and sea transportation, and rail transportation to the warehouse located in Northern Europe. Figure 7 illustrates the Asian flow.

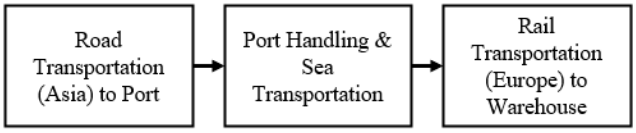

Figure 7: Overview of the Asian flow

For Europe, three different transport flows were identified: *(1) road only (2) combination of road and rail (3) multimodal flow involving road, rail, and short sea shipping.* Figure 8 presents an overview of the Asian and European flows considered in this research. The choice of transport flow was determined by the geographical location of the supplier and the optimal logistics route to the warehouse. However, based on the case company's preferences, European Flows 2 and 3 were used to the greatest extent, as the company aims to maximize the use of rail transportation.

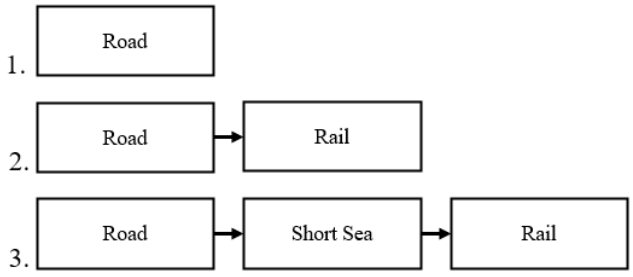

Figure 8: Overview of the European flows

Table 3 presents an overview of the brainstorming and benchmarking meetings conducted. Data collection for each part of the transportation flows was collected separately. That is, separate meetings were held to identify and classify road, rail and short-term risks within Europe, as well as road and sea transport risks from Asia.

Table 3: Brainstorming and Benchmarking of potential risk failures, with employees at the case company

Day	Time (min)	Role
27-Mar	60	Sourcing & Commodity Leader
		Sr. Supply Chain Developer
1-Apr	60	VP Logistics International
2-Apr	60	Sr. Supply Chain Developer
		Supply Chain Developer
7-Apr	15	Head of Transport Operations Korea
7-Apr	50	Supplier Manager
		Supplier Manager
7-Apr	60	Director Transport Operations China
7-Apr	60	Transport Coordinator
8-Apr	45	Director Transport Material

The following step of the FMEA was to evaluate the risk of failures. *Structured interviews* were used to gather expert opinions on transportation failures identified within inbound logistics. A structured interview is described as a type of interview in which the interviewer asks a set of predetermined questions that are asked in a specific order. The predetermined questions follow a strict structure and are usually used when objective data collection is important [10]. A structured interview includes closed or open questions, or both types depending on the goal. Bell et al. [10] mention that closed questions limit the possible way of answer. In contrast, open questions gives an opportunity for the respondent to answer without constraints. The questions used in the structured interviews, for this study, include both closed and open types. *Closed questions* were used to gain a clear understanding of the risk assessment. The risks were evaluated based on three criteria: *(1) Severity - the consequence of the failure should it occur (2) Occurrence - the probability or frequency of the failure occurring (3) Detection - the probability of the failure being detected before the impact of the effect is realized* [15]. In combination, *open questions* were used to understand the reasoning behind how the risks were evaluated. Different people were interviewed based on their specific areas of expertise related to the various transportation modes. To ensure consistency in the risk assessment process, all interviewed experts were provided with a standardized ranking scales (ranging from 1 to 10) to assess severity, occurrence, and detection. These ranking scales were used to reduce subjectivity and improve consistency in the FMEA process, and are presented in Appendix D.

In addition, selecting the right participants for the interviews is crucial to ensure the collection of high-quality data [22]. Carlsson [22] states that *"only a team composed of the right disciplines can provide the necessary input and discussion to ensure all concerns are surfaced and addressed"*. The respondents selected for these interviews were the same individuals who participated in the brainstorming sessions as well as additional participants, chosen based on their in-depth knowledge of the topic. All structured interviews performed for the risk evaluation are presented in Table 4.

Table 4: Structured interviews: Ranking of the identified risks with employees at the case company

Day	Time (min)	Ranked fields	Role
15-Apr	60	Truck Risks in Asia	Head of Transport Operations Korea
			Director Transport Operations China
15-Apr	60	Sea Risks for flows Asia-Europe and shortsea in Europe	VP Logistics International
			Sourcing & Commodity Leader
17-Apr	60	Truck Risks in Europe	Global Logistic Developer
			Sr Supply Chain Developer
22-Apr	60	Rail Risks in Europe	Supply Chain Developer
			Regional Buyer

3.2.1.2 Delphi Study

The Delphi method is a technique used to gather experts' opinions on a complex problem [86]. The Delphi method helps the researcher in developing interview guides by having different rounds of semi-structured interviews or questionnaires and iteratively refine questions and collect consensus [19]. In addition, Brady [19] stated that the purpose of a Delphi study is to explore whether there is a consensus among the respondents within a specific question. The Delphi method was therefore used to gather expert insights on the future of the transportation sector to answer RQ2. This research used the Delphi method for two rounds, to refine the questions and receive relevant, consensus based answers from experts in the industry. The first round of Delphi was done using semi structured interviews, aimed at exploring key themes and perspectives. Based on the insights gathered in this first round, a self-completion questionnaire was developed and distributed to the same respondents. In line with Bell et al. [10], a self-completion questionnaire is a method in which respondents answer questions individually, without interaction with researchers.

A purposive sampling method was used with the aim of collecting different views on the future of transportation. Transportation providers were strategically selected to to represent a range of viewpoints and operational context. Specifically, carriers in both Asia and Europe were selected, given their relevance as potential suppliers of inbound materials for future battery cell production. Furthermore, carriers of different sizes and with operations in various geographic regions were chosen to provide various perspectives on sustainable transportation.

The first round of the Delphi method was using *semi-structured* interviews with 20 different transportation providers. The number of participants varied in each inter-

view, which is shown in Table 5. 17 of the interviews were conducted via Microsoft Teams, and 3 interviews were answered by the respondent in written text. Written interviews were used due to the complexity of communication and language barriers with some Asian transport providers. Semi-structured interviews were used to gather information from transportation companies about the kind of transportation they are aiming for in the future and their thoughts on how environmental sustainability will develop within the sector. Different kind of transportation providers were interviewed, some of them are larger global transportation providers, and some provide transportation only in smaller geographical parts. The sampled transportation providers were also chosen to provide their insights into inland or sea transportation. Therefore, this round provided a deeper understanding of the experts' perspectives and helped lay the foundation for refining the questions for the final round of Delphi. The semi-structured interview guide for the first round of Delphi is presented in Appendix A.

Table 5: First round of Delphi: Semi-structured interview and written answers by transportation providers

Company	Date	Time (min)	Geographical Location	Primarily Discussed Mode	Role of Respondents
C1	6-Mar	60	Europe	Inland	Operations Manager
C2	10-Mar	60	Global	Inland	Account Manager
C3	10-Mar	60	Europe	Inland	Sustainability Manager
C4	12-Mar	60	Global	Inland	Business Director
					Global Coordinator
C5	19-Mar	60	Europe	Inland	Bussiness Developer
					Project Manager
C6	19-Mar	60	Europe	Inland	Sustainability Manager
					Account Manager
C7	20-Mar	60	Europe	Inland	Sustainability Manager
C8	21-Mar	60	Europe	Inland	Bussiness Developer
C9	24-Mar	60	Asia	Inland	Sustainability Manager
					President
C10	24-Mar	60	Europe	Inland	Account Manager
					Sustainability Manager
					Fleet Manager
C11	24-Mar	60	Global	Sea	Account Manager
					Sustainability Manager
C12	25-Mar	30	Asia	Inland	Business Director
C13	25-Mar	30	Global	Inland	Sustainability Manager
C14	25-Mar	60	Global	Sea	Sustainability Manager
C15	26-Mar	60	Europe	Sea	Account Manager
					Global Trade Director
					Bussiness Developer
C16	26-Mar	60	Global	Sea	Account Manager
					Sustainability Manager
C17	28-Mar	60	Global	Sea	Global Coordinator
C18	24-Mar	-	Asia	Inland	Account Manager
C19	25-Mar	-	Asia	Inland	Account Manager
C20	31-Mar	-	Asia	Inland	Account Manager

For the second round of Delphi, a questionnaire was used. The respondents were asked to complete the questionnaire online using Microsoft Forms, and submit the

answers through the same platform. Each transportation company was allowed to submit multiple responses from different individuals, and the questionnaire was completely anonymous. In total, 33 responses were collected from the questionnaire. The questionnaire consisted of yes or no questions followed by open-ended "why" questions to provide context and better understand the reasoning behind the answers. This allowed respondents to respond freely without constraints while also capturing collective opinions. An additional response option, "I don't know" was included to allow respondents to skip questions where they felt they lacked sufficient knowledge. In total 12 statements were used in the questionary, presented in Appendix C.

3.2.2 Secondary Data

Johnstron [77] defines secondary data as information collected originally for another purpose collected by someone other than the researcher. The secondary data collected mainly consist of company reports and previous company findings. The reason for using secondary data analysis is that it provides high-quality information while significantly reducing the time required for data collection [10].

The secondary data collection included previous company findings, documents, and reports that were found to be relevant for this thesis. To build on existing findings and avoid redundant work, this was an important step. The secondary data were used to gain knowledge on the current structure of the inbound supply chain, to identify the location of the inbound material supplier, and calculate transportation costs. Transportation costs for different carriers in different countries were collected to evaluate cost variations between Asian and European suppliers. Transportation costs are determined by specific negotiated agreements between the shipper and the carrier. Therefore, to ensure that cost calculations are relevant and as accurate as possible, company-specific data was used to the greatest extent possible. As a result, a significant amount of secondary data regarding contracts between the case company and its carriers needed to be collected. When data were not available at the case company, assumptions were made, which will be further explained in the Data Analysis, Section 3.3.

3.3 Data Analysis

This chapter includes both qualitative and quantitative approaches to analyzing the collected data. The data analysis has three main focus areas: *(1) Evaluation of risks and risk implications on lead time variations (2) Calculation of transportation costs (3) Delphi method.* These combined techniques support a comprehensive understanding of resilience and environmental sustainability.

3.3.1 Risk & Safety Stock Analysis

Once data collection was completed for brainstorming and risk classification, the analysis began with the aim of translating the identified risks into quantifiable terms.

This was done by first calculating the risk priority number (RPN) for each failure mode [15], using Equation 1. The RPN value quantifies the priority of the risk, enabling further analysis.

$$\text{RPN} = \text{Severity (S)} \cdot \text{Occurrence (O)} \cdot \text{Detection (D)} \tag{1}$$

The RPN values were then classified into three categories using a percentile-based approach: *(1) low (2) medium (3) high*. Bornmann et al. [17] described a percentile as "a value below which a certain proportion of the observations fall". The use of percentiles is an alternative to the use of mean-based quotients. The advantages of using percentiles are that the effect of extreme values is lower, does not require normal distributed data, works well for uneven data, and is a great tool for grouping data [17]. In this case, 25th and 75th percentile were used as thresholds for the categorization. Resulting in a distribution where risks with RPN values lower than the 25th percentile were classified as low risk, RPN values between the 25th and 75th percentiles were classified as medium risk, and RPN values above the 75th percentile were considered as high risks. The percentiles were calculated using all identified risks collectively, meaning rail, truck, sea, and general risks were used together to find the classification limits.

Additionally, to enable a comparison between the different transportation modes, the total RPN value for each mode was normalized to the maximum possible RPN score. This maximum RPN represents the highest theoretical risk score based on the FMEA scale, see Equation 2. The maximum RPN value was then used to obtain a normalized risk value for each transport mode, see Equation 3. This value was then used as the foundation for understanding the risks of the different inbound flows, particularly in terms of how these risks may lead to lead time variation.

$$\text{Sum Max RPN} = 10 \cdot 10 \cdot 10 \cdot \#\text{risks identified for each transportation mode} \tag{2}$$

$$\text{Normalized Risk} = \frac{\text{Sum RPN}}{\text{Sum Max RPN}} \tag{3}$$

3.3.1.1 Safety Stock Analysis

One widely used method to determine safety stocks is based on cycle service. This approach is based on the total standard deviation of the demand during the lead time, with lead time variability being a critical influencing factor. However, due to the case company's lack of historical data on the standard deviation of demand and lead time, this study adopts an alternative approach. Specifically, supply and demand are assumed to be stable and excluded from the study, as their variability lies outside the scope of this thesis. Instead, the analysis focuses solely on uncertainties in the inbound logistics flow and how they affect lead time variability. Finally, this study discusses the implications the calculated lead time variability has on safety stock.

Firstly, the normalized risk values for each mode were used to obtain a risk value for each flow, according to Figure 7 and Figure 8, and presented below. This enables better comparison of flows instead of specific transportation modes.

1. Truck in Europe
2. Truck and Rail in Europe
3. Truck, Rail, and Short Sea in Europe
4. Truck in Asia, Sea, and Rail in Europe

For flow 1,2, and 3 each transportation mode was given an equal weight. This means that if two modes were used in a flow, each was assigned 50% of the normalized risk value. For flow 4, the sea transport mode was assigned a greater weight, reflecting its proportionally longer lead time compared to the other modes. The calculated risk values for the flows were multiplied by the corresponding lead time for each flow to obtain the effect the risks have on lead time deviation.

3.3.2 Transportation Costs Calculations

The secondary data collected from the case company provided contracts with different carriers that were used to calculate the total transportation costs for each inbound material from suppliers in Europe and Asia. The secondary data collected contained current contracted transportation costs for full truckload (FTL) in Europe, less than truckload (LTL) in Europe and Asia and full container load (FCL) for sea transportation from Asia to Europe. FTL contracts included information on whether intermodal transportation was used or not, such as combinations of sea and truck, truck and rail, or just truck. The current contracts did not include the exact same routes that are used for inbound materials in this study. Consequently, comparable routes were identified that were comparatively close to the supplier and the warehouse location. The comparable routes could vary by 0-100 km from the actual route, which in this case was considered negligible to the total cost. The contracts were compiled into multiple Microsoft Excel sheets, to obtain the total transportation costs. As the data collected were not a perfect fit for this case study, the following assumptions were made for all calculations:

- All trucks and containers are fully loaded.
- FTL contracts were used to the greatest extent possible. If data were lacking, LTL contracts were used. In that case, the maximum load capacity was applied to estimate costs equivalent to an FTL. The maximum load capacity was assumed to be 25 tons.
- If more than one comparable route was available, intermodal routes were prioritized.
- Transportation cost was assumed to be zero for materials supplied from the same city as the warehouse.

For the routes from Asia the following assumptions were made:

- Three transportation modes were used: Truck, sea, and rail.
- Truck was used for inland transportation in Asia to the port. For certain routes where data was lacking, the average cost per kilometer for a specific country in Asia was used to estimate the transportation cost for the specific route.
- Sea freight covers the journey from Asia to Europe and then it is considered to use rail directly from the port to the warehouse in Northern Europe.

All transportation costs were calculated and consolidated in Microsoft Excel, with two supplier options per material, one in Europe and one in Asia. To maintain confidentiality, the exact cost calculations were not disclosed. Instead, the total transportation cost for each material on the Asian route was used as a reference point. By dividing the total cost for both the Asian and European routes by the Asian route cost, for each material, it is possible to quantify how much more or less expensive it is to ship from Europe compared to Asia. For the European routes where the cost was assumed to be zero, a comparison could not be made, these are marked with a '-' in the calculations. This enables a comparative analysis of transportation costs on the European route, helping to identify cost differences between shipments from either region.

3.3.3 Policy Delphi

The data analysis for Research Question 2 followed a two-round Policy Delphi approach aimed achieving expert consensus on sustainable transportation solutions for the future. A qualitative analysis developed by Malterud [89] called Systematic Text Condensation (STC) was used to identify key patterns and concepts gathered from the first round of semi-structured Delphi interviews. The analysis consists of the following four steps: *1. Total impression – from chaos to themes, 2. Identifying and sorting meaning units, 3. Condensation, 4. Synthesizing.* To get a total impression, all semi-structured interviews were summarized in Microsoft Excel where the answers were connected to the interview questions. The data were then analyzed and a corresponding category was developed for each theme, including the percentage of respondents who mentioned each category. Thereafter, the condensation process was carried out and all information deemed irrelevant to the study was systematically excluded. Afterward, the most relevant and important topics were identified from the semi-structured interviews and could be further developed into statements for the final round of the Delphi study.

For the final round of the Delphi study, the questionnaire responses were analyzed according to the Average Percent of Majority Opinion (APMO) to reach consensus among the respondents. A majority is reached when more than 50% of the respondents have the same opinion about a specific statement, also described as consensus rate [54]. The consensus rate just considers the answers with "Yes" (Agreement) and "No" (Disagreement), which means that the responses answered "I don't know" is not considered when calculating the consensus rate. APMO is used to calculate the cut off rate and is shown in Equation 4, [54].

$$\text{APMO} = \frac{\text{Majority Agreements} + \text{Majority Disagreements}}{\text{Total Opinions Expressed}} \cdot 100\,\% \tag{4}$$

The APMO cut off rate is used to determine whether consensus has been reached on the various statements in the questionnaire. Equation 5 describes that, if a statement's consensus rate is equal to or higher than the APMO cut off rate, consensus is reached. Conversely, if the consensus rate falls below the cut off rate, consensus is not achieved, indicating that carriers hold differing views on that particular statement.

$$\text{Consensus is achieved if: Consensus Rate} \geq \text{APMO cut off rate} \tag{5}$$

Once consensus was evaluated, whether it was reached or not, the focus shifted to understanding the reasons behind the respondents' answers. At this stage, the "why" questions were analyzed for each statement. For this analysis, the STC model by Malterud [89] was also used to help structure and condense the data.

3.4 Research Quality

To evaluate the quality of a research study, Bell et al. [10] mention that reliability and validity are important factors to ensure trustworthiness of the results. Reliability refers to the ability to repeat the results of a study, compared to the validity that ensures that the results of a study represent the reality [10]. The authors [10] note that, to increase the quality of a research study, it is beneficial to take use of various sources during data collection. In this study, both primary and secondary data such as information from the case company, and various interviews with both internal and external stakeholders were included to gain information from different sources, and increase the reliability and validity.

To further strengthen validity, data was collected through interviews with a diverse group of transportation providers operating across different regions in Europe and Asia. The sample included seven companies providing transportation globally, six operating across Europe, and five operating within Asia. Similarly, 15 companies mainly focused on inland transportation during the interviews, while 5 mainly discussed sea transportation. As a result, the data reflect a broader perspective on transportation. This with a stronger perspective on inland transport, and a more limited input on maritime transport. Accordingly, reliability could also be enhanced due to the Delphi study, as the same experts could answer statements that were built on the first round of interviews which made it possible for the respondents to repeat their insights.

For the FMEA, separate brainstorming sessions and risk assessments were conducted with experts in rail, road, and sea in Europe or Asia. These sessions were held separately due to difficulties in scheduling a common session with all participants. This

separation allowed for more focused discussions on each mode of transport and regional expertise. However, it may have influenced the consistency of the risk ranking, as different participants were part of each meeting. Thus, creating a risk of bias in the risk assessment. To mitigate the risk of bias and improve validity, a standardized ranking scale was used in all sessions, followed by a consistent explanation of how to apply these, see Appendix D.

When working with sensitive company information, it is important to consider the ethical aspect of confidentiality in order not to harm the participating company. Company reports may include confidential data, which were anonymized or generalized in order to protect sensitive information. The company name, interview participants, specific suppliers and inbound materials were anonymized to ensure confidentiality and protect sensitive business information. Sustainability is an important aspect to consider when designing a supply chain especially when it comes to transportation. This research focuses on sustainable transportation and highlights the importance of ecological aspects.

4
Empirical Findings

This chapter presents the empirical findings gathered from the data collection. The chapter is divided into two parts, each part presenting the findings corresponding to a research question. Firstly, the findings for the first research question are presented with two distinct findings: *(1) Risk identification, classification, and LT variation (2) Transportation costs*. Secondly, the results of the Delphi study are presented to answer the second research question.

4.1 Findings for Research Question 1

This section presents the empirical findings relevant to answering research question 1 Firstly, the identified risks for rail, truck, and sea transportation are presented. Together with the corresponding RPN value and the classification for each risk. Secondly, lead time variations derived from the risks assessment are presented for each material and for both the European and Asian flow. Thirdly, transportation cost calculations are presented.

4.1.1 Risk Identification & Classification

This section presents the findings related to the risks identified through the FMEA. The calculated ranges, based on the 25th and 75th percentiles for the high, medium, and low ranking classes, are presented in Table 6. These ranking ranges were used to classify the potential failure modes. The potential failure modes, associated RPN values, the corresponding ranking classes are presented in Tables 7, 8, 9, 10, 11, 12, and 13, with a separate table provided for each transportation mode in each region.

Table 6: The ranking classes and their corresponding RPN rang.

Ranking Class	Range
High	>166
Medium	31-165
Low	0-30

For rail 44% of total identified risks are classified to be high, 50% medium, and 6% low. One reason for this is that the severity got a high value in many potential failure modes, as many failures within rail transportation often lead to operational stops for a period of time. During the ranking process, it was also discussed that severity, occurrence, and detection can vary significantly from case to case. As a

result, a median value was applied in certain cases. Occurrence varied a lot between the different potential causes of failure, where e.g. rail track planned maintenance, mechanical or technical failure on train, and weather disruptions causing operational stop received the highest rating of 6. However, when it comes to occurrence it was noted that depending on the location within Europe this value can differ a lot. From the benchmarked data, in some weeks approximately 2,5-5% of shipments had delays because of "Late/cancelled vessel/train". In some weeks, no delays related to train transportation were identified.

Table 7: The potential failure modes for rail transportation

Potential Failure Mode	Potential Cause of Failure	S	O	D	RPN	Ranking Class
Infrastructure & Track Issue Risks	Rail track planned maintenance	2	6	2	24	Low
	Signal not working	7	5	6	210	High
	Train power issues	7	5	5	175	High
	Accidents or obstructions on track	8	5	7	280	High
	Wrong tracks / train goes wrong way	6	1	9	54	Medium
	Rail track issues (e.g., poor quality, damage, bad conditions)	6	5	7	210	High
Train Risks	Mechanical or technical failure on train	9	6	8	432	High
Transportation Provider Risks	Missed time slot	8	4	4	128	Medium
	Cancelled train	9	2	3	54	Medium
	Rail strikes	9	3	2	54	Medium
	Lack of train wagons	8	3	4	96	Medium
	Capacity restrictions	8	3	4	96	Medium
	Service stops / low volume	10	4	2	80	Medium
Other Failure Modes	Weather disruptions causing operational stop	9	6	6	324	High
	Theft	9	2	10	180	High
	Weather disruptions causing slower operations	6	3	3	54	Medium

For potential failure modes in Europe, 6,7% are classified to be high, 60% are medium, and 33% are low. Road accident on own trucks is the only potential cause of failure that received a high ranking class. This is due to the risk being assessed with the highest ranking for both severity and detection, which means that it would have significant consequences and is difficult to detect prior. However, the occurrence rate is low, rating of 2, affecting less than 1,5% of total shipments according to the ranking list. This is the lowest possible value, as a rating of 1 indicates that the risk has been effectively eliminated.

One reason for the overall lower RPN values was that occurrence was generally ranked vary low. Occurrence, was ranked 4 or below, thus all risks are assumed to occur less 6% per total shipments. With an average value of 2,2, which means that on average the occurrence of truck risks in Europe is less than 2% of total shipments. Severity got an average value of 6,5, which corresponds to moderate delays according to the defined risk assessment scale. Detection has on average values below 5, which according to the ranking scale is medium likelihood of detection. Road accidents on own trucks and theft received significantly higher detection values, with the reasoning that these risks are impossible to detect and not much can be done to correct the failures. Similarly, as for train transportation, it was discussed that some risk rankings depend on the country. Especially when it comes to strikes. The benchmarked data indicates that traffic jam/disturbance, planning error/driving time, wether, breakdown, and capacity have led to delays. However, each accounts for only a small percentage of total shipments.

Table 8: The potential failure modes for truck risks in Europe

Potential Failure Mode	Potential Cause of Failure	S	O	D	RPN	Ranking Class
Infrastructure & Road Condition Risks	Road accidents own trucks	10	2	10	200	High
	Road accidents	8	3	5	120	Medium
	Charging availability and charger malfunctions (in case of electric truck usage)	3	2	4	24	Low
	Traffic congestion /traffic disturbance	3	4	5	60	Medium
	Repairs and maintenance of worn-out infrastructure	2	2	2	8	Low
Vehicle Risks	Mechanical failures/breakdowns	9	1	2	18	Low
Transportation Provider Risks	Lack of trucks	5	4	4	80	Medium
	Capacity limitations	5	1	5	25	Low
	Strikes	10	2	4	80	Medium
	Driver shortages	5	4	4	80	Medium
	Planning error	1	1	6	6	Low
Other Failure Modes	Weather disruptions causing operational stop (e.g. hurricanes, floods, earthquakes, wildfires, earthquakes, tsunamis)	10	1	5	50	Medium
	Theft	10	1	9	90	Medium
	Weather disruptions causing slower operations (e.g., snow, fog, heavy rain)	7	4	5	140	Medium
	Cybersecurity threats	10	1	4	40	Medium

For truck risks in Asia the results are presented for two countries, China and South Korea. The results are similar for both countries, but with small differences, as presented in table 9 and 10. China received 14% high risks, 57% medium risks, and 29% low risks. South Korea received 21% high risks, 43% medium risks, and 36% low risks. One of the significant differences identified was the risk of strikes. South Korea received a much higher RPN value for strikes, primarily due to the occurrence being rated as 4, compared to a rating of 1 for China. For the potential cause of failure 'repairs and maintenance of worn-out infrastructure' it was ranked low for Korea and medium for China. Compared to European truck risks, Asia received higher values on both wether related risks and cybersecurity threats. However, it is important to note that the rankings were made on separate meetings with different participants, which may have influenced the outcome.

Table 9: The potential failure modes for truck risks in China, Asia

Potential Failure Mode	Potential cause of failure	S	O	D	RPN	Ranking
Infrastructure & Road Condition Risks	Road accidents	3	2	6	**36**	Medium
	Charging availability, Charger broken (If use of electric trucks)	2	2	3	**12**	Low
	Traffic congestion / traffic disturbance	3	5	5	**75**	Medium
	Repairs and maintenance of worn-out infrastructure	4	4	2	**32**	Medium
Vehicle Risks	Mechanical failures/breakdowns	7	2	2	**28**	Low
Transportation Provider Risks	Lack of trucks	8	2	3	**48**	Medium
	Capacity limitations	8	2	3	**48**	Medium
	Strikes	10	1	10	**100**	Medium
	Driver shortages	10	3	4	**120**	Medium
	Planning error	4	2	2	**16**	Low
Other Failure Modes	Larger weather-related delays (Pause in operations) (e.g. hurricanes, floods, earthquakes, wildfires, earthquakes, tsunamis)	10	2	9	**180**	High
	Theft	10	1	1	**10**	Low
	Bad weather conditions (sluggish operations) (e.g., snow, fog, heavy rain)	8	3	4	**96**	Medium
	Cybersecurity threats	9	2	10	**180**	High

Table 10: The potential failure modes for truck risks in South Korea, Asia

Potential Failure Mode	Potential cause of failure	S	O	D	RPN	Ranking
Infrastructure & Road Condition Risks	Road accidents	3	2	6	**36**	Medium
	Charging availability, Charger broken (If use of electric trucks)	2	2	3	**12**	Low
	Traffic congestion / traffic disturbance	3	4	5	**60**	Medium
	Repairs and maintenance of worn-out infrastructure	3	3	2	**18**	Low
Vehicle Risks	Mechanical failures/breakdowns	7	2	2	**28**	Low
Transportation Provider Risks	Lack of trucks	8	2	3	**48**	Medium
	Capacity limitations	8	2	3	**48**	Medium
	Strikes	10	4	10	**400**	High
	Driver shortages	10	2	3	**60**	Medium
	Planning error	4	2	2	**16**	Low
Other Failure Modes	Larger weather-related delays (Pause in operations) (e.g. hurricanes, floods, earthquakes, wildfires, earthquakes, tsunamis)	10	2	9	**180**	High
	Theft	10	1	1	**10**	Low
	Bad weather conditions (sluggish operations) (e.g., snow, fog, heavy rain)	8	2	2	**32**	Medium
	Cybersecurity threats	10	2	10	**200**	High

For potential failure modes in short sea, 21,7% were ranked as high, 43,5 as medium, and 34,8% as low. The severity rankings were high, mainly because it was discussed that issues in sea transportation are not easily resolved and typically result in delays longer than 24 hours. During the assessment meeting it was clearly stated that short sea has fewer risks involved and are more predictable compared to long sea transportation.

Table 11: The potential failure modes for short sea transportation in Europe

Potential Failure Mode	Potential Cause of Failure	S	O	D	RPN	Ranking Class
Vessel Risks	Fire on board a vessel	9	1	6	54	Medium
	Mechanical or technical failure on vessel (engine, systems, etc.)	9	3	7	189	High
	Not enough capacity on vessel	10	2	1	20	Low
	Loss of containers overboard	10	1	2	20	Low
Transportation Provider Risks	Withdrawal of vessel services	10	1	1	10	Low
	Cancelled vessel	10	2	1	20	Low
	Delayed departure	4	3	2	24	Low
	Bookings that are rolled to next sailing	10	2	7	140	Medium
	Port omission	10	1	2	20	Low
	Sailing schedule change	10	2	2	40	Medium
Port Risks	Fully occupied yards	9	2	3	54	Medium
	Port closes due to holiday closures	10	2	1	20	Low
	Port strikes	10	2	2	40	Medium
	Unexpected port closures	10	2	9	180	High
	Cargo forgotten/left behind at dock	10	2	7	140	Medium
	Cargo damaged during port handling	10	1	6	60	Medium
	Port congestion	9	2	3	54	Medium
	Labour shortage	5	3	2	30	Low
	Cargo loaded onto wrong vessel	10	2	10	200	High
Other Failure Modes	Weather disruptions causing operational stop (E.g. Typhoon, rough sea, fog, winter storms or other extreme weather conditions)	8	3	7	168	High
	IT system breaks down	10	2	7	140	Medium
	Weather disruption causing slower operations	8	3	7	168	High
	Rerouting due to geopolitical or operational constraints	10	1	7	70	Medium

The potential failure modes for sea transportation between Asia and Europe received 48% high ranked risks, 39% medium, and 13% low. This transportation mode got significantly higher rankings compared to the other modes. This is because all potential causes of failure were ranked with a value of 10 on severity. This is because all failure modes causes delays longer than 24 hours, in many cases up to a week of delay. For example, if vessel services are withdrawn, you would typically have to wait for the next available vessel, which may not arrive for another week. Therefore, the severity ranking is considered very high compared to other transportation mode, leading to a higher number of risks being classified as high. During the data collection, it was discussed that the level of risk also heavily depends on whether the flow is direct or indirect, as well as the number of ports that are part of the flow. The case company explained that they strive to have as direct flow as possible, which means the ship stops at a limited number of port, to mitigate risks. Furthermore, the case company stated that they work a lot with buffer lead times for sea transportation. This buffer lead time is approximately 6 days, but can vary a lot depending on how the contracted route looks. When the flow is direct, a lot of risks are emitted and less buffer lead time is used.

Table 12: The potential failure modes for sea transportation between Asia and Europe

Potential Failure Mode	Potential Cause of Failure	S	O	D	RPN	Ranking
Vessel Risks	Fire on board a vessel	10	1	6	60	Medium
	Mechanical or technical failure on vessel	10	3	7	210	High
	Not enough capacity on vessel	10	3	1	30	Low
	Loss of containers overboard	10	1	2	20	Low
Transportation Provider Risks	Withdrawal of vessel services	10	2	1	20	Low
	Cancelled vessel	10	5	1	50	Medium
	Delayed departure	10	7	2	140	Medium
	Bookings rolled to next sailing	10	4	7	280	High
	Port omission	10	4	2	80	Medium
	Sailing schedule change	10	6	2	120	Medium
Port Risks	Fully occupied yards	10	3	3	90	Medium
	Port closes due to holidays	10	4	1	40	Medium
	Port strikes	10	4	2	80	Medium
	Unexpected port closures	10	3	9	270	High
	Cargo left behind at dock	10	4	7	280	High
	Cargo damaged during handling	10	3	6	180	High
	Port congestion	10	6	3	180	High
	Labour shortage	10	4	2	80	Medium
	Cargo loaded on wrong vessel	10	3	10	300	High
Other Failure Modes	Weather disruptions causing operational stop (E.g. Typhoon, rough sea, fog, winter storms or other extreme weather conditions)	10	4	7	280	High
	IT system breaks down	10	2	8	160	Medium
	Weather disruptions causing slower operations	10	4	7	280	High
	Rerouting due to geopolitical or operational constraints	10	3	7	210	High

The general failure modes are additional risks that are added when modal transportation is used. Both causes of failure are classified as medium risks. Despite both risks being classified as medium, this serves as a good example of how the RPN value can still vary significantly within the same ranking class. Miss of modal change is slightly more severe, however, according to the ranking it is easier to detect.

Table 13: General potential failure modes for all transportation

Potential Failure Mode	Potential Cause of Failure	S	O	D	RPN	Ranking Class
General Failure Modes	Miss the modal change	**10**	**2**	**3**	**60**	**Medium**
	Damage of goods when changing transportation mode/handling	**9**	**2**	**9**	**162**	**Medium**

One of the main advantages with conducting an FMEA is that it enhances risk visibility. This in turn allows companies to prioritize risks and implement proactive and targeted mitigation measures. In this thesis, the FMEA identified which transport flows carry the highest risk, by quantifying risks through RPN values. Ultimately, this enables a shift from reactive problem solving to more proactive strategies with risk management, a critical step toward building resilient inbound logistics networks.

4.1.2 Lead Time Variation

From the potential failure modes and RPN values identified in section 4.1.1, a normalized risk value was calculated for each transport mode and are presented in Table 14 and Figure 9. This normalized risk value enables comparison of risk levels for different transportation modes. The results show that sea transportation between Asia and Europe got the highest value of 0,19, closely followed by rail transportation in Europe with a value of 0,15. This was followed by general risks, truck transportation in both Asia and Europe, and short sea transportation in Europe. A significant gap can be observed between the normalized risk values, with rail and long sea transportation ranking notably higher than the other modes. This stems from the severity number being much higher for sea and rail transportation. When it comes

to failure modes for long sea and rail the effect usually leads to longer stop, usually longer than 24h, compared to e.g. road transportation.

Table 14: Normalized risk values calculated using RPN from FMEA

Transportation mode/region	Normalized Risk Value
Truck Europe	0.068
Truck Asia	0.076
Rail Europe	0.150
Sea Asia	0.190
Short Sea Europe	0.068
General	0.079

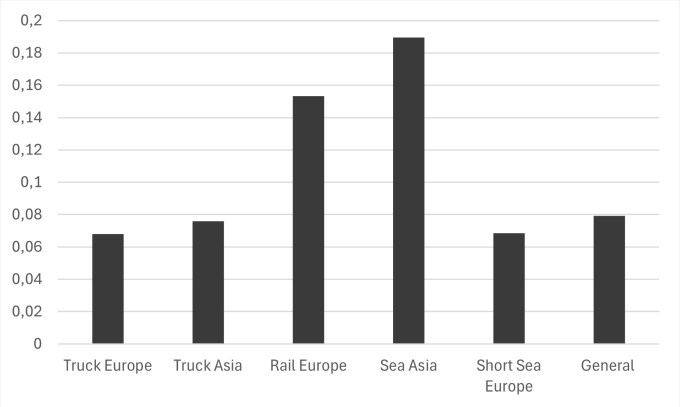

Figure 9: Visualization of the normalized risk values for different transportation modes

Table 14 serves as the basis for calculating the normalized risk values for all European flows, which are presented in Table 15. The results show that a transportation flow consisting of a 50/50 split between rail and truck results in the highest risk values, followed by a split between truck, sea, and rail. This means that while multimodal solutions are often preferred for environmental and cost aspects, they result in additional risk implications in terms of lead time uncertainty. For the Asian flow, truck in Asia, long sea and rail in Europe, one risk value was used, calculated to 0.1866%. This value is much higher compared to any of the European flows, highlighting the increased risks within this flow. Figure 10 presents the normalized risk values for European and Asian flows.

Table 15: Normalized risk values for the three different transportation flows in Europe

Transportation Flows in Europe	Normalized Risk Value
Flow 1 (Road)	0.068
Flow 2 (Road, Rail)	0.11
Flow 3 (Road, Short Sea, Rail)	0.096

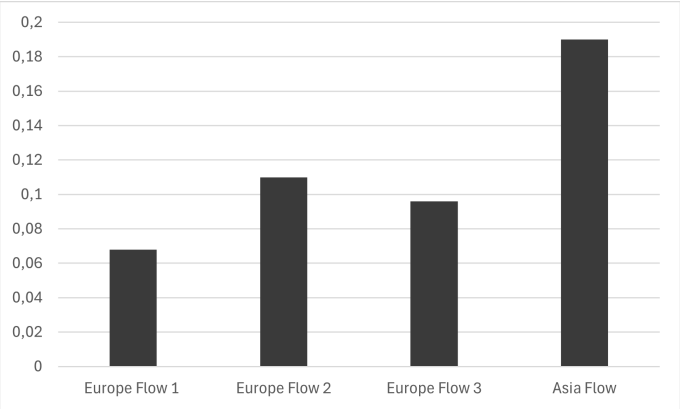

Figure 10: Normalized risk values for European and Asian flows

Finally, these values were multiplied by the corresponding LT for each material to demonstrate the LT variation. The final results of the LT variation for the European and Asian flows are presented in Table 16. From the table it is evident that the LT for the Asian flow varies much more compared to the European. The LT variation for the Asian flow ranges from 8,77 to 10,08 days, compared to significantly lower values in Europe, which range from 0,07 to 0,39 days. This stems both for the higher normalized risk value for the Asian flow, but also the significantly longer total LT for this flow. This variation in LT is an important aspect that influences the amount of safety stock needed to cover this variation. Thus, it can be concluded, solely looking at the transportation risks, there is a greater need for buffer stock and risk mitigation strategies in the Asian flow. However, it is important to note that LT variation is only one out of many aspect influencing safety stock allocation. Other aspects such as demand variability, service level targets, and inventory strategies should also be included.

Table 16: LT Variation for the two flows

Material no.	Europe [Days]	Europe [H]	Asia [Days]
1	0.29	6.88	10.08
2	0.10	2.29	9.14
3	0.29	6.88	8.77
4	0.07	1.63	9.14
5	0.39	9.29	8.77
6	0.33	8.03	9.33
7	0.11	2.66	9.14
8	0.38	9.18	9.33
9	0.38	9.18	10.08
10	0.38	9.18	9.14
11	0.11	2.66	9.70
12	0.24	5.73	9.33
13	0.07	1.63	8.96
14	0.07	1.63	8.96
15	0.29	6.88	9.14

4.1.3 Transportation Cost Calculations

The transportation cost calculations indicate that, when considering transport costs alone, sourcing materials from Europe is generally more cost-effective than sourcing from Asia. This result is expected because longer transportation from Asia naturally results in higher transportation costs. However, these findings are based on real contracted costs and provide concrete percentage differences in costs. The complete cost calculations cannot be directly presented, therefore, a comparative ratio of the two routes for each material are shown. Figure 11 presents the cost rations between Europe and Asia and table 17 presents the cost difference between Asia and European sourcing. The materials marked with '-' in Table 17 are supplied from the same city as the delivery location, therefore these materials are assumed to have zero transportation costs. As a result, a comparison could not be made.

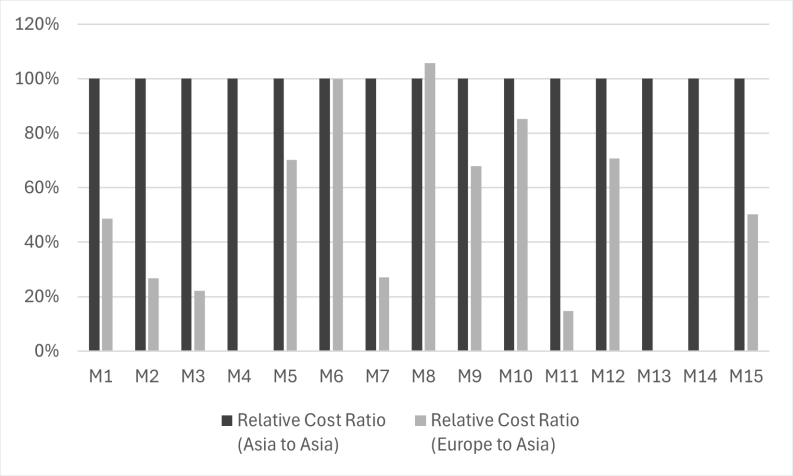

Figure 11: Transportation cost comparison by sourcing in Asia or Europe

From table 17 it can be seen that some transportation costs are up to 85% lower when using European suppliers, with cost differences ranging from 6% higher to 85% lower. On average the total European transportation costs are 57% of the costs in Asia, thus Europe transport is on average 43% cheaper compared to Asian transport. However, an exception is observed with material M6 and M8, for which transport from the European supplier is equal to or approximately 6% more expensive than from the Asian supplier. As shown in Table 17 for M8, the transportation cost from Asia was lower compared to other Asian routes, and the cost of the European route was higher than the other routes in Europe. The explanation for this is that specific negotiated contracts are used in the calculations which influence pricing based on factors such as shipment volume, port selection, and other logistical details. Although transportation costs are generally lower for European logistic flows, it is important to remember that these costs represent only one aspect of the overall logistics costs. When designing an inbound logistics a total cost of ownership approach should be applied.

Table 17: Cost differences for each material, Europe relative to Asia

Material	Cost Difference (Europe vs. Asia, %)
M1	51%
M2	73%
M3	78%
M4	-
M5	30%
M6	0%
M7	73%
M8	-6%
M9	32%
M10	15%
M11	85%
M12	29%
M13	-
M14	-
M15	50%

4.2 Delphi study

This section presents the empirical findings relevant to addressing RQ2. The insights gathered from the first round of the Delphi study are based on the responses from semi-structured interviews, shown in Appendix A. This is followed by the results of the second round, which involved a questionnaire assessing whether consensus among respondents was reached or not.

4.2.1 First round of Delphi

The first round of the Delphi study was conducted using semi-structured interviews to explore the general views of transportation providers on environmentally sustainable transportation. The responses are summarized in Appendix B, where the answers are presented as percentages, reflecting the proportion of respondents who discussed similar subjects.

4.2.1.1 Current transportation operations

From the semi-structured interviews it is clear that transportation providers in both Europe and Asia are today relying on fossil fuels. All interviewed companies are today using fossil fuels, but the degree of usage varies among them. In general, the results show that European transportation providers are today using more sustainable transportation solutions compared to Asia.

For Asian transportation providers, some differences were identified for the current state of their operations. Company 9, an Indian transportation provider, state that they use diesel for 100% of their transportation. Furthermore, this company states that, "It is only recently Indian OEMs have started launching electric vehicles and LNG vehicles. For LNG, unlike Europe, this solution has just now entered India and there is today no fueling infrastructure" [Company 9]. Company 19, a Chinese transportation provider, uses less than 10% sustainable transportation. Meanwhile, another Chinese company, Company 20, stated that their only current environmental initiative is compliance with Euro 6 standards, which focus on reducing local air pollutants. However, these standards still apply to vehicles that use fossil fuels and do not significantly reduce greenhouse gas emissions. Similarly, Company 12, a Korean company, stated that their only environmental initiative is Euro 6 engines. Additionally they are not using any biofuels today.

Despite the general view being that today European transportation providers use more environmental sustainable transportation significant differences were observed for companies within Europe. For example, Company 10, based in northern Europe, is currently using diesel for 50% of its truck transport, the remaining transport is covered by more sustainable transportation solutions. In contrast, Company 5, uses HVO for only 3-4% of their total fuel consumption. The interviews reveal significant differences among European transportation providers. Some transportation providers stated that the limited availability of both technology and sustainable fuels makes it currently impossible to adopt more sustainable transport solutions, while another company stated, "We are doing the change now, it should not be that hard for other companies to do the same. The technology is available, but it is the market that controls the change" [Company 10]. Furthermore, the results show that many transportation providers think that different countries create different opportunities to have more environmentally sustainable solutions today. Company 1 operating in southern Europe stated, "We are using HVO where it is possible today, but right now we can only do it in our primary country of operation".

Within sea industry Company 17 stated that they are today using Very Low Sulfur Fuel Oil (VLSFO), and that they believe this fuel will remain the main fuel type for the next couple of years. Additionally, this company explained that, "The alternate fuels that are available are not available to the extent to cover our entire fleet". Thus today they continue to rely primarily on conventional fossil fuels. Company 14 stated, "Right now fossil fuels are dominating, with a small percentage of more sustainable solutions". However, company 14 has this year introduced a small number of duel fuel vessels that are able to run on green methanol. Indicating a small shift to more sustainable transportation modes. Additionally, during several interviewed it was discussed that vessels have a long operational lifetime which makes it hard to transition quickly to more sustainable alternatives. However, it was also discussed as the transition takes longer time, the change needs to start now.

4.2.1.2 General Perspectives

When discussing the general perspectives of transportation providers on the future of sustainable transportation, several technologies were highlighted. The majority of European companies discussed HVO as a good short term solution to reduce CO_2 emissions. Company 5 stated, "Right now our focus is on blending HVO100 into our network" and Company 6, "In the closer years HVO is the solution". In addition, multimodal transportation and improved operational efficiency were discussed as effective immediate solution that delivers a significant immediate emission reduction.

Regarding the future technologies, electrification and hydrogen were discussed as a viable solution. Company 7 stated, "Electric power is the most sustainable long-term solution for heavy duty truck – however we also need alternative technologies to reduce greenhouse gas emissions now". In addition, Company 10 stated that they believe the EU favors technologies such as electric trucks and hydrogen. Thus, making these technologies more promising in the future.

Within the maritime sector, increased vessel utilization was identified as a necessary and immediate improvement. In addition, several companies mentioned that there is no single solution and that vessel companies need to diversify their product portfolios. Alternative fuels and carbon capture technologies were frequently mentioned, Company 11 sated, "The strategy is for now just to focus on those new alternative fuels, but we'll just keep an eye on carbon capture technology because in the end it's it may be impossible to reduce for 100%". Many companies also stated that they are using a blend of HVO into their vessels today. From a future perspective, ammonia and methanol were frequently pointed out by companies as promising solutions.

4.2.1.3 Company Strategy and Vision

When it comes to company strategy in terms of sustainability targets the answers were divided, either the companies had clearly defined goals or none at all. Many European companies had a net zero target of 2050, with several key milestones However, the goals varied greatly between companies. Company 6, had a goal of having no diesel-powered trucks in their fleet by 2035, and Company 10 with the aim to be fossil-free end of 2025. However, Company 8, also a European company, has not set any targets. They stated, "We do not have any specific targets. We are working on sustainability, but as it is not possible to be fossil free today, we have not set any targets".

Company 18, a Korean transportation provider, has the goal to achieve fully fossil free transportation by 2050. Company 20, a Chinese company, has the aim of achieving zero emissions by 2040. The rest of the Asian countries did not communicate any specific targets. These goals are ambitious compared to the current state of their fleets.

4.2.1.4 Barriers and Drivers in Transition to Sustainable Transportation

A theme mentioned by several respondents was the need to move towards fossil-free transportation in order to remain competitive in the market. Therefore, competitiveness was repeatedly mentioned as a driver for the transition to sustainable transportation. One respondent stated, "sustainability is no longer just a value-added option, it has started to become an expected baseline". The developed baseline, in turn, sets even more pressure on carriers to support with less emission-transport alternatives. Consequently, respondents indicate that it is challenging for them as carriers to meet customer demands when other parts, such as customers, are unwilling to pay a premium for sustainable options. Cited by a respondent "Customers think the problem will be solved but they are not willing to invest anything into it. They are just considered that the service provider does most of the emission fix".

Many carriers identified that customer demand is one of the main drivers behind the shift towards fossil-free transportation. At the same time, customer demand was also discussed as a barrier, as stated by Company 17, a global sea transport company, "Customers say that they are not able to cover the cost increase for the use of more sustainable transportation solutions, as their customers in turn are unwilling to pay more". However, some European and global transportation providers noted that a small percentage of their customers are willing to pay extra for sustainable transportation solutions. Multiple respondents also mentioned that larger companies and companies closer to the end consumer are more willing to pay a premium. This is because they can use environmental sustainability as an marketing advantage. As one respondents mention, "it can also depend on the business of the buying company, higher margin business, or products that have financial benefits, which are generally more willing to pay a premium" [Company 1].

Additionally, a key theme that was mentioned as a barrier in the interviews was uncertainty about the regulatory frameworks. Many carriers expressed concerns about how changing regulations in different regions could impact their ability to make long-term sustainability plans. This uncertainty is not limited to carriers operating across multiple regions, but is also common for those operating within a single country. In many interviews, carriers mentioned that regulations change frequently, making it difficult to predict future requirements. However, some carriers expressed optimism, hoping that sustainability efforts will become more globally consistent over time, allowing them to operate under the same set of rules around the world. An example of this, mentioned by multiple sea freight providers, is that the international maritime organization (IMO) has established a mandatory emission limits regulation for the entire maritime industry sector which is stated going in the right direction. Accordingly, many respondents highlight the need for stable and predictable government incentives as a potential solution to solve this challenge. Cited by one respondent, "We need clear guidance and laws on what they want us to do", referring to the governments".

The respondents also discussed the challenges related to the availability of fossil-free transportation options. Several carriers, offering inland or sea transportation,

stated that the charging infrastructure or the availability of alternative fuel is not widely available and varies significantly by country and also location. Company 17 stated, "The alternate fuels that are available are not available to the extent to cover our entire fleet". In addition, the availability of alternative fuels for sea is often available in specific bunker locations, often major ports. This means that even if alternative fuels are available at the departure port, they may not be accessible at the destination. As a result, logistical challenges arises, as routes may need to be changed, or operations may need to be limited to specific routes compatible with certain fuel types. Similar challenges occur in inland transportation due to the availability of charging and alternative fuel infrastructure. Respondents noted that rerouting is common and often results in longer driving distances that impact lead times, something customers generally prefer to avoid. However, some transportation providers have addressed this by offering sustainable solutions somewhere in their fleet network. While the sustainable transport may not be used directly on the customer's route, the customer can still pay for it as part of carbon offset. Company 2 explained, "A customer's cargo might travel by diesel truck, but they pay extra so that another shipment on a different route uses HVO or electric transport, balancing the carbon impact".

In addition, some respondents discussed that the availability of alternative fuels and electricity will not be sufficient to meet the needs of the entire transportation sector. Regarding electricity, respondents also mentioned that even when using electric trucks instead of diesel ones, electricity still must come from renewable electricity sources to fully realize the potential reduction in emissions. Therefore, a challenge discussed was the uncertainty of emission reduction by using electric trucks, as renewable energy is not available worldwide, with particular difficulties in Asian countries. Consequently, a few respondents also expressed uncertainty about the emission reductions from alternative fuels. One respondent stated, "the level of reduction depends on the specific fuel batch, making it difficult to predict the actual decrease in emissions" [Company 7].

4.2.1.5 Costs and Investments

Many carriers noted that investments in sustainable transportation modes are significantly higher compared to regular options. In addition to investment costs, alternative fuel prices are today also more expensive compared to diesel. Company 17 explained that VLSFO, which is a fossil fuel for vessels costs approximately $550 per ton while LNG costs $1000 to $1200 per ton, and biofuels cost between $1300 $1400 per ton. Thus more sustainable fuels are approximately 2,5 times more expensive per ton of fuel. The company further explains that customers generally are not willing to pay that much more, and therefore it is the carriers that have to cover the extra costs.

Despite this, many transportation providers are optimistic that these prices will go down in the future. One respondent stating, "In the short term transportation costs will rise, but in the long run with technological advancements and policy support the costs will stabilize. There will come a moment when costs for diesel and more

sustainable solution cross each other" [Company 18]. One additional response, "If we don't invest now, we can be certain that costs will rise for customers in the future due to increasing taxes on emissions" [Company 16]. However carriers state that the problem today is that fossil fuels, such as diesel, are too cheap compared to fossil-free alternatives. Also stating that this is the result of insufficient government regulations. This observation aligns with other carriers views, that stable governmental initiatives are needed to advance towards zero emissions.

Regarding future investments and the choice of technology, one respondent stated, "We will invest in the sustainable solutions that is the best one for the time and place" [Company 4]. This view reflects the opinions of many other respondents, who mean that it is hard to know now what technology will be the correct one to invest in and use in the future. As there today are a lot of uncertainties when it comes to regulations, infrastructure, and demand. Another respondent stated, "We believe that Hydrogen Fuel is the most promising technology, but we are not planned for any investments now as the technology is not there" [Company 8] and "We are not planning any investments in sustainable transportation in the coming 10 years, but we are pushing to increase the HVO consumption instead of using only diesel fuels" [Company 1]. In addition, many carriers mention that regulations are not stable, one respondent stating, "what is considered the right solution one year may be replaced by another the next" [Company 13]. The regulatory uncertainty makes it difficult for companies to invest and commit to a certain technology, especially due to the high investment costs. However, one sea transportation provider, Company 17, explained that they currently have an order book of approximately 130 ships which really shows their sustainability efforts. They are investing in dual fuel engine vessels which will be able to use both diesel and alternative fuels.

4.2.2 Second round of Delphi

The analysis of empirical findings from the first round of the Delphi study provided the foundation for the development of the questionnaire used in the second round. In this round, each statement is evaluated to determine whether consensus among participants was achieved or not, presented in tables 19, 20 and 21. The cut off rate is calculated to be 77%, presented in table 18 accordingly to the methodology presented in section 3.3.3. Additionally, the respondents' reasoning behind their answers is presented to offer deeper insight into their perspectives. For clarification, two flows are discussed in the statements, where *Flow 1* is the transportation of goods within Europe, and *Flow 2* is the transportation of goods from Asia to Northern Europe.

Table 18: Data for calculating APMO cut off rate

APMO	
Total number of opinions	749
Majority of agreements	491
Majority of disagreements	86
APMO cut off rate	77%

Table 19: Consensus rate for policy Delphi round two: Statement 1-10

Statement #	Number of agreements	Number of disagreements	I don't know	Consensus Rate	Consensus Achieved
S1	23	5	5	82%	Yes
S2	16	5	12	76%	No
S3	27	1	5	96%	Yes
S4	25	4	4	86%	Yes
S5	18	7	8	72%	No
S6	31	0	2	100%	Yes
S7	26	6	1	81%	Yes
S8	20	7	6	74%	No
S9	25	3	5	89%	Yes
S10	17	5	11	77%	Yes

4.2.2.1 Statement 1

I believe transportation providers are responsible to lead the shift toward environmental sustainability by testing new technologies, rather than waiting for regulations to enforce it.

The answers for this statement agreed that the statement was correct, resulting in the agreement that consensus was achieved. The respondents expressed a wide range of opinions of why they answered as they did. However, five respondents who disagreed highlighted that economic constraints limit the space for carriers to test new technologies. The respondents who disagreed also emphasized that the responsibility for driving the shift should not rest solely on transportation providers. Instead, they argued that it is a shared responsibility, stating that "all actors in the supply chain are to drive change towards more sustainable technologies & transportation modalities".

However, the respondents who agreed with the statement also emphasize that the change requires collaboration among all parties, but that it must happen immediately. The agreed respondents state that regulatory decisions often take too long as they must consider numerous scenarios. They emphasized that there is no time to wait, as new regulations can already be outdated by the time they are implemented, due to the slow decision-making process. It was also noted that transportation providers are industry experts, since they are processing the resources, capabilities and a lot of practical experience. As such, they have the responsibility to address and reduce their increased emissions. The respondents also mean that taking advantage of being the ones that lead the shift strengthens the carriers competitive edge.

4.2.2.2 Statement 2

I believe that the availability of biofuels, in terms of fuel infrastructure and supply, will be larger for Flow 1 compared to Flow 2.

The respondents had various opinions on agreeing or disagreeing on this statement, which resulted in no consensus being achieved. The respondents who disagreed stated that biofuel availability would be the same for both flows. They noted that ongoing technical developments would be applied in both Europe and Asia, leading to equal availability. One respondent also means that these fuels are transferable worldwide, making the location of bunkering irrelevant.

However, respondents who agreed with the statement emphasized regional differences in infrastructure and policy support. They argued that Europe has already established more advanced systems for biofuels than Asia, and further improvements could lead to increased availability and usage. Accordingly, one respondent stated "Biofuels are relatively available in various Asian countries, but their feasibility is relatively difficult to implement", aligning with the views of those who agreed with the statement. Several respondents supported this view, highlighted EUs stricter environmental regulations as a key driver for greater adoption advantages. One respondent explained, "I also believe that the mindset from Europe is already much more focused on sustainability, precisely because in Europe we have much more extensive regulations on this compared to the rest of the world". The respondents mean that the future remains uncertain, but for now, Europe is at the forefront, while biofuels are not widely available in most Asian countries.

4.2.2.3 Statement 3

I believe that the availability of charging infrastructure for electric trucks, powered by renewable energy sources, will be larger for Flow 1 compared to Flow 2.

For this statement, consensus was achieved, where it was agreed that the availability will be larger for Flow 1 compared to Flow 2 which is attributed to several factors. The respondents stated that Flow 1 involves more road transport compared to Flow 2, which therefore will be easier to electrify. Additionally, EU is investing heavily in charging infrastructure and renewable energy, aiming for net zero 2050. The respondents believe that Europe has a stronger environmental awareness and economic capacity to support these initiatives. As a result, EU's infrastructure for electric trucks and renewable energy is significantly more advanced. As one respondent noted:

> EU is supporting this initiative with investing in charging infrastructure and renewable energy, as well targeting net zero by 2050. It's likely that Asia-area will pick up on the charging infrastructure and overtake Europe, but unlike to have renewable energy available at same time.

Moreover, Europe has a more developed infrastructure for electric vehicles and renewable energy sources. This is theme is mentioned by multiple respondents, including following cites "The European Union is actively expanding its power grid based on renewable energy sources such as wind, hydro, and solar power, and charging stations that utilize this clean energy are steadily increasing.", and "The share

of renewable electricity in Europe is already significant and is expected to increase further in the future". The share of renewable energy in Europe is expected to grow significantly. As Europe started earlier with electric vehicle and renewable energy initiatives, they are much more in the forefront. Although Europe currently leads in this area, Asia is rapidly developing its infrastructure and has significant potential to catch up in the future.

4.2.2.4 Statement 4

I believe customers ask for environmentally sustainable transportation but don't choose them due to higher costs.

The majority of the respondents agreed that customers ask for environmentally sustainable transportation but do not choose them due to higher costs. Accordingly, consensus was achieved. However, there were still 4 respondents who disagreed with the statement. These respondents believe that customers are increasingly aware of sustainability and are willing to pay for environmentally friendly transportation. One respondent state that "most cargo owners are willing to pay for environmentally friendly transport" and mean that their experiences is that leading international companies are willing to invest in sustainability. It was highlighted that this willingness varied depending on the type of customer, with larger global companies showing greater willingness compared to smaller and medium sized business.

However, respondents who agreed with the statement shared a not so different perspective based on their experiences. These respondents believe that while customers ask for environmentally sustainable transportation, they often do not choose these options due to higher costs. Some respondents noted that they still have customers who choose the sustainable option, often larger companies, which is still more on the uncommon side. One respondent states that the statement is not entirely accurate, saying, "Not 100% yes, but in 99% of the cases we see that customers do not want to pay for more in case that's more environmental friendly". Still, all customers understand the need for environmentally sustainable transportation solutions, but the respondents believe that cost remains a major driver in the procurement of supply chain services and are often prioritize the cheapest alternative to survive, as stated "economic outflow for consumers occurs immediately, while the benefits of eco-friendliness are not always directly felt or appreciated in the short term".

One respondent mean that this issue can be influenced by the competition of companies in regions such as Asia, US and Middle East often has a more cost effective production compared to plants in Europe. Cited by the respondent, "To remain competitive in Europe and not lose market share, we notice that our customers are not yet fully committed to sustainable solutions because of their additional costs.", which can be a reason why consensus is achieved for this statement.

4.2.2.5 Statement 5

I believe customers closer to the end consumer in the supply chain are more likely to buy environmentally sustainable transportation.

The respondents had various opinions about this statement, which resulted in no consensus being reached. The respondents who disagreed with the statement believe that customers closer to the end consumer in the supply chain are not necessarily more likely to buy environmentally sustainable transportation. One respondent argued that the pressure to lower the products environmental impact is more relevant in business-to-business (B2B) relationships where buyers and suppliers consider environmental impacts during procurement processes. Again, cost is a significant influencing factor, since environmentally sustainable transportation options are more expensive than traditional ones. The respondents continue to explain that financial considerations remain an important factor regardless of where the customer is positioned in the supply chain. Although, there is a gradual shift towards greater awareness of sustainable products among consumers, this change is slow, and many customers are not yet willing to bear the additional costs. Some respondents also noted that they do not observe this behavior among end customers.

On the other hand, respondents who agreed with the statement believe that customers closer to the end consumer in the supply chain are more likely to buy environmentally sustainable transportation. They argue that consumer demand drives this trend, as end consumers are increasingly seeking for more eco-friendly products and services. Therefore, respondents state that companies closer to the end consumer feel more pressure to show their sustainability initiatives and therefore want to offer that to customers. These companies want to satisfy the demands and maintain their brand image and consumer trust which makes them more likely to choose sustainable transportation options.

Accordingly, respondents state that the added cost for environmentally sustainable transportation is often relatively marginal compared to the total cost of the product, which generally make the end consumers more willing to pay this extra. One respondent noted, “The more you are able to communicate to end consumers that they are paying for a premium green product the easier it is”, while another stated that, “Customers closer to the end consumer are naturally more sensitive to environmental sustainability because they have to reflect consumer demands and expectations more directly”. Both responses highlighted a common theme among the experiences of respondents who agreed with S5. Although similar responses were gathered from respondents who agreed on the same topic, no clear consensus was reached.

4.2.2.6 Statement 6

I believe that it is worth investing in environmentally sustainable transportation solutions, even if there can be high investment and operational costs today

According to the result of statement 6 all respondents with an opinion agreed that it is indeed worth investing in environmentally sustainable transportation solutions,

even if there can be high investment and operational costs today. Therefore, a consensus was reached on 100%. The respondents believe that the future benefits of the investments will make the short-term investment cost worthwhile. However, one respondent noted that the investments may only be worthwhile if all stakeholders share the same goals and values towards sustainable solutions. However, many respondents mean that the importance of taking responsibility for the planet and the appreciation from end customers for such investments, giving them an edge in the market. Accordingly, one respondent answered:

> Although the initial investment and operational costs may be high, sustainable solutions can help companies prepare for future regulatory changes and strengthen brand image and consumer trust. ... Making environmentally responsible choices not only fulfills a company's social responsibility but also offers the potential for greater economic benefits, which is why such investments are highly valuable.

Continuously, some respondents indicated that their company's strategy and sustainability targets involve investing in more sustainable fuels and modes of transport, making such investments a natural choice for them. Accordingly, one respondent noted following: "We should be very clear that choosing not to invest is also a risk, because the market/economy will change, and if you don't invest or invest too late, you will be outdated and uncompetitive in the new economy". Therefore, respondents mean that it makes sense to invest now and learn from our own experiences, as this might become mandatory in the future. In line with that, one respondent explained:

> We have to invest, but we also need to get the customer to pay for it. If we invest too much, and don't get any extra for it, we will suffer and lose market shares. If the market price is only based on standard diesel solutions, and the freight buyers are not interested in paying for a better solution then we don't get any business.

4.2.2.7 Statement 7

> *I believe larger carriers must lead the shift to environmentally sustainable transport, setting the standard for subcontractors to follow in the future.*

In this statement, the majority of respondents agreed with the statements, although some disagreed, a consensus was still reached. The disagreed respondents believe that both large and small carriers are equally responsible for leading the shift to environmentally sustainable transport. They emphasize that all actors in the supply chain must contribute, regardless of size. Smaller carriers, even with limited resources, play a crucial role in setting examples and ensuring their future business. The disagreed respondents believe that environmental sustainable development should be a collective effort, with everyone contributing within their capabilities. Although larger companies may have more resources, smaller carriers can also be pioneers in adopting sustainable practices.

However, the respondents who agreed with this statement had other opinions. They believe that large companies have the resources, technical capabilities, and market influence to set standards for smaller businesses. Therefore, many believe that larger carriers have a significant role in driving the industry forward. Additionally, government support programs or incentives are suggested by the agreed respondents to support these efforts to avoid economic losses. In general, these respondents believe that larger carriers are viewed as having the responsibility and capability to lead the transition to sustainable transportation. A statement from one respondent supports the general view shared by all respondents, "The drive for sustainability is becoming increasingly important in the life of every company. A larger company will presumably have more opportunities to make the transition to sustainability, but a smaller company can do as much as it can".

4.2.2.8 Statement 8

I believe small carriers will struggle to adapt to the shift toward environmentally sustainable transportation

As a result of this statement, respondents expressed differing opinions, and no consensus was reached. The disagreed respondents highlight that small businesses operations might have less administrative burden and be closer to financial decisions. Consequently, small carriers are seen as more flexible and able to adapt easier to market changes, provided they have a solid business to secure necessary investments. Some respondents also mention that small carriers are already investing in sustainable solutions, believing that adapting to environmentally sustainable transportation would not be a problem for them. Meaning that small carriers, overall, can take advantage of new technologies and make environmental improvements in their daily operations.

Even though, the other side of the respondents agree that small carriers will struggle to adapt to the shift toward environmentally sustainable transportation. Respondents agree that small carriers will struggle to adapt to the shift toward environmentally sustainable transportation. Several reasons of this are highlighted including limited financial resources, high initial investment costs, and high costs of assets and infrastructure. Accordingly, one respondent noted, "Small carriers are likely to struggle with adapting to environmentally sustainable transportation because they have limited resources and capabilities compared to larger carriers".

Additionally, small carriers often face challenges in covering the expenses required for infrastructure and training to implement sustainable technologies. "Due to the high investment and close working with the customer to create an ecosystem to develop faster turnaround for these high investment products", one respondent explained. The financial burden and lack of specialized knowledge in sustainability are seen as significant barriers. Another respondent stated that, "It will be a great challenge for all companies, small and large, to make this transition. But especially for smaller companies, who often lack specialized knowledge in sustainability and

room for large investments". Accordingly, some respondents believe that to motivate participation of smaller carriers, strong support programs are essential. In general, respondents believe that while the transition will be challenging for all companies, it will be particularly difficult for smaller carriers due to their limited resources and capabilities.

4.2.2.9 Statement 9

I believe that transportation providers would transition to fossil-free long-haul transportation faster if the regulatory framework was stronger

This statement reached a consensus that transportation providers would transition to fossil-free transportation if the regulatory framework was stronger. The respondents who agreed to the statement mean that regulatory framework is the most important factor to speed up the transition. Many who agree with this statement mean that regulatory frameworks could speed up the transition by putting pressure on the companies. They mean that regulations and especially subsidies will drive change,

> Regulation sets the speed, and money speaks. If there's a "punishment" to sit on your hands, as well if there's no consequences, it's a simple ROI calculation to see when there's breakeven and it will 110% show in willingness to transition and the speed. Even though there's e.g. range issues or fossil-free fuel shortage, it will be a short term issue and market will pick-up soon.

Despite this, one respondent states that the regulatory framework could speed up the transition into fossil-free transportation, though it may also have negative consequences by creating an unfair competitive market between the EU and rest of the world. One respondent agreed on this statement and answered:

> Yes, but I don't think it is good. We follow all rules, so if the rule changes then we adapt. But I don't think it is good for the market, or the competitiveness for EU to impose too extensive regulations.

Therefore, some respondents mention that it is necessary to have regulatory frameworks on a global level to achieve a positive environmental impact. Some respondents stated that regulations promote consistent change across the industry, which can encourage companies to adopt sustainable transportation practices while remaining competitive. Respondents who did not agree with this statement highlighted other factors that are more important in affecting the speed of the transition, particularly customer demand and the availability of infrastructure.

4.2.2.10 Statement 10

I believe that international differences in regulations create an unfair competitive environment for fossil-free long-haul transport.

This statement reached a consensus, however it was very close to the APMO cut off rate. Thus, indicating that while there was overall agreement, opinions were still somewhat divided and not strongly aligned. Respondents who agree with this statement mean that international differences in regulations can create an unequal playing field for companies trying to comply with the same environmental standards. One respondent stated that, "Each country or region has a different level of economic development, and regional differences are very obvious". A common theme in the respondents who agree with this statement is that international differences in regulations mean that today some countries encourage fossil-free transportation more than others. Thus, resulting in differences in costs, where transportation providers in countries with stricter regulations may face higher costs, while those in countries with looser regulations may have a competitive advantage. This ultimately creates an unfair competitive environment. Some responders highlighting the difficulties this creates for big companies in selling mass balance principles to customers. One respondent states,

> An example is cross-border transportation between the Netherlands and Germany. The Netherlands has favorable regulations for environmental practices, whereas Germany does not to the same extent (depending on which field exactly). Therefore, it becomes difficult to create a competitive product.

The respondents who disagreed with S10 did not think that international differences creates an unfair competitive environment for fossil-free long-haul transport. One respondent mean that the statement is partly true, and align the answer similar to the ones who agreed to the statement. The respondent believe that each country have different opportunities and levels of support and stated, "EU funding and programs apply uniformly to all Member States (e.g. toll discounts in a country for electric vehicles can be applied to all electric vehicles in the EU, provided the rules are properly designed)". However, other respondents who disagreed with S10 mean that most regulations are created by EU and therefore are similar across borders.

4.2.2.11 Statement 11

I believe the following solutions will be a part of the future, year 2050, inland transportation solutions.

Table 20 presents an overview of the consensus rate for the seven alternative solutions. In addition Figure 12 visualizes the results. All solutions except LNG and fossil fuels reached consensus. Additionally, HVO was close to the APMO cut off rate, indicating somewhat divided opinions despite the reached consensus.

Table 20: Consensus rate for policy Delphi round two: Statement 11

Alternatives	S11 Number of agreements	Number of disagreements	I don't know	Consensus Rate	Consensus Achieved
Electric	31	0	2	100%	Yes
Intermodal	31	0	2	100%	Yes
Hydrogen	28	3	2	90%	Yes
HVO	20	6	7	77%	Yes
LNG	17	8	8	68%	No
Optimized efficiency and planning	29	0	4	100%	Yes
Fossil fuels (e.g. Diesel)	13	13	7	50%	No

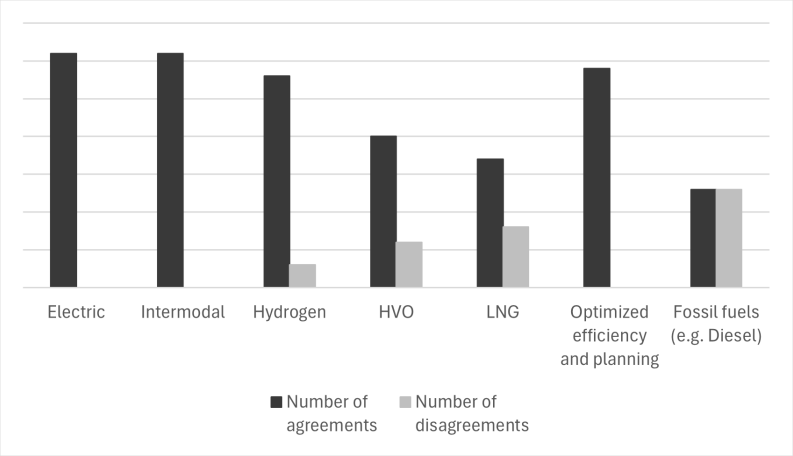

Figure 12: Presents the number of agreements and disagreements for each inland transportation solution

A common theme across a majority of responses is that a mix of technologies is needed to reach the goal of being CO_2 neutral by 2050. One answer stating, "I believe we're looking into a multi-fuel future". An additional perspective expressed was "There will be a need of different solutions pending on distance, availability, and culture". The overall view is that all or many of these solutions will be on the market in the future, because there is not one technology that fits all. Some meaning that there are differences when it comes to the market, maturity, and regulations which point towards the use of multiple technologies in the future. One additional perspective mentioned by one respondent is that multiple solutions are needed as the supply of one alternative solution is not enough.

For electric solution, it is clear that the transportation providers believe this technology will be a part of 2050. One respondent stating that, "the future is electric, since it would be cheapest and most efficient way". Another respondent stating, "Electric seems to be the way to go". Many agree that electric vehicles will be the future, but longer range and faster charging need to be in place. While most responses was optimistic, one respondent expressed a pessimistic opinion regarding electric trucks, "Unless new fundamental inventions in charging and energy storing technologies happen, it's hard to see electric trucks using regular batteries as

a viable solution for long haul transport". In addition, one respondent states that electric and hydrogen solutions will rapidly grow in combination with optimization and multi modality. Another view on hydrogen is, "The electric balance is not very good for H2. Depends on the energy system. If we produce a lot of "waste" energy (very high production with solar or wind when the conditions are right) H2 can be a solution but not if we have a energy shortage". Another respondent stated, "The future will mostly be electric but for long distance hydrogen will be used". For intermodal transportation, all respondents agreed that it is part of the future and a good way to reduce CO_2 emissions.

HVO is agreed to be a good alternative to diesel. However, one respondent states that, "Biofuels are currently in the pilot production stage and have not yet been effectively popularized". Additionally, one respondent stated that HVO will be used as an interim solution.

For LNG and fossil fuels consensus was not reached, indicating a wide range of different views among the respondents. Some believe that it is likely that there will still be a share of diesel used in the future. It is interesting to note that just as many people believe fossil fuels will still be present in 2050 as those who believe they will not. One respondent stated, "We can not reach the targets in the Paris agreement with fossil fuels by 2050", another responder pointed out that, "The application of fossil fuels cannot be completely replaced temporarily". This means that some transport providers believe that there is a probability that diesel will still be used in the future. Others state a more optimistic view, one respondent stating, "All non-fossil fuels will pave the way", and, "I have doubts about the future of LNG and Diesel. Fossil fuels availability will reduce and their costs will increase in the future". The addition of carriers means that it is important to choose eco-friendly solutions as a transportation provider. One respondent stating,

> At this point, it is not possible to say that any solution is 100% the right answer. However, with technological advancements, it is expected that progress will occur in stages, or even leap over some stages. What is certain is that the solution I have chosen is part of the eco-friendly solutions.

For LNG some respondents discuss if this solution should be considered as a "green" fuel. One respondent stating, "LNG is not green in the full supply chain". An additional respondent stated, "I am unsure if LNG will continue to pass the criteria of a "green" fuel due to methane slip and GHG effect of Methane".

4.2.2.12 Statement 12

I believe the following solutions will be a part of the future, year 2050, sea transportation solutions.

Table 21 presents the answers and an overview of the consensus rate, also visualized in Figure 13. Consensus was reached for all alternative solutions, except fossil fuels. For this statement a high number of "I don't know" answers were received. This

comes from the fact that the majority of the companies that participated in this study only have inland transportation and therefore do not have knowledge about sea transportation solutions. Therefore, this result was expected.

Table 21: Consensus rate for policy Delphi round two: Statement 12

Alternatives	S12 Number of agreements	Number of disagreements	I don't know	Consensus Rate	Consensus Achieved
Methanol	16	0	17	100%	Yes
Ammonia	12	0	21	100%	Yes
Carbon Capture Technology	19	1	13	95%	Yes
LNG	14	4	15	78%	Yes
Optimized efficiency and planning	27	0	6	100%	Yes
Fossil fuels (e.g. Diesel)	11	9	13	55%	No

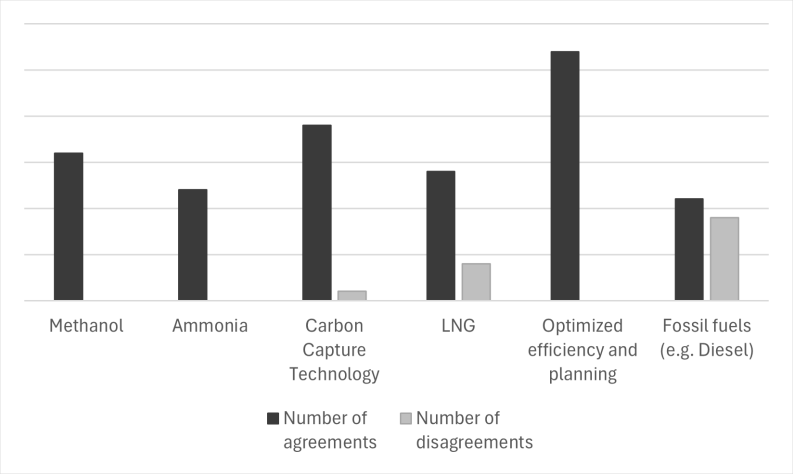

Figure 13: Presents the number of agreements and disagreements for each sea transportation solution

Similarly to inland transportation, the majority of respondents believe that the future of sea transportation will consist of a combination of multiple solutions. With one person stating: "All solutions/technologies are to be pursued & developed to be fully CO_2 neutral by 2050". Additional response, "Same as with inland transport. I believe we are looking into a multi-fuel future. All non-fossil fuels will pave the way towards 2050".

No consensus was reached regarding the use of LNG for inland transportation. However, for sea transportation, a consensus was reached but with small margins. Respondents noted that LNG may not be truly fossil-free which could explain the lower consensus rate, close to the cut-off rate. With one respondent stating, "LNG not sustainable I think but a good interim solution".

Methanol and ammonia have been mentioned several times, likely to be present in 2050. Two respondents stating , "Methanol and ammonia most likely the greenest" and "Methanol is already available today so yes i do believe it will be mature

enough to last into 2050 Ammonia is still being researched for scalable safe global sea transport, and is capable of being a true zero emission fuel". In addition, carbon capture technologies are also mentioned several times, with statements such as, "Carbon capture must be used for the remaining emissions that cannot be abated through green fuels" and "I believe that Carbon capture technology and Optimized efficiency and planning may be solutions for the future for inland transport".

For fossil fuels no consensus was reached, meaning the respondents have conflicting opinions. Two pessimistic views were, "For fossil fuels no consensus was reached, meaning the respondents have deflecting opinions" and "Sea transportation is very slow in implementing new technologies. And with many cargo vessels registered in low regulation countries the change will take time". While a more optimistic view was, "In the year 2050 we need to have come to a place where we do not use fossil fuels". An additional interesting statement regarding diesel was that, "Global ocean freight is harder to change. So it might still be fossil fuel for these ship on the market in 2050".

5
Discussion

The purpose of this thesis is to explore how environmental sustainability and resilience can be balanced in the design of inbound logistics flows for battery cell production in Europe. Through a FMEA, transport cost analysis, and a Delphi study, the research revealed key trade-offs between the design of inbound logistics flows. The following sections begin with a discussion on environmentally sustainable transportation, followed by an exploration of the trade offs between sustainability and resilience.

5.1 Environmentally Sustainable Transportation

The research findings confirm that the transportation sector plays an important role in global emissions which needs urgent transformation. This aligns with Blanco and Sheffi's [12] view that transportation accounts for approximately 90% of freight related remissions and must be adjusted to increase environmental sustainability awareness. The study presents that transportation providers feel a sustainable responsibility in transitioning to environmentally sustainable transport, but also see it as a strategic decision that offers competitiveness and opportunities to gather experiences of new emerging technologies. This supports the view by Vyacheslavovna Larina et al. [84], who argue that environmnetal sustainable transport requires coordination across sectors and is partly driven by competitive pressure.

This section discusses the importance of transitioning to environmentally sustainable transportation, highlighting the role of the transportation sector in global emissions and the need for urgent transformation. It emphasizes the competitive pressure and social responsibility driving this shift. Six main factors are discussed by transportation providers to influence the transition to fossil-free transportation by 2050. Those are: *Regulations and policies, Market competitiveness and global context, Customer demand and social pressure, Decarbonization strategies (technology and operations), Infrastructure and availability, and Carriers investments and innovation.* All of those influences each other, interact close, driving progress towards the fossil-free goals and are discussed further below.

5.1.1 Decarbonization Strategies

The study's findings supports the decarbonization strategies proposed by the International Transport Forum [69]. Transportation providers highlighted that an

integrating approach for the five decarbonization strategies is more effective than relying on a single solution to realize the full potential of fossil-free long-haul transportation. This aligns with earlier investigation by Ahmad et el. [5], who confirm that route planning, vehicle fill rates, and network design is an important step. The alignment shows the importance of efficient operations and smarter logistics when reducing emissions and improving sustainability.

However, results shows that continued reliance on alternative low emission fuels remains important as there is a limited availability of alternative technologies. These findings supports previous studies by IEA [64], who elaborate on that the relevance of different decarbonization technologies often depends on the transport mode. For instance, while electrification is valued as a lower emissions significantly for road transport, the maritime sector may continue to utilize biofuels or other emerging alternatives like ammonia, due to technological constraints.

Furthermore, the study highlights a strong believe among transportation providers for biofuels such as HVO, especially for road transportation, which aligns with earlier literature describing HVO as an immediate solution compatible with existing diesel engines [13]. However, the uncertainty findings remains in the long-term view and the viability of fuels like LNG. Earlier research can may explain this uncertainty, as LNG can decrease CO_2 emissions with 20-30% [23], and bio LNG can decrease it by 93% or even more [31, 136], which means that respondents can have a different views on LNG as one solution.

Transportation providers also noted the importance of intermodal transportation solutions, particularly in the role of rail transport in reducing emissions. This finding aligns with Anagnostopoulos [7], who highlight rail as one of the most environmentally sustainable transport modes. In this context, modal shift that is supported by demand management, can be one complementary strategy to decrease transportation emissions.

Although the long-term transition to environmentally sustainable transportation solutions is widely supported in the literature, transportation providers still expect fossil fuels such as oil to be part of the future share of inland and maritime transportation. The IEA [64, 66] state that renewable and alternative fuels will be increasingly important for the future, and fossil fuels will continue to be a part of it. This is primarily due to existing infrastructure and technological challenges. However, the findings of this study have diverse views among respondents, where some state that fossil fuels will remain, and other believe they will phase out to meet the climate targets. This reflection is also highlighted by Vyacheslavovna Larina et al. [84], who describe the complexity of environmentally sustainable transportation.

Nilsson et al. [106], argue that investments in innovation are important for transformation. Transportation providers align with this, meaning that it is worth investing in environmentally sustainable transportation solutions to support innovation and change. Aligned, Vyacheslavovna Larina et al. [84] state that investments by various

transport carriers are important in driving this shift. Some transportation providers argued that investments are crucial for companies to remain competitive and meet customer expectations, aligning well with the frame of reference. However, transportation providers also emphasized the need for regulatory support, as financial challenges will always be a significant factor.

The findings support the idea that no single decarbonization strategy is sufficient on its own [69]. Transportation providers mean that achieving fossil-free transportation requires combining multiple strategies and a collective effort from all stakeholders such as policymakers, shippers, infrastructure providers, and technology developers, to drive meaningful change [84, 106].

5.1.2 A refined approach to the barriers and drivers of decarbonization

The results show that transportation providers identified several key barriers and drivers shaping the transition to fossil-free transportation, which align with themes commonly discussed in the frame of reference: regulations, customer demand, and infrastructure availability. Accordingly, regulations and policies shape industry standards, influencing companies to adopt more environmentally sustainable practices [49, 41]. Accordingly, Gupta et al. and Jha et al. [56, 76] highlights that current regulations are insufficient, a view shared by transportation providers that also notes that the European market is leading the way in decarbonization efforts. This highlights the importance of regulations speeding up the transition. However, transportation providers also expressed that regulations can create an unfair competitive market between the EU and other regions of the world. Aligned it is noted that the EU is at the forefront and has more capabilities compared to other continents [42]. Transportation providers agree that stronger and clearer regulations would accelerate the decarbonization, but is now an unfair competition globally, also noted by IRENA [71]. Additionally, regulatory uncertainty increases investment risks, complicating carriers' decisions about adopting new technologies.

Social awareness and customer pressure are key drivers, consistent with McKinnon's findings on the role of environmnetal impact in brand positioning [92]. Although demand for sustainable options is increasing and higher costs often limit customers choice of transportation which is a challenge for wider implementation. Larger companies and those closer to end consumers tend to drive demand more effectively, while financial considerations remain decisive for many clients. This dynamic highlights the conflict between growing expectations and economic environments within the sector.

Infrastructure remains a critical barrier, particularly for electrification and alternative fules, as described by Sikandar et al. [1] and Guno et al. [55]. The limited availability of charging stations, refueling infrastructure and renewable energy sources slow down the implementation of environmental sustainable transport solutions [110,

142]. Transportation providers note that Europe's renewable infrastructure is in general more advanced in comparison to Asia. However, transportation providers also note that Asia has significant potential to catch up in the future. In addition, to developing infrastructure for various decarbonization strategies, transportation providers believe that technological advancements, such as improved range, are crucial for electrification to be a viable solution, aligning with challenges identified by Monteforte et al. [103] and Sikandar et al. [1]. Transportation providers believe that this lack of availability slows the transition, as increased lead times and costs are unavoidable with current solutions.

In line with critics from studies [38, 104], transportation providers state that the availability of environmentally sustainable solutions, regulatory support and customer demand are essential and will provide transportation providers with greater opportunities to transform. Without these factors, transportation providers will struggle to transition towards fossil-free transportation. However, optimistic views, supported by McKinsey and Nelldal [93, 105], highlight that with better support and investments, it is not a question of if the transition will happen, but when. The transportation providers' feedback underscores the importance of regulations and customer demand in driving this change. When these elements are in place, carriers are more likely to invest in and adopt sustainable technologies, aligning with optimistic projections of a shift towards electric, hydrogen, and biofuel-powered transportation.

5.2 Tradeoffs in Inbound Logistics

According to Kasilingam [80] logistics management has traditionally focused on maximizing customer service while minimizing total cost. However, our findings show that in today's competitive market where environmental sustainability and resilience has gained a lot of attention, this approach must advance. Modern inbound logistics design must balance cost efficiency with environmental sustainability and resilience, requiring difficult trade offs between these goals. In an ideal state, a company aims to achieve environmental sustainability, high resilience, and low costs simultaneously, which is hard to achieve. This section explores what realistically can be achieved today and in the future, grounded in the findings of this study. To better understand the trade-offs between environmental sustainability and resilience, a matrix has been developed that presents the different strategic positions a company can occupy.

The matrix is presented in Figure 14, and provides a framework for evaluating systems or strategies based on two dimensions: resilience and environmental sustainability. This framework is useful within inbound logistics, where trade-offs often exist between operational stability and environmental impact. Although cost is not directly included in the framework, it is still a critical variable that is heavily affected by the strategic positioning of both axes. By positioning resilience on the vertical axis and environmental sustainability on the horizontal axis, the matrix generates four quadrants: Undesirable Zone, Risk Zone, Emission Zone, and Ideal

Zone. Each quadrant represents a unique combination of these two dimensions, helping decision makers understand the current state and define strategic directions for improvement. Each axis in the matrix involves significant trade-offs related to resilience and environmental sustainability. The following sections will explore these trade-offs individually for each axis.

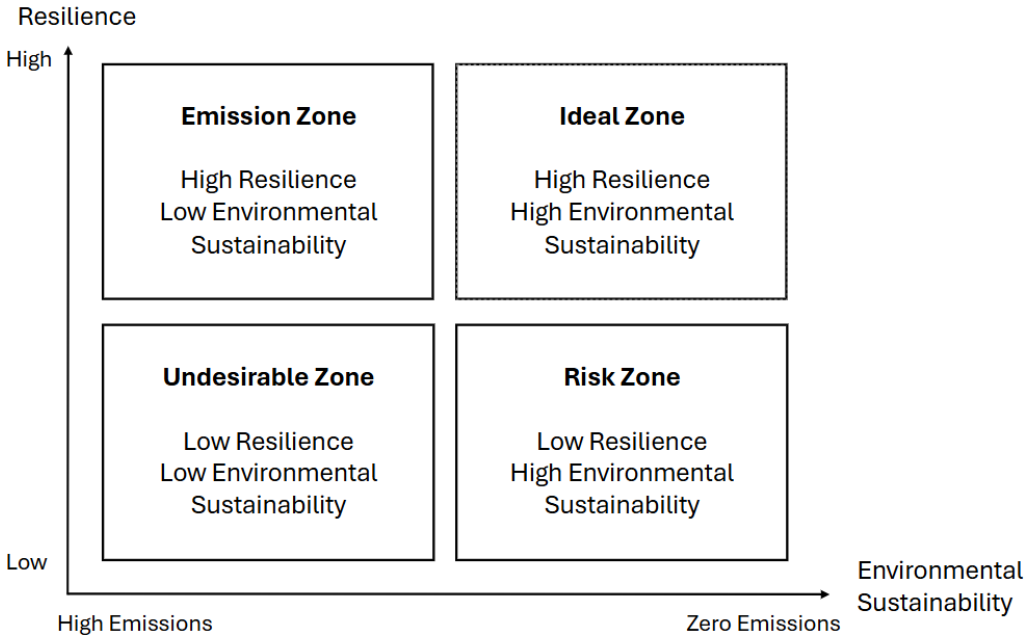

Figure 14: Matrix of resilience and environmental sustainability

Within the **vertical axis**, representing resilience, a company must make strategic positioning decisions, each involving trade-offs between different design factors. According to Choi et al. [27] resilience is increasingly becoming a priority in supply chain management, especially with growing geopolitical tensions and disruptions. The findings of this study show that resilience in inbound logistics is highly dependent on the geographical location of suppliers and the transportation modes being used. Which aligns with the findings of Li and Yang [115]. Based on the FMEA conducted in this thesis, the Asian transport flows is exposed to more risks with high RPN values. Especially for sea transport which was ranked at the maximum level in terms of severity. The result provide further evidence to Liang et al. [85] that highlights the risks associated with maritime transportation. While longer routes inherently increase risk, our findings also show that shorter transport modes used within Europe, such as rail, short sea, and truck also introduce uncertainties that impact a company's resilience. However, to a much smaller extent.

In addition, as explained by Zijm et al. [144], a fundamental decision must be made whether to adapt a more lean approach that focuses on cost efficiency that minimizes inventory or a resilient approach that builds on buffers to mitigate risks and uncertainties. The results provide further evidence regarding the scenarios in which a lean approach is appropriate, and where it may not be suitable. When

creating an Asian based inbound logistic flow, with long LTs and LT variations, resilience can still be achieved. However, proactive mitigation strategies must be in place. One proactive mitigation strategy is to maintain higher levels of safety stock, which increases inventory carrying costs [128]. In contrast, sourcing within Europe results in more stable and reliable lead times with less LT variation. This reduces the need for costly risk mitigation measures and enables leaner operations without compromising service levels. Therefore, the greater the risks associated with a route, the more mitigation strategies are required to proactively ensure resilience. Which aligns perfectly with the findings of Yang et al. [143].

The **horizontal axis** of the matrix represents the environmental sustainability, primarily influenced by the level of emissions associated with the inbound logistics operations. The left side is characterized by high emissions, typically resulting from long-distance transportation and the dependency on fossil fuels. In contrast, the right side of the axis reflects efforts toward zero emissions, often achieved through nearshoring and the use of the five decarbonization strategies presented by ITF [70]. The results show that, despite a growing ambitions for fossil-free transportation, the widespread adoption of such modes remains limited, as most freight operations still are dependent on fossil fuel methods. However, this dependence on fossil fuels varies significantly between continents and within Europe. The achievement of net zero emissions remains difficult today due to the challenges discussed earlier. In addition, an environmentally sustainable inbound logistics design involves high operational or/and investment costs, making it a strategic decision for companies [52, 55]. Furthermore, transportation distance also critically impacts both emissions and costs. Sourcing from Europe typically results in lower emissions and transport costs, while Asian sourcing offers cheaper materials, but increases emissions and transportation costs in most cases.

Reliance and environmental sustainability create a matrix consisting of four zones. The first quadrant, **undesirable zone**, has low resilience and low environmental sustainability, making it the least favorable zone. Systems positioned here face high sensitivity to disruptions and have a significant environmental impact. A typical example is sourcing from Asia without implementing relevant risk mitigation strategies. Asian flows often depend on long, multimodal transportation routes that often use fossil-fuels, leading to high emissions [67]. At the same time, without identifying risks or using risk mitigation strategies such as inventory buffers, the inbound logistic is heavily affected by uncertainties [128]. Although this approach may seem cost-effective due to low inventory and cheaper unit costs, it often leads to low resilience and high environmental impact, which put both production and sustainability at risk.

The second quadrant, **risk zone**, has high environmental sustainability, but low resilience. High environmental sustainability is reached through the use of e.g., electric trucks, rail, and HVO. Low resilience means that there is a high exposure to risks such as unreliable delivery times [114]. When a company is part of the risk zone, the company does not acknowledge the risks that are part of their logistics

network and therefore does not implement any mitigation strategies. The FMEA revealed that multimodal transportation, involving rail, resulted in a higher normalized risk value. Indicating a greater need for proactive risk mitigation measures. In addition, the infrastructure of more sustainable transportation solutions, such as charging of electric trucks, and alternative fuel stations, are not yet reliable or widely available. Thus, also resulting in increased transportation risks. This zone reflects a well-intentioned but operationally vulnerable setup. It highlights the risk of pursuing sustainability goals without matching investment in risk management and risk mitigation strategies.

The third quadrant, **emission zone**, has high resilience and low environmental sustainability. Companies in this zone have invested in robust inbound logistics strategies, but continue to operate with high emissions. E.g. Sourcing from Asia offers high resilience when supported by inventory buffers, which leads to longer distances and more emissions. Alternatively, European sourcing with more stable lead times and low variability also results in high resilience. If no environmental initiatives are implemented, the logistics operation remains producing large emissions. According to the findings of this thesis, in the short term, fossil fuel transportation is more cost-effective, as transportation providers estimate approximately 2,5 times higher costs for biofuels. However, many transportation providers believe future regulations will lead to an increase of fossil-fuel prices. Therefore, companies in this zone will need to move toward reducing emissions to prepare for the future.

However, the empirical findings show that designing an inbound logistics flow within Europe tends to position companies closer to the ideal zone. In addition, the findings indicate that customer demand for sustainable transportation remains limited, particularly during periods of economic downturn. In addition, companies are likely to remain in the emission zone, driven by a combination of today's cost advantages, technological uncertainties, lack of regulatory pressure today, and limited customer willingness to pay for sustainable transport. However, the increased focus on environmental sustainability, growing customer expectations and policy changes, companies in this zone will need to transition toward lower-emission solutions to stay competitive in the long run.

The fourth quadrant, **ideal zone**, is reached when both environmentally sustainable and resilience is reached. Based on the findings of this study and current market conditions, this quadrant is difficult to reach today. A vary limited number of European transportation providers offer services close to zero emissions, but typically come with a significantly higher cost. However, Sharmil et al. [127] explained that the market for inbound battery cell materials is heavily concentrated in Asia, making it challenging to achieve high levels of environmental sustainability. In addition, sustainable transportation options in Asia are more limited due to limited availability and underdeveloped infrastructure. Furthermore, from the empirical findings it is clear that when sourcing from Asia it is today not possible to reach net zero targets. However, the transformation toward this ideal zone is expected to accelerate in the coming years, driven by regulatory pressure, technological innovation, and

investments in fossil-free transportation solutions. Many experts expect fossil free transportation to become viable by 2050, and state that different decarbonization strategies will be developed and infrastructure will be expanded. Furthermore, the ambition of European Commissions to expand their production base for battery raw materials will also increase the possibility of creating an European based battery cell supply chain. Until then, positioning close to the ideal zone is especially hard when working in the context of battery cell manufacturing. However, it is still important to note that European suppliers may still be reliant on Asian mining materials and suppliers, and therefore may have hidden costs and emissions. As many materials travel long distances before ending up at the European supplier [116].

By mapping sourcing strategies and current market within this framework, companies can better identify opportunities to move closer to the ideal quadrant. This may involve investments in transport decarbonization, reshoring or nearshoring, or strategically increasing inventory buffers. A dynamic and context-sensitive approach allows companies to tailor their strategies to balance cost, risk and environmental goals effectively. At the same time, it is important to recognize that external factors can impact these strategies. This thesis was written during a time of ongoing discussions and uncertainty about tariffs, which can have a major impact on supply chain structures, strategic decisions, and overall outcomes [29]. The changing conditions related to tariffs were not included in the scope of this research. However, they should be mentioned and considered when evaluating the findings of this thesis.

6
Conclusion

The purpose of this research is to investigate the interplay between the design parameters of sustainable and resilient inbound logistics flows. This was investigated within the context of an European battery cell production facility, with the aim of understanding the trade-offs and opportunities in designing such inbound logistics systems. This was operationalized into the following two research questions, which were answered on the basis of the frame of reference, empirical findings, and discussion.

RQ1: How do transportation costs and risks impact the inbound logistics design when sourcing EV battery components from Asian versus European suppliers?

The findings show that transportation costs and risks significantly influence inbound logistics design. Sourcing from Asian suppliers generally results in higher risk levels. As shown in the FMEA analysis, sea transportation was ranked highest, reflecting its exposure to many high ranked risks. This is driven by long delays, port risks, weather related risks, and geopolitical tensions. Rail within Europe also presented relatively high risks. In contrast, truck transport, both in Europe and Asia, showed lower risks. The risk analysis was then used to calculate the lead time variation for both an European and Asian flow. The Asian flow showed a variation of approximately 8 to 10 days, while the Europe flow showed far more predictable performance, with variation between just 2 to 9 hours. This gap in stability for the two flows directly impacts the inventory strategy. When sourcing from Asia, more risk mitigation strategies are needed to cover the variation. In contrast, European sourcing enables leaner inventory levels, leading to lower inventory buffer levels needed. Transportation costs from Europe were on average 43% lower than transportation from Asian suppliers. This still varied for each route and contract. For two materials transportation from European suppliers, the cost difference was small compared to Asian sourcing. This indicates that negotiated agreements and different routes can strongly influence the total transportation cost. In addition, these findings must be discussed within the context of battery cell production, where current conditions still rely heavily on Asian suppliers. This underlying dependency results in significant trade offs between sustainability, resilience, and cost that companies must decide on when designing their inbound logistics flows.

RQ2: What are the joint perspectives of Asian and European carriers on the potential of a fossil-free long-haul transportation solution for European supply chains?

The perspectives collected from Asian and European carriers highlight a common understanding of the need to move to fossil-free transportation. However, several barriers were identified, including limited fuel availability in both quantity and geographical location, high investment costs, and uncertain regulations. Carriers providing transportation in Europe generally expressed a stronger alignment with fossil-free targets. The interviewed Asian transportation providers have less environmental sustainability efforts compared to European providers. However, many carriers in both Europe and Asia highlighted a willingness to invest in new sustainable transportation technologies, as long as the infrastructure, regulatory framework, and customer support develop. One finding highlighting that customer demand for sustainable solutions remains small, which limits carriers' ability to make new investments. In conclusion, it is clear that transportation providers agree that fossil-free solutions are the future. However, the key uncertainty is when these targets can realistically be achieved. All stakeholders in the supply chain are needed to be able to achieve a successful transition to environmentally sustainable transportation solutions.

6.1 Theoretical Implications

This study contributes to the theoretical development of risk management and environmentally sustainable transportation by extending the use of FMEA. This research integrates FMEA with lead time variability and safety stock analysis, providing a dynamic view on how risks influence inventory planning in inbound logistics. This approach creates a better understanding of how various risks affect lead times and inventory requirements, which is essential for designing resilient supply chains. Additionally, existing theory states that transport from Europe is generally less expensive compared to transport from Asia. However, this study adds to that understanding by using real case transportation contracts. This shows that on average transportation costs are 43% lower. However, transportation is not cheaper in all cases due to specific negotiated contracts.

In addition, the study also contributes to the literature on supply chain resilience and environmentally sustainable transportation. The proposed 2x2 matrix, illustrated in Figure 14, is a structured matrix that can offer a new way to analyze trade-offs in supply chain design. These contributions bridge gaps in existing theory by showing how previous literature on risk management and environmental sustainability interact and must be balanced together. It provides a foundation for evaluating strategic decisions such as inventory and sourcing location, and use of transportation mode. This not just by efficiency, but also through resilience and environmental sustainability. When comparing this research to established theories that prioritize costs and efficiency, this research highlights the importance of environmental sustainability and resilience into inbound logistics design. This challenges the traditional view on logistics management theories.

However, it is important to remember that this study has been conducted in current conditions of sourcing battery components from Asia or Europe. Given that today's

constraints are limited due to fossil-free transport infrastructure, regulations and global supply chains. The findings show that full alignment of resilience and environmental goals may not yet be feasible across all flows. Although achieving high resilience with low environmental impact is challenging under current conditions, this shift is expected to accelerate, making such strategies valuable even though investments can be needed.

6.2 Implication for Practice

The findings of this research provide valuable insights into the design of environmentally sustainable and resilient inbound logistics, especially when sourcing EV battery components. This research provides tools and decision-making frameworks that practitioners can use to balance competing goals of resilience, cost efficiency, and environmental sustainability.

To integrate risk assessment and inventory management, it is showed how FMEA can be used not only as a risk identification and assessment tool, but also for decision making. By mapping risks in a structured way, companies gain greater visibility of their risks, allowing them to better prioritize and implement proactive and targeted risk mitigation strategies. This enables practitioners to use this approach to better justify inventory positioning, based on risk scenarios. An example from the findings is that sea freight from Asia to Europe is associated with high-risk scores due to politics, port congestion, weather-related delays, etc. Instead of treating all suppliers the same, managers can adjust inventory levels depending on how risky each supply route is.

In addition, many companies have set net-zero targets, this thesis shows the complexity of achieving zero emission within the transportation sector. The findings show that despite ambitions from many actors, practical barriers such as limited infrastructure, uncertainties in regulation, and cost constraints continue to hinder progress. Furthermore, transportation providers have deflecting opinions on the future of sustainable transportation. The findings show that the opinions are vary split when it comes to whether fossil fuels will be part of 2050 or not. Approximately half of the interviewed transportation providers believe that fossil fuels will still be part of 2050. This suggests that companies heavily reliant on transportation may need to reconsider the feasibility of achieving their net zero targets. Furthermore, the findings show that customers of transportation services will need to be willing to pay an extra fee for the transition to accelerate. Interviews with transportation providers also revealed that the transition requires coordinated efforts across the supply chain, as well as clearer regulatory guidance and financial incentives.

This study also shows that transportation providers vary significantly in both their current state and their sustainability ambitions. One transportation providers have set a net zero target at the end of 2025, while others believe it is too early to set such targets as there today are too many uncertainties. While European carriers tend to be more aligned with fossil free goals, Asian carriers often lack clear targets and have

not implemented environmentally sustainable solutions to the same extent as the European providers. Therefore, companies that rely on international transportation should consider the sustainability maturity of their partners and select carriers based on alignment with their own net zero goals.

6.3 Limitation and Future Research

This study is limited by its geographical and industrial scope, focusing specifically on inbound logistics for battery cell production in Europe. The findings are relevant for similar manufacturing contexts, they may not fully apply to other industries or regions. The FMEA was based on interviews and available data, which might not consider all variables or disruptions in real time. Additionally, carrier perspectives may be shaped by current market conditions, such as the fact that the case company is a potential customer to them.

Future research could investigate the long-term cost evolution of fossil-free transport solutions as regulations and infrastructure evolve. Especially when regulatory frameworks tighten. In addition, comparative studies across different industries and locations could further explore the resilience–sustainability trade-offs identified in this work. Furthermore, as the value chain for battery production is long and complex, future research could investigate the continued dependence on Asia, even when companies choose to source from European suppliers. While suppliers may be geographically located in Europe, many still rely on upstream materials or components that originate in Asia, particularly for critical battery-grade raw materials. This hidden dependency can significantly affect both the resilience of the supply chain and its overall environmental footprint. Therefore, a deeper examination of indirect sourcing patterns and the multi-tier supplier base could be made. It would also be interesting to combine the findings from this research with further studies on battery cell inbound material costs, particularly how they vary depending on the sourcing location. This would provide a comprehensive understanding with a total cost perspective. In addition, as new battery cell technologies are emerging with new chemistry, further research could explore the impact of emerging battery cell technologies. In particular, investigate whether such advancements could reduce the current dependency on Asian suppliers, who are currently dominating both mining and raw material processing for battery cell production.

Bibliography

[1] Sikandar Abdul Qadir et al. "Navigating the complex realities of electric vehicle adoption: A comprehensive study of government strategies, policies, and incentives". In: *Energy Strategy Reviews* 53 (May 2024), p. 101379. ISSN: 2211467X. DOI: 10.1016/j.esr.2024.101379.

[2] Canan Acar and Ibrahim Dincer. "The potential role of hydrogen as a sustainable transportation fuel to combat global warming". In: *International Journal of Hydrogen Energy* 45.5 (Jan. 2020), pp. 3396–3406. ISSN: 03603199. DOI: 10.1016/j.ijhydene.2018.10.149.

[3] Nana Adu-Pipim Boaduo. "Systematic analysis and interpretation of collected data for a research study: A practical methodological framework for writing research report". In: *Academic Journals* (2011). ISSN: 1990-3839. URL: https://academicjournals.org/article/article1379670097_Boadou.pdf.

[4] Behdad Afkhami, Babak Akbarian, and Ehsan Ansari. "Adoption of battery electric vehicles for reduction of greenhouse gases and air pollutant emissions: A case study of the United States". In: *Energy Storage* 4.1 (Feb. 2022). ISSN: 2578-4862. DOI: 10.1002/est2.280.

[5] Salman Ahmad et al. "Packaging design, fill rate and road freight decarbonisation: A literature review and a future research agenda". In: *Cleaner Logistics and Supply Chain* 4 (July 2022), p. 100066. ISSN: 27723909. DOI: 10.1016/j.clscn.2022.100066.

[6] Gustav Albertzeth et al. "Mitigating transportation disruptions in a supply chain: a cost-effective strategy". In: *International Journal of Logistics Research and Applications* 23.2 (Mar. 2020), pp. 139–158. ISSN: 1367-5567. DOI: 10.1080/13675567.2019.1648640.

[7] Apostolos Anagnostopoulos. "Modal Shift to Rail Transport as a Mitigation Measure to Decarbonize the Transport Sector: Review of Barriers and Opportunities". In: *E3S Web of Conferences* 585 (Nov. 2024), p. 12001. ISSN: 2267-1242. DOI: 10.1051/e3sconf/202458512001.

[8] Phillip J. Ansell. "Hydrogen-Electric Aircraft Technologies and Integration: Enabling an environmentally sustainable aviation future". In: *IEEE Electrification Magazine* 10.2 (June 2022), pp. 6–16. ISSN: 2325-5897. DOI: 10.1109/MELE.2022.3165721.

[9] Maria Grazia Attinasi et al. *Global production and supply chain risks: insights from a survey of leading companies*. DOI: xx.xxxx/xxxxxx. URL: https://www.ecb.europa.eu/press/economic-bulletin/focus/2023/html/ecb.ebbox202307_01~2a0bcf0b48.en.html.

[10] Emma Bell, Alan Bryman, and Bill Harley. *Business research methods*. 5th ed. United Kingdom: Oxford University Press, 2019.

[11] Georg Bieker et al. *MORE BANG FOR THE BUCK: A COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSION BENEFITS AND INCENTIVES OF PLUG-IN HYBRID AND BATTERY ELECTRIC VEHICLES IN GERMANY AUTHOR CONTRIBUTIONS*. Tech. rep. 2022. URL: www.theicct.orgcommunications@theicct.org.

[12] Edgar E. Blanco and Yossi Sheffi. "Green Logistics". In: 2017, pp. 147–187. DOI: 10.1007/978-3-319-29791-0{_}7.

[13] Thomas Bohl et al. "Particulate number and NO trade-off comparisons between HVO and mineral diesel in HD applications". In: *Fuel* 215 (Mar. 2018), pp. 90–101. ISSN: 00162361. DOI: 10.1016/j.fuel.2017.11.023.

[14] Jaime Bonnin Roca and Eoin O'Sullivan. "The role of regulators in mitigating uncertainty within the Valley of Death". In: *Technovation* 109 (Jan. 2022), p. 102157. ISSN: 01664972. DOI: 10.1016/j.technovation.2020.102157.

[15] Books. "FMEA Book 2". In: *Quality Management* (2009), pp. 138–157. ISSN: 1098-6596.

[16] Bulin Boonrod et al. "Environmental impact assessment of bio-hydrogenated diesel from hydrogen and co-product of palm oil industry". In: *International Journal of Hydrogen Energy* 46.17 (Mar. 2021), pp. 10570–10585. ISSN: 03603199. DOI: 10.1016/j.ijhydene.2020.03.183.

[17] Lutz Bornmann, Loet Leydesdorff, and Rüdiger Mutz. "The use of percentiles and percentile rank classes in the analysis of bibliometric data: Opportunities and limits". In: *Journal of Informetrics* 7.1 (Jan. 2013), pp. 158–165. ISSN: 1751-1577. DOI: 10.1016/J.JOI.2012.10.001. URL: https://www.sciencedirect.com/science/article/pii/S1751157712000831.

[18] Boston Consulting Group (BCG) and Europeans Federation for transport and environment (T&E). "Impact Assessment of the Transition to Zero-Emission Trucks in Europe". In: (Sept. 2023). URL: https://www.transportenvironment.org/uploads/files/20230919-Transport-Environment_EU-Truck-CO2-Standards_Final_Report_TE_vF.pdf.

[19] Shane R. Brady. "Utilizing and Adapting the Delphi Method for Use in Qualitative Research". In: *International Journal of Qualitative Methods* 14.5 (Dec. 2015). ISSN: 1609-4069. DOI: 10.1177/1609406915621381.

[20] Judith Brand et al. "Modelling multimodal transit networks integration of bus networks with walking and cycling". In: *2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*. IEEE, June 2017, pp. 750–755. ISBN: 978-1-5090-6484-7. DOI: 10.1109/MTITS.2017.8005612.

[21] Selma Brynolf et al. "Review of electrofuel feasibility—prospects for road, ocean, and air transport". In: *Progress in Energy* 4.4 (Oct. 2022), p. 042007. ISSN: 2516-1083. DOI: 10.1088/2516-1083/ac8097.

[22] Carl S. Carlson. "Effective FMEAs : Achieving Safe, Reliable, and Economical Products and Processes Using Failure Mode and Effects Analysis." In: (2012). URL: https://openurl.ebsco.com/contentitem/cat07472a:

clec.EBC827069?sid=ebsco:plink:crawler&id=ebsco:cat07472a:clec.EBC827069&crl=c.

[23] Edward W Carr et al. *Options for Reducing Methane Emissions from New and Existing LNG-Fueled Ships Prepared for Options for Reducing Methane Emissions from New and Existing LNG-Fueled Ships*. Tech. rep. 2023.

[24] Davide Castellano et al. "Optimizing production-inventory replenishment and lead time decisions under a fill rate constraint in a two-echelon sustainable supply chain with quality issues". In: *International Journal of Systems Science: Operations & Logistics* 10.1 (Dec. 2023). ISSN: 2330-2674. DOI: 10.1080/23302674.2023.2173540.

[25] Rahul S. Chauhan. "Unstructured interviews: are they really all that bad?" In: *Human Resource Development International* 25.4 (Aug. 2022), pp. 474–487. ISSN: 1367-8868. DOI: 10.1080/13678868.2019.1603019.

[26] Xingguang Chen et al. "Cooperation-Oriented Multi-Modal Shared Mobility for Sustainable Transport: Developments and Challenges". In: *Sustainability* 16.24 (Dec. 2024), p. 11207. ISSN: 2071-1050. DOI: 10.3390/su162411207.

[27] Tsan Ming Choi, Chun Hung Chiu, and Hing Kai Chan. "Risk management of logistics systems". In: *Transportation Research Part E: Logistics and Transportation Review* 90 (June 2016), pp. 1–6. ISSN: 1366-5545. DOI: 10.1016/J.TRE.2016.03.007.

[28] Wenming Chung, Srinivas Talluri, and Gyöngyi Kovács. "Investigating the effects of lead-time uncertainties and safety stocks on logistical performance in a border-crossing JIT supply chain". In: *Computers & Industrial Engineering* 118 (Apr. 2018), pp. 440–450. ISSN: 03608352. DOI: 10.1016/j.cie.2018.03.018.

[29] Farok J. Contractor. "Assessing the economic impact of tariffs: adaptations by multinationals and traders to mitigate tariffs". In: *Review of International Business and Strategy* 35.2/3 (Apr. 2025), pp. 190–213. ISSN: 20596022. DOI: 10.1108/RIBS-01-2025-0013/FULL/PDF.

[30] Rui Cruz et al. "Smart Rail for Smart Mobility". In: *2018 16th International Conference on Intelligent Transportation Systems Telecommunications (ITST)*. IEEE, Oct. 2018, pp. 1–7. ISBN: 978-1-5386-5544-3. DOI: 10.1109/ITST.2018.8566842.

[31] Cycle0. *How is biomethane carbon neutral?* Nov. 2023. URL: https://www.cycle0.com/how-is-biomethane-carbon-neutral.

[32] Stefano d'Ambrosio, Alessandro Mancarella, and Andrea Manelli. "Utilization of Hydrotreated Vegetable Oil (HVO) in a Euro 6 Dual-Loop EGR Diesel Engine: Behavior as a Drop-In Fuel and Potentialities along Calibration Parameter Sweeps". In: *Energies* 15.19 (Sept. 2022), p. 7202. ISSN: 1996-1073. DOI: 10.3390/en15197202.

[33] Florian Degen. "Lithium-ion battery cell production in Europe: Scenarios for reducing energy consumption and greenhouse gas emissions until 2030". In: *Journal of Industrial Ecology* 27.3 (June 2023), pp. 964–976. ISSN: 15309290. DOI: 10.1111/jiec.13386.

[34] Rommert Dekker, Jacqueline Bloemhof, and Ioannis Mallidis. "Operations Research for green logistics – An overview of aspects, issues, contributions

and challenges". In: *European Journal of Operational Research* 219.3 (June 2012), pp. 671–679. ISSN: 03772217. DOI: 10.1016/j.ejor.2011.11.010.

[35] M. A. Delucchi et al. "An assessment of electric vehicles: technology, infrastructure requirements, greenhouse-gas emissions, petroleum use, material use, lifetime cost, consumer acceptance and policy initiatives". In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372.2006 (Jan. 2014), p. 20120325. ISSN: 1364-503X. DOI: 10.1098/rsta.2012.0325.

[36] Kapil Dev et al. *Failure Mode and Effect Analysis (FMEA) Implementation: A Literature Review*. Tech. rep. 2018. URL: https://www.researchgate.net/publication/333209894.

[37] Anna Dubois and Lars-Erik Gadde. "Systematic combining: an abductive approach to case research". In: *Journal of Business Research* 55.7 (July 2002), pp. 553–560. ISSN: 01482963. DOI: 10.1016/S0148-2963(00)00195-8.

[38] Christoph Elhardt. *Heavy trucks likely not zero-emission in the near future*. Oct. 2023. URL: https://ethz.ch/en/news-and-events/eth-news/news/2023/10/heavy-trucks-likely-not-zero-emission-in-the-near-future.html.

[39] EMBER. *Electricity landscape in ASEAN*. URL: https://ember-energy.org/latest-insights/asean-insights-2024/power-sector-2023.

[40] Enerdata. *The New Frontier of Road Transport Electrification*. Aug. 2024. URL: https://www.enerdata.net/publications/executive-briefing/transition-electric-mhdv.html.

[41] International Energy Agency. *Global Supply Chains of EV Batteries*. Tech. rep. URL: www.iea.org/t&c/.

[42] European Commission. *2050 long-term strategy*. URL: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en#:~:text=Striving%20to%20become%20the%20world%27s%20first%20climate-neutral%20continent,binding%20target%20thanks%20to%20the%20European%20Climate%20Law..

[43] European Commission. *Connecting Europe Facility*. URL: https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/connecting-europe-facility_en.

[44] European Commission. "Delivering the European Green Deal". In: *European Comission* (). URL: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en.

[45] European Commission. *The European Green Deal Striving to be the first climate-neutral continent*. URL: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

[46] European Commission. *Transport and the Green Deal*. URL: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/transport-and-green-deal_en.

[47] European Parliamentary Research Service (EPRS). *South Korea's pledge to achieve carbon neutrality by 2050*. Tech. rep. 2020. URL: https://www.

europarl.europa.eu/RegData/etudes/BRIE/2021/690693/EPRS_BRI(2021)690693_EN.pdf.

[48] Europeans Federation for transport and environment (T&E). "Financing transport decarbonisation". In: (Nov. 2024). URL: https://www.transportenvironment.org/uploads/files/202411_investment_needs_study.pdf.

[49] Jacco Farla, Floortje Alkemade, and Roald A.A. Suurs. "Analysis of barriers in the transition toward sustainable mobility in the Netherlands". In: *Technological Forecasting and Social Change* 77.8 (Oct. 2010), pp. 1260–1269. ISSN: 00401625. DOI: 10.1016/j.techfore.2010.03.014.

[50] John Ferreira and Len Prokopets. "Does offshoring still make sense?" In: *Supply Chain Management Review* 13.1 (Jan. 2009). ISSN: 1521-9747.

[51] Andrea Galieriková and Jarmila Sosedová. "Environmental Aspects of Transport in the Context of Development of Inland Navigation". In: *Ekológia (Bratislava)* 35.3 (Sept. 2016), pp. 279–288. ISSN: 1337-947X. DOI: 10.1515/eko-2016-0022.

[52] Larry C. Giunipero and Reham Aly Eltantawy. "Securing the upstream supply chain: A risk management approach". In: *International Journal of Physical Distribution and Logistics Management* 34.9 (2004), pp. 698–713. ISSN: 09600035. DOI: 10.1108/09600030410567478/FULL/XML.

[53] Pooja Goel et al. "Understanding transport users' preferences for adopting electric vehicle based mobility for sustainable city: A moderated moderated-mediation model". In: *Journal of Transport Geography* 106 (Jan. 2023), p. 103520. ISSN: 09666923. DOI: 10.1016/j.jtrangeo.2022.103520.

[54] Heiko A. von der Gracht. "Consensus measurement in Delphi studies". In: *Technological Forecasting and Social Change* 79.8 (Oct. 2012), pp. 1525–1536. ISSN: 00401625. DOI: 10.1016/j.techfore.2012.04.013.

[55] Charmaine Samala Guno, Angelie Azcuna Collera, and Casper Boongaling Agaton. "Barriers and Drivers of Transition to Sustainable Public Transport in the Philippines". In: *World Electric Vehicle Journal* 12.1 (Mar. 2021), p. 46. ISSN: 2032-6653. DOI: 10.3390/wevj12010046.

[56] Anshu Gupta and Ananya Garg. "Modelling the enablers for adoption of electric vehicles in India". In: *International Journal of System Assurance Engineering and Management* 15.2 (Feb. 2024), pp. 635–645. ISSN: 0975-6809. DOI: 10.1007/s13198-022-01687-1.

[57] Rudraksh S. Gupta, Arjun Tyagi, and S. Anand. "Optimal allocation of electric vehicles charging infrastructure, policies and future trends". In: *Journal of Energy Storage* 43 (Nov. 2021), p. 103291. ISSN: 2352152X. DOI: 10.1016/j.est.2021.103291.

[58] Florian Habermacher and Paul Lehmann. "Commitment Versus Discretion in Climate and Energy Policy". In: *Environmental and Resource Economics* 76.1 (May 2020), pp. 39–67. ISSN: 0924-6460. DOI: 10.1007/s10640-020-00414-3.

[59] N.P. Hariram, A. Megalingam, and K. Sudhakar. "Flying cars and hyperloops: A glimpse into the future sustainable vehicles". In: *Sustainable Energy Technologies and Assessments* 75 (Mar. 2025), p. 104196. ISSN: 22131388. DOI: 10.1016/j.seta.2025.104196.

[60] Qusay Hassan et al. "Green hydrogen: A pathway to a sustainable energy future". In: *International Journal of Hydrogen Energy* 50 (Jan. 2024), pp. 310–333. ISSN: 03603199. DOI: 10.1016/j.ijhydene.2023.08.321.

[61] William Ho et al. "Supply chain risk management: a literature review". In: *International Journal of Production Research* 53.16 (Aug. 2015), pp. 5031–5069. ISSN: 1366588X. DOI: 10.1080/00207543.2015.1030467. URL: https://www.tandfonline.com/doi/abs/10.1080/00207543.2015.1030467.

[62] Quentin Hoarau and Etienne Lorang. "An assessment of the European regulation on battery recycling for electric vehicles". In: *Energy Policy* 162 (Mar. 2022). ISSN: 03014215. DOI: 10.1016/j.enpol.2021.112770.

[63] Cui Jun Hor et al. "Techno-economic assessment of hydrotreated vegetable oil as a renewable fuel from waste sludge palm oil". In: *Environmental Research* 220 (Mar. 2023), p. 115169. ISSN: 00139351. DOI: 10.1016/j.envres.2022.115169.

[64] IEA. *Aviation and shipping*. 2023. URL: https://www.iea.org/reports/aviation-and-shipping.

[65] IEA. *Net Zero by 2050*. 2021. URL: https://www.iea.org/reports/net-zero-by-2050.

[66] IEA. *Road transport*. 2023. URL: https://www.iea.org/reports/road-transport.

[67] *Intermodal transportation | Port of Rotterdam*. URL: https://www.portofrotterdam.com/en/logistics/connections/intermodal-transportation.

[68] International Energy Agency (IEA). *Global EV Outlook 2023: Catching up with climate ambitions*. Tech. rep. 2023. URL: https://www.iea.org/reports/global-ev-outlook-2023.

[69] *International Transport Forum*. URL: https://www.itf-oecd.org/tcad.

[70] International Transport Forum. *About ITF*. URL: https://www.itf-oecd.org/about-itf.

[71] IRENA. "China's route to carbon neutrality: Perspectives and the role of renewables". In: *International Renewable Energy Agency* (2022).

[72] IRENA. *Global energy transformation: A roadmap to 2050 (2019 edition)*. Tech. rep. 2019. URL: https://www.irena.org/apps/DigitalArticles/-/media/652AE07BBAAC407ABD1D45F6BBA8494B.ashx.

[73] Fredj Jawadi et al. "Geopolitical risks and business fluctuations in Europe: A sectorial analysis". In: *European Journal of Political Economy* 85 (Dec. 2024), p. 102585. ISSN: 0176-2680. DOI: 10.1016/J.EJPOLECO.2024.102585.

[74] Cynthia Jayapal et al. "Enhancing Fleet Operations with a Vehicle Route Management Solution". In: *2023 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*. IEEE, June 2023, pp. 1–6. ISBN: 979-8-3503-0681-1. DOI: 10.1109/ICAECA56562.2023.10199496.

[75] Faissal Jelti, Amine Allouhi, and Kheira Anissa Tabet Aoul. "Transition Paths towards a Sustainable Transportation System: A Literature Review". In: *Sustainability* 15.21 (Oct. 2023), p. 15457. ISSN: 2071-1050. DOI: 10.3390/su152115457.

[76] Rakesh Jha and Mukesh Kumar Singh. "Driving towards Sustainability: Understanding Drivers and Barriers in Adoption of Green Mobility". In: *International Journal of Intelligent Transportation Systems Research* 23.1 (Apr. 2025), pp. 126–145. ISSN: 1348-8503. DOI: 10.1007/s13177-024-00443-y.

[77] Melissa P Johnston. "Secondary Data Analysis: A Method of which the Time Has Come". In: *Qualitative and Quantitative Methods in Libraries (QQML)* 3 (2014), pp. 619–626. ISSN: 2241-1925.

[78] Patrik Jonsson and Stig-Arne Mattson. *Manufacturing Planning and Control*. 1st ed. McGraw Hill, Feb. 2009, pp. 263–280. ISBN: 9780077117399.

[79] Kwanjira Kaewfak et al. "A Risk Analysis Based on a Two-Stage Model of Fuzzy AHP-DEA for Multimodal Freight Transportation Systems". In: *IEEE Access* 8 (2020), pp. 153756–153773. ISSN: 21693536. DOI: 10.1109/ACCESS.2020.3018669.

[80] Raja G. Kasilingam. *Logistics and Transportation*. Boston, MA: Springer US, 1998. ISBN: 978-1-4613-7407-7. DOI: 10.1007/978-1-4615-5277-2.

[81] Mikael Kervall and Henrik Pålsson. "A Multi-Stakeholder Perspective on Barriers to a Fossil-Free Urban Freight System". In: *Sustainability* 15.1 (Dec. 2022), p. 186. ISSN: 2071-1050. DOI: 10.3390/su15010186.

[82] Vu Dinh Khoa et al. "Impact of Green Logistics Practices on Sustainable Performance: A Comprehensive Analysis". In: *International Journal of Religion* 5.11 (Sept. 2024), pp. 8302–8312. ISSN: 2633-352X. DOI: 10.61707/0dar3a78.

[83] Theodora Konstantinou and Konstantina Gkritza. "Examining the barriers to electric truck adoption as a system: A Grey-DEMATEL approach". In: *Transportation Research Interdisciplinary Perspectives* 17 (Jan. 2023), p. 100746. ISSN: 25901982. DOI: 10.1016/j.trip.2022.100746.

[84] Irina Vyacheslavovna Larina et al. "Green logistics - modern transportation process technology". In: *Production Engineering Archives* 27.3 (Sept. 2021), pp. 184–190. ISSN: 2353-7779. DOI: 10.30657/pea.2021.27.24.

[85] Jing Liang and Jingpeng Liu. "Maritime transportation risk assessment: A multilevel node relationship-based fuzzy bayesian network". In: *Ocean Engineering* 312 (Nov. 2024), p. 119204. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2024.119204.

[86] Harold A. Linstone and Murray Turoff. *The Delphi Method*. 2002. ISBN: 0201042932.

[87] *Lithium-based batteries supply chain challenges*. URL: https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749.

[88] Tessa Lukehurst and Eleni Anoyrkati. "Policy Directions for Enhancing Transport Innovation Infrastructure for Smarter Regions". In: 2021, pp. 335–346. DOI: 10.1007/978-3-030-61075-3{_}33.

[89] Kirsti Malterud. "Systematic text condensation: A strategy for qualitative analysis". In: *Scandinavian Journal of Public Health* 40.8 (Dec. 2012), pp. 795–805. ISSN: 1403-4948. DOI: 10.1177/1403494812465030.

[90] James G. March and Zur Shapira. "Managerial Perspectives on Risk and Risk Taking". In: *https://doi.org/10.1287/mnsc.33.11.1404* 33.1 (Nov. 1987), pp. 1404–1418. ISSN: 00251909. DOI: 10.1287/MNSC.33.11.1404. URL: https://pubsonline.informs.org/doi/abs/10.1287/mnsc.33.11.1404.

[91] FABIO LUIZ MARIOTTO, PEDRO PINTO ZANNI, and GUSTAVO HERMÍNIO SALATI MARCONDES DE MORAES. "WHAT IS THE USE OF A SINGLE-CASE STUDY IN MANAGEMENT RESEARCH?" In: *Revista de Administração de Empresas* 54.4 (Aug. 2014), pp. 358–369. ISSN: 0034-7590. DOI: 10.1590/S0034-759020140402.

[92] Alan McKinnon. *Environmental sustainability. A new priority for logistics managers*. 3rd ed. Green Logistics, 2015, pp. 3–31. ISBN: 9780749471859.

[93] McKinsey & Company. *Europe's economic potential in the shift to electric vehicles*. Oct. 2024.

[94] Joyce McLaren et al. "CO2 emissions associated with electric vehicle charging: The impact of electricity generation mix, charging infrastructure availability and vehicle type". In: *The Electricity Journal* 29.5 (June 2016), pp. 72–88. ISSN: 10406190. DOI: 10.1016/j.tej.2016.06.005.

[95] *Medium and Heavy-Duty Vehicles. The new Frontier of Road Transport Electrification*. Aug. 2024. URL: https://www.enerdata.net/publications/executive-briefing/transition-electric-mhdv.html?utm.

[96] Sara Mehar et al. "Sustainable Transportation Management System for a Fleet of Electric Vehicles". In: *IEEE Transactions on Intelligent Transportation Systems* 16.3 (June 2015), pp. 1401–1414. ISSN: 1524-9050. DOI: 10.1109/TITS.2014.2367099.

[97] S. Mekhilef, R. Saidur, and A. Safari. "Comparative study of different fuel cell technologies". In: *Renewable and Sustainable Energy Reviews* 16.1 (Jan. 2012), pp. 981–989. ISSN: 13640321. DOI: 10.1016/j.rser.2011.09.020.

[98] Lisa Melander, Camilla Nyquist-Magnusson, and Henrik Wallström. "Drivers for and barriers to electric freight vehicle adoption in Stockholm". In: *Transportation Research Part D: Transport and Environment* 108 (July 2022), p. 103317. ISSN: 13619209. DOI: 10.1016/j.trd.2022.103317.

[99] Hokey Min, Heekeon Park, and Seung Bum Ahn. "Measuring the supply chain risk in offshoring countries using data envelopment analysis and the analytic hierarchy process". In: *Benchmarking* 24.7 (2017), pp. 1977–1994. ISSN: 14635771. DOI: 10.1108/BIJ-04-2016-0054/FULL/XML.

[100] Transport Ministry of Land Infrastructure and Tourism. *Japan sets a target for global shipping of achieving net-zero GHG emissions by 2050*. Oct. 2021. URL: https://www.mlit.go.jp/en/report/press/kaiji07_hh_000001.html.

[101] Stefan Minner. "Inbound Logistics". In: 2019, pp. 233–249. URL: http://link.springer.com/10.1007/978-3-319-92447-2_11.

[102] Shaik Khaja Mohiddin, Shaik Sharmila, and Mandula China Pentu Saheb. "Zero Emission". In: *Energy Efficient Vehicles*. Boca Raton: CRC Press, Mar. 2024, pp. 19–32. DOI: 10.1201/9781003464556-2.

[103] Michelle Monteforte et al. *European Market Monitor Quarterly European car and van market and charging infrastructure development: January–December 2023*. Mar. 2024. URL: https://theicct.org/publication/eu-car-and-van-market-development-quarterly-december23-mar24.

[104] Mihai Neagoe et al. “Road logistics decarbonization challenges”. In: *Journal of Cleaner Production* 434 (Jan. 2024), p. 139979. ISSN: 09596526. DOI: 10.1016/j.jclepro.2023.139979.

[105] Bo-Lennart Nelldal and Evert Andersson. “Mode Shift as a Measure to Reduce Greenhouse Gas Emissions”. In: *Procedia - Social and Behavioral Sciences* 48 (2012), pp. 3187–3197. ISSN: 18770428. DOI: 10.1016/j.sbspro.2012.06.1285.

[106] Måns Nilsson and Annika Rickne. “Governing Innovation for Sustainable Technology”. In: Paving the Road to Sustainable Transport, 2012. Chap. 1, pp. 1–16.

[107] Theo Notteboom, Athanasios Pallis, and Jean-Paul Rodrigue. *Port Economics, Management and Policy*. London: Routledge, Dec. 2021. ISBN: 9780429318184. DOI: 10.4324/9780429318184.

[108] Maja Novakovic et al. “Fresh and Aged Organic Aerosol Emissions from Renewable Diesel-Like Fuels HVO and RME in a Heavy-Duty Compression Ignition Engine”. In: Apr. 2023. DOI: 10.4271/2023-01-0392.

[109] Hilde Nykamp, Allan Dahl Andersen, and Frank Willem Geels. “Low-carbon electrification as a multi-system transition: a socio-technical analysis of Norwegian maritime transport, construction, and chemical sectors”. In: *Environmental Research Letters* 18.9 (Sept. 2023), p. 094059. ISSN: 1748-9326. DOI: 10.1088/1748-9326/acf67a.

[110] Richard A. Oduro and Peter G. Taylor. “Future pathways for energy networks: A review of international experiences in high income countries”. In: *Renewable and Sustainable Energy Reviews* 171 (Jan. 2023), p. 113002. ISSN: 13640321. DOI: 10.1016/j.rser.2022.113002.

[111] Office of the Principal Scientific Adviser to the Government of India. “Bharat Zero Emission Trucking (ZET) Policy Advisory”. In: (Aug. 2024). URL: https://psa.gov.in/CMS/web/sites/default/files/psa_custom_files/Bharat%20ZET%20Policy%20Advisory.pdf.

[112] Joan Ogden. “Introduction to a Future Hydrogen Infrastructure”. In: *Transition to Renewable Energy Systems*. Wiley, May 2013, pp. 795–811. DOI: 10.1002/9783527673872.ch38.

[113] Ualison Rébula de Oliveira et al. “The ISO 31000 standard in supply chain risk management”. In: *Journal of Cleaner Production* 151 (May 2017), pp. 616–633. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2017.03.054.

[114] Angela Pennisi di Floristella and Xuechen Chen. “Building resilient supply chains in uncertain times: a comparative study of EU and ASEAN approaches to supply chain resilience”. In: *Asia Europe Journal* 20.4 (Dec. 2022), pp. 457–475. ISSN: 16121031. DOI: 10.1007/S10308-022-00652-8/METRICS. URL: https://link.springer.com/article/10.1007/s10308-022-00652-8.

[115] Li Ping and Yang Jia-Qi. “Optimizing the vehicles allocation of multi-modal freight transportation considering the transshipment delay risk”. In: *2017 4th International Conference on Transportation Information and Safety (ICTIS)*. IEEE, Aug. 2017, pp. 818–824. ISBN: 978-1-5386-0437-3. DOI: 10.1109/ICTIS.2017.8047862.

[116] "Powering the Future: Overcoming Battery Supply Chain Challenges with Circularity A N U A R Y 2 0 2 5 In collaboration with RMI and the Global Battery Alliance". In: (2025).

[117] Shiv Prasad, V. Venkatramanan, and Anoop Singh. "Renewable Energy for a Low-Carbon Future: Policy Perspectives". In: *Sustainable Bioeconomy*. Singapore: Springer Singapore, 2021, pp. 267–284. DOI: 10.1007/978-981-15-7321-7{_}12.

[118] Jiaqi Qian et al. "Policy implications of electrifying land freight transport towards carbon-neutral in China". In: *Transport Policy* 160 (Jan. 2025), pp. 116–124. ISSN: 0967070X. DOI: 10.1016/j.tranpol.2024.11.004.

[119] Baher Rahma et al. "Investigating customers' purchase intentions for electric vehicles with linkage of theory of reasoned action and self-image congruence". In: *Business Process Management Journal* (Sept. 2024). ISSN: 1463-7154. DOI: 10.1108/BPMJ-03-2024-0182.

[120] Emilio Rodriguez-Diaz, J. I. Alcaide, and R. Garcia-Llave. "Challenges and Security Risks in the Red Sea: Impact of Houthi Attacks on Maritime Traffic". In: *Journal of Marine Science and Engineering* 12.11 (Oct. 2024), p. 1900. ISSN: 2077-1312. DOI: 10.3390/jmse12111900.

[121] L.F.A. Roque et al. "Experimental analysis and life cycle assessment of green diesel (HVO) in dual-fuel operation with bioethanol". In: *Journal of Cleaner Production* 389 (Feb. 2023), p. 135989. ISSN: 09596526. DOI: 10.1016/j.jclepro.2023.135989.

[122] Eleonora Ruffini and Max Wei. "Future costs of fuel cell electric vehicles in California using a learning rate approach". In: *Energy* 150 (May 2018), pp. 329–341. ISSN: 03605442. DOI: 10.1016/j.energy.2018.02.071.

[123] Sulabh Sachan and Praveen Prakash Singh. "Charging infrastructure planning for electric vehicle in India: Present status and future challenges". In: *Regional Sustainability* 3.4 (Dec. 2022), pp. 335–345. ISSN: 2666660X. DOI: 10.1016/j.regsus.2022.11.008.

[124] Kamuran Samar. *From renewables to fossil fuels in Europe: How does your country generate electricity?* Dec. 2024. URL: https://www.euronews.com/green/2024/12/17/from-renewables-to-fossil-fuels-in-europe-how-does-your-country-generate-electricity.

[125] R. L. Sapra. "How to Calculate an Adequate Sample Size?" In: *How to Practice Academic Medicine and Publish from Developing Countries?* Singapore: Springer Nature Singapore, 2022, pp. 81–93. DOI: 10.1007/978-981-16-5248-6{_}9.

[126] Oksana Seroka-Stolka and Agnieszka Ociepa-Kubicka. "Green logistics and circular economy". In: *Transportation Research Procedia* 39 (2019), pp. 471–479. ISSN: 23521465. DOI: 10.1016/j.trpro.2019.06.049.

[127] Nowsheen Sharmili, Rakesh Nagi, and Pingfeng Wang. "A review of research in the Li-ion battery production and reverse supply chains". In: *Journal of Energy Storage* 68 (Sept. 2023), p. 107622. ISSN: 2352-152X. DOI: 10.1016/J.EST.2023.107622. URL: https://www.sciencedirect.com/science/article/pii/S2352152X23010198.

[128] ManMohan S. Sodhi and Christopher S. Tang. *Managing Supply Chain Risk*. Vol. 172. Boston, MA: Springer US, 2012. ISBN: 978-1-4614-3237-1. DOI: 10.1007/978-1-4614-3238-8.

[129] Tempcon. *Still low willingness to pay for fossil-free*. URL: https://www.tempcongroup.se/en/nyhet/still-low-willingness-to-pay-for-fossil-free.

[130] Ronald S. Tibben-Lembke. "The Impact of Reverse Logistics on the Total Cost of Ownership". In: *Journal of Marketing Theory and Practice* 6.4 (Oct. 1998), pp. 51–60. ISSN: 1069-6679. DOI: 10.1080/10696679.1998.11501810.

[131] Tim Stapenhurst. *The Benchmarking Book: A How-to-Guide to Best Practice for Managers and Practitioners*. First Edition. Elsevier, 2009.

[132] Rao Tummala and Tobias Schoenherr. "Assessing and managing risks using the Supply Chain Risk Management Process (SCRMP)". In: *Supply Chain Management* 16.6 (Sept. 2011), pp. 474–483. ISSN: 13598546. DOI: 10.1108/13598541111171165/FULL/PDF.

[133] Jyri P.P. Vilko and Jukka M. Hallikas. "Risk assessment in multimodal supply chains". In: *International Journal of Production Economics* 140.2 (Dec. 2012), pp. 586–595. ISSN: 0925-5273. DOI: 10.1016/J.IJPE.2011.09.010.

[134] Zheng Wan et al. "Analysis of the impact of Suez Canal blockage on the global shipping network". In: *Ocean & Coastal Management* 245 (Nov. 2023), p. 106868. ISSN: 09645691. DOI: 10.1016/j.ocecoaman.2023.106868.

[135] Sandun Wanniarachchi et al. "Transforming road freight transportation from fossils to hydrogen: Opportunities and challenges". In: *International Journal of Sustainable Transportation* 17.5 (May 2023), pp. 552–572. ISSN: 1556-8318. DOI: 10.1080/15568318.2022.2068389.

[136] Wärtsilä. *LNG as fuel for ships: expert answers to 17 important questions*. June 2024. URL: https://www.wartsila.com/insights/article/lng-fuel-for-thought-in-our-deep-dive-q-a.

[137] Tao Wen et al. "Exploring the vulnerability of transportation networks by entropy: A case study of Asia–Europe maritime transportation network". In: *Reliability Engineering & System Safety* 226 (Oct. 2022), p. 108578. ISSN: 09518320. DOI: 10.1016/j.ress.2022.108578.

[138] Martha C. Wilson. "The impact of transportation disruptions on supply chain performance". In: *Transportation Research Part E: Logistics and Transportation Review* 43.4 (July 2007), pp. 295–320. ISSN: 13665545. DOI: 10.1016/j.tre.2005.09.008.

[139] Michal Wojcieszyk et al. "Effect of Alternative Fuels on Marine Engine Performance". In: Dec. 2019. DOI: 10.4271/2019-01-2230.

[140] Yiwei Wu et al. "Integrating operations research into green logistics: A review". In: *Frontiers of Engineering Management* 10.3 (Sept. 2023), pp. 517–533. ISSN: 2095-7513. DOI: 10.1007/s42524-023-0265-1.

[141] Xinhua. *China maps path to carbon peak, neutrality under new development philosophy*. Oct. 2021. URL: https://english.www.gov.cn/policies/latestreleases/202110/24/content_WS61755fe9c6d0df57f98e3bed.html.

[142] Christopher Yang et al. “The Future of Low-Carbon Transportation Fuels”. In: 2011, pp. 259–270. DOI: 10.1063/1.3653857.

[143] Cuihong Yang, Kailan Tian, and Xiang Gao. “Supply chain resilience: Measure, risk assessment and strategies”. In: *Fundamental Research* (Apr. 2023). ISSN: 26673258. DOI: 10.1016/j.fmre.2023.03.011.

[144] Henk Zijm et al. “Operations, Logistics and Supply Chain Management: Definitions and Objectives”. In: 2019, pp. 27–42. DOI: 10.1007/978-3-319-92447-2{_}3.

Appendix

A

Semi-Structured Interview Questions

Interview guide that was used for the first round of Delphi study.

Part 1: Current transportation operations

1. In which countries do you provide transportation?
   (a) Follow-up: If multiple countries, do you provide the same transportation solutions for each country?
2. To better understand the scale of your operations, approximately how many vehicles does your company operate in long-haul transportation?
3. How big part of your fleet is own trucks or sub-contractors?
4. What transportation solutions does your company currently provide for long-haul logistics? (Road, sea, rail, or a combination of these?)
5. What types of vehicles and fuels sources does your company currently use in your transportation operations? (e.g., diesel, hydrogen, biofuel, BEV)
   (a) How come you are using those? (economic benefits, ease of use, time, capacity etc.)
6. How big part of your company's logistics fleet currently consists of low-emission or alternative fuel vehicles?

Part 2: General Perspectives

1. What emerging technologies do you believe will have the most significant impact on sustainable transportation industry according to the 5 main strategies [70]?
   (a) Which strategy would you say tour company has the strongest focus on, is there any of these strategies you find are not fitting?
2. European Commission has established a goal of reducing transportation-related emissions by 90% by 2050, do you believe these targets are realistic and achievable [42]?
   (a) European Green Deal: Reducing net greenhouse gas emissions in Europe by at least 55% by 2030 [45]. Are the goals of Asian countries more feasible? E.g. China 2060 [141], India 2070 [111].
   (b) If 2050 is not feasible, when is it?
3. What do carriers need to make it feasible for you contributing to the decarbonization?
4. How fast do you expect the industry to only have fossil-free long-haul transportation?

   (a) Will it be an incremental shift or a rapid transformation?
5. Do you believe that fossil-free long-haul transportation will become available at a large scale?
   (a) When do you think it is possible for your company to provide 100% fossil free transportation in the future?
6. When comparing 2030 and 2050, what do you think is possible to achieve when it comes to heavy duty truck for long-haul transportation?

Part 3: Company Strategy and Vision

1. Did you notice a shift in the importance of sustainability?
   (a) If so, when did this change occur?
2. Do you have any sustainability targets?
   (a) Does your company have a roadmap for reducing emissions in transportation?
   (b) If yes, any key milestones?
   (c) How did you set these targets?
   (d) Formalized sustainability strategy?
   (e) Why do you set these goals?
3. When looking at the company's overall strategy, how is sustainability prioritized compared to cost-efficiency? (How big part of your strategy is sustainability?)
   (a) Has this changed over time?
4. How are you actively working to be updated on new transportation technologies and solutions to know what strategy that is the best one? (Innovation and up-scaling)
   (a) Do you have any team actively working with sustainability?

Part 4: Challenges/barriers and drivers in the transition to sustainable transportation

1. Why are your company striving towards sustainable transportations?
   (a) What main drivers do you see in the transformation to sustainable transportation? (E.g. regulatory pressure, customer/market obligations, new market opportunities, competitiveness)
   (b) Do you think the transformation to sustainable transportation is essential for carriers to stay competitive?
2. Do you see an increased trend for the demand of sustainable transportation solutions?
   (a) Have you seen any regional differences in the demand?
3. How do you think current and upcoming regulations impact your transition to fossil-free transportation?
   (a) How much are you adapting to the governmental regulations and targets?
4. What are the challenges your company faces in transitioning to more sustainable transport solutions? (e.g. infrastructure, costs, policies, technology acceptance, ease of use, payback time, range)
   (a) Of these challenges, which do you consider to be the most significant or most pressing for your company?

   (b) How are you working with these challenges today?
5. Given your current position with the transportation methods you use today, how challenging do you perceive the transition to fossil-free transportation?

Part 5: Costs & Investments

1. What are the biggest cost-related barriers your company faces in adopting sustainable transport solutions?
   (a) High initial investment in vehicles and infrastructure?
   (b) Higher operational costs (e.g., fuel, maintenance)?
   (c) Uncertain return on investment (ROI)?
2. How do you think the implementation of sustainable transportation will affect the costs for the customers?
   (a) Follow up: Do you anticipate higher prices compared to e.g. diesel options?
3. Do you see that customers are willing to pay a premium for sustainable transportation services?
   (a) Follow up: Have you seen a shift in customer priorities regarding sustainability versus cost?
4. Has your company made any investments (or are planning to make investments) in sustainable transport solutions (e.g., electric or hydrogen trucks, biofuels, multimodal logistics)?
   (a) Which decarbonization transportation solution will you prioritize [70]?

B

Results of Delphi Round 1

Table 22: Proportion of responses (%) in Delphi round 1

	Inland Transportation: Europe	Inland Transportation: Asia	Sea Transportation
Used Vehicles/Fuels	Diesel/Fossil Fuel: 100% Electric: 70% Biofuels (HVO, Hydrogen, LNG): 100% Intermodal/Rail: 50%	Primary Fuel, Diesel: 100% Small amount of Electric: 40% Small amount of Hydrogen: 20% Intermodal/Rail: 40%	Diesel/Fossil Fuel: 100% Biofuel (Methanol, LNG etc.): 80%
Own fleet or Subcontractors	Uses subcontractors and don't own all of the vehicles by themselves: 90% Find it difficult to set pressure on subcontractors to provide sustainable transportation: 20%		Uses subcontractors and don't own all of the vehicles by themselves: 80%
Future Sustainable Vehicle Technologies (Long Haul)	Intermodal/Rail: 60% Electric: 60% HVO: 80% Hydrogen: 50% Hard to say since it depends on the time and place: 10% Needs a mix of technologies to make it sustainable: 40%	Intermodal/Rail: 40% Electric: 60% Hydrogen: 20% LNG: 20%	Ammonia: 60% Methanol: 100% Carbon Capture Technology: 20% Needs a mix of technologies to make it sustainable: 40% Environmental Coatings: 40%
EU goals feasible	Think it is feasible. But they also mean that there are things to need to be developed: 50% Mentions that it is challenging and requires change and it is hard to say if the target is feasible or not: 50%	Think it is feasible, anything is possible with 25 years but things need to be changed: 40% Highly challenging: 40%	Think there is a ambitious goal, but hope it is feasible: 100% They have to be met since they otherwise have to pay penalties, IMO standards: 20%
Percentage of Sustainable transportation	10% or more of the operations are done with sustainable transportation (EV, HVO etc.): 20%	Mainly uses diesel as their fuel source: 100% 10% of the operations with sustainable transportation: 20%	Fossil free fuel is mainly used: 100% Uses 1% of the operations with sustainable transportation: 40%
Sustainability targets	Has sat sustainability targets that they are striving to reach: 80% Have no targets and are waiting for better technologies and legislation: 20%	Has sat sustainability targets: 60%	Has sat sustainability targets: 100%
Sustainability vs Costs	Cost is more important for the company to survive: 30%	Cannot risk the company and therefore cost will be a priority: 40% Mentions that investments will be beneficial in the long-term: 60%	Invest in new sustainable technologies and solutions, but have to look at cost as well: 100%

	Inland Transportation: Europe	Inland Transportation: Asia	Sea Transportation
Challenges of transformations to Sustainability	Infrastructure: 100% Amount of energy and alternative fuels: 50% Availability of charging and refueling stations: 60% Distance EV (weather conditions etc.): 40% Uncertain amount of emissions that are being reduced with the sustainable transportation alternatives: 40% How the infrastructure, availability etc. differs from country to country: 10% Uncertain technology development: 20% Charging time for EV: 40% Diesel/Fossil Fuel is too cheap: 20% Energy Sources are challenging out of Europe: 10% Lead times of sustainable alternatives: 10% Rail can just go certain routes (not flexible): 10%	Infrastructure: 80% Cost is too high: 80% Capacity of EV, small vehicles: 20% Driving range for long distance: 40% Availability of charging and refueling stations: 20% Customer don't have the mindset of transformation: 20% Regional infrastructure differences: 20%	Investment and operating costs are expensive: 100% Customers have to demand it and not think this problem will be solved automatically: 60% Infrastructure for green electricity: 20% Charging stations with alternative fuels are not available in so many locations (Availability): 80% Uncertain of future technology development: 20% Find partners that are willing to pay the price for the transformation: 20% Different regulations worldwide, it is an unfair competition: 20% Amount of alternative fuels: 20% Ammonia is toxic and dangerous to handle: 20%
Drivers of transformations to Sustainability	Customer demand: 100% Want to be a part of the change and the new solutions: 40% Regulations: 50% Own responsibility: 30%	Customer demand: 60% Want to be a part of the change and the new solutions: 20% Own responsibility: 20% Essential to stay competitive on the market: 80% Regulations: 60%	Customer demand: 60% Want to be a part of the change and the new solutions: 100% Regulations: 40% Be prepared for the future: 60%
Increased demand of Sustainable solutions	Larger and Global customers: 30% Nordic countries companies: 10% Many time asked but not used: 30%	Larger and Global customers: 100%	Increased demand, yes: 100% Decreased demand the last year: 20% Many time asked but not used: 20%
Will costs increase of Sustainable Transportation (ST)	Investments are much higher: 70% Operational costs are higher: 20% Short term costs will increase: 10% Long term cost don't necessary have to increase if infrastructure change: 50%	Investments are much higher: 80% Long term costs can decrease: 60%	Investments are much higher: 60% Operational costs are higher: 60%
Customer is willing to pay premium price for ST + Trends	Few customers are willling to pay: 80% Customers can pay a part of the extra price: 10% A lot interest but many think it is too expensive: 10% Companies close to customers in the supply chain are more willing to pay: 10% Customers can pay extra in this development phase for short term, not in the long run: 10%	No: 80% Large and Global customers are willing to pay a part of the extra price: 40%	Yes some of the customers: 60% Depends on the product that the customer are selling, higher margin products can pay extra: 40% Companies close to customers in the supply chain are more willing to pay: 20% Need pressure on the entire industry: 20%
Investments and future investments	Sustainable vehicles 80% Research for new technologies 80%	Solarpanels: 20% Intermodal/Rail transportation: 20% Electric trucks: 60% Research for new technology: 40%	Research for new technologies: 40% Methanol fuels: 40% Hydrogen vessels: 20% LNG and biofuels: 20%

C

Questionnaire for Delphi Round 2

The following text and set of statements were used when distributing the questionnaire to multiple respondents. Participants were given the option to select one of three responses: Yes, No, or I don't know. After each answer, they were also asked to explain 'Why' they chose that response, providing further insight into their reasoning.

Welcome!

The purpose of this study is to gather your insights on environmentally sustainable long-haul transportation solutions for the year 2050. The research focuses on two primary transport flows, which will be addressed in the survey:

Flow 1 = Transportation of goods from Europe to Sweden
Flow 2 = Transportation of goods from Asia to Sweden

The survey will take approximately 15 minutes to complete.

All responses are fully anonymous and will be used solely for research and improvement purposes. The answers will be analyzed as collective group opinions, not as the views of individual companies.

Your input is highly valued and will contribute to shaping future transportation strategies. Thank you for your participation!

If you have any questions in the meantime, please contact Sofia or Nathalie.

Statement 1
I believe transportation providers are responsible to lead the shift toward environmental sustainability by testing new technologies, rather than waiting for regulations to enforce it.

Yes ☐, No ☐, I don't know ☐
Why?

Statement 2
I believe that the availability of biofuels, in terms of fuel infrastructure and supply, will be larger for Flow 1 compared to Flow 2.

Examples of biofuels (HVO, hydrogen, LNG etc.)

Flow 1 = Transportation of goods from Europe to Sweden
Flow 2 = Transportation of goods from Asian to Sweden

Yes ☐, No ☐, I don't know ☐
Why?

Statement 3
I believe that the availability of charging infrastructure for electric trucks, powered by renewable energy sources, will be larger for Flow 1 compared to Flow 2.

E.g. of renewable energy sources are wind-, hydro- or solar power.

Flow 1 = Transportation of goods from Europe to Sweden
Flow 2 = Transportation of goods from Asian to Sweden

Yes ☐, No ☐, I don't know ☐
Why?

Statement 4
I believe customers ask for environmentally sustainable transportation but don't choose them due to higher costs.

Yes ☐, No ☐, I don't know ☐
Why?

Statement 5
I believe customers closer to the end consumer in the supply chain are more likely to buy environmentally sustainable transportation.

Yes ☐, No ☐, I don't know ☐
Why?

Statement 6
I believe that it is worth investing in environmentally sustainable transportation solutions, even if there can be high investment and operational costs today

Yes ☐, No ☐, I don't know ☐
Why?

Statement 7
I believe larger carriers must lead the shift to environmentally sustainable transport, setting the standard for subcontractors to follow in the future.

Yes ☐, No ☐, I don't know ☐
Why?

Statement 8
I believe small carriers will struggle to adapt to the shift toward environmentally sustainable transportation

Yes ☐, No ☐, I don't know ☐
Why?

Statement 9
I believe that transportation providers would transition to fossil-free long-haul transportation faster if the regulatory framework was stronger

Yes ☐, No ☐, I don't know ☐
Why?

Statement 10
I believe that international differences in regulations create an unfair competitive environment for fossil-free long-haul transport.

Yes ☐, No ☐, I don't know ☐
Why?

Statement 11
I believe the following solutions will be a part of the future, year 2050, inland transportation solutions

	Yes	No	I don't know
Electric	☐	☐	☐
Intermodal	☐	☐	☐
Hydrogen	☐	☐	☐
HVO	☐	☐	☐
LNG	☐	☐	☐
Optimized efficiency and planning	☐	☐	☐
Fossil fuels (e.g. Diesel)	☐	☐	☐

Why did you answer yes/no on the different solutions for inland transportation?
Please answer for each solution.

Statement 12
I believe the following solutions will be a part of the future, year 2050, sea transportation solutions.

	Yes	No	I don't know
Methanol	☐	☐	☐
Ammonia	☐	☐	☐
Carbon Capture Technology	☐	☐	☐
LNG	☐	☐	☐
Optimized efficiency and planning	☐	☐	☐
Fossil fuels (e.g. Diesel)	☐	☐	☐

Why did you answer yes/no on the different solutions for sea transportation? *Please answer for each solution.*

D

Ranking Scales for the FMEA

Table 23: Ranking scale: Severity

Effect	Criteria: severity of effect	Rank
Very long delay	Period of stop often >24 hours	10
Long delay	Period of stop for 12-24 hours	9
Moderate delay	Period of stop is 6-12 hours	8
	Period of stop is often <6 hours or period of sluggish operation >18 hours	7
	Period of sluggish operation 12-18 hours	6
Minor delay	Period of sluggish operation 6-12 hours	5
	Period of sluggish operation 3-6 hours	4
Slight delay	Period of sluggish operation 2-3 hours	3
	Period of sluggish operation often <2 hours	2
No delay	There is no stop or sluggish operation	1

Table 24: Ranking scale: Occurrence

Occurance of failure	Possible failure rates - Incidents per total shipments	Rank
Very high	>36%	10
	30 - 36%	9
	24- 30%	8
	18- 24%	7
Moderate	12 - 18%	6
	6 - 12%	5
	3 - 6%	4
Low	1.5 - 3%	3
	<1.5%	2
Very low	Failure is eliminated through preventive control	1

Table 25: Ranking scale: Detection

Detection	Criteria: likelihood of detection by design control	Rank
Extremely unlikely	Controls will almost certainly not able to detect the existence of a defect	10
	Defect is detectable after operation & operators won't be able to correct it	9
	Operators will be able to correct the defect with limitations after operation	8
	Operators will be able to correct the defect after operation	7
Moderate low likelihood	Operators will be able to correct the defect during operation	6
	Controls have medium effectiveness for detection	5
	Defect is detectable prior operation	4
High likelihood	Controls have high effectiveness for detection prior operation	3
	Controls have a very high probability of detecting the existence of delay prior operation	2
Extremely likely	Controls will almost certainly detect the existence of the defect and correct it	1

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY