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Opportunities for the logistical competitive advantages of Finnish cobalt produced for the European electric vehicle market

Case study: Latitude 66 Cobalt Oy

School of Technology and Innovations
Master's thesis in Economics and
Business Administration
Industrial Management

Vaasa 2022

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Title of the Thesis: Opportunities for the logistical competitive advantages of Finnish cobalt produced for the European electric vehicle market: Case study: Latitude 66 Cobalt Oy
Degree: Master of Science in Economics and Business Administration
Programme: Industrial Management
Supervisor: Petri Helo
Year: 2022 **Pages:** 118

ABSTRACT:
The downsides of the electrification of the automotive industry are the sustainability and responsibility issues in the international supply chains of critical minerals, especially cobalt, contained in the lithium-ion batteries used to power electric vehicles. The activities are highly concentrated for more than half of the world's cobalt is mined as a by-product in Central Africa, the Democratic Republic of Congo, in mines mainly controlled by Chinese operators, where the general problem is labour abuse.

Based on the above issues, three main objectives have been defined for this thesis: to clarify the backgrounds and prospects for cobalt need in the battery industry, to identify requirements, standards, and development directions of cobalt supply chains transparency and traceability of mineral origin, and to demonstrate the logistical competitive advantages of cobalt mined and refined in Finland compared with cobalt mined in Congo and refined in China. The European electric vehicle industry has been selected as the target market for the study. The case company of the thesis is Latitude 66 Cobalt, aiming to produce traceability requirements meeting cobalt in Finland for the European electric vehicle market.

This thesis is a management science study that has applied an analytical decision-making process. The study has been carried out by mapping the material flows of cobalt and creating two comparable supply chain scenarios based on them, the Nordic scenario and the Chinese-controlled scenario. The scenario-based comparison has been carried out with three indicators measuring transports performance: transit time, greenhouse gas emissions, and transport costs. Uncertainties in the indicators have been considered and their impact on the research results has been highlighted in the sensitivity analyses conducted by Monte Carlo simulations.

Based on the literature review findings, despite new innovations in battery technology, the demand for cobalt seems to continue to grow towards the end of the decade. The planned requirements for improving the transparency of supply chains and the traceability of mineral origin for companies targeting the European market may be a challenge for the current main producing countries but, on the other hand, an opportunity for Finnish cobalt production. Considering the uncertainties, the quantitative analysis of the study shows that the logistical competitive advantages in favour of Finnish cobalt production are 72%–78% in transit time, 77%–82% in greenhouse gas emissions, and 51%–70% in costs.

KEYWORDS: case study, cobalt, electric vehicles, lithium-ion batteries, logistics, supply chains, traceability

VAASAN YLIOPISTO
Teknologian ja innovaatiojohtamisen yksikkö

Tekijä:	Topias Mäkelä
Tutkielman otsikko:	Mahdollisuudet Euroopan sähköajoneuvomarkkinoille tuotetun suomalaisen koboltin logistisiin kilpailuetuihin: Case tutkimus: Latitude 66 Cobalt Oy
Tutkinto:	Kauppatieteiden maisteri
Koulutusohjelma:	Tuotantotalous
Työn ohjaaja:	Petri Helo
Valmistumisvuosi:	2022 **Sivumäärä:** 118

TIIVISTELMÄ:
Autoteollisuuden sähköistymisen varjopuolia ovat sähköajoneuvojen voimanlähteenä käytettävien litiumioniakkujen sisältämien kriittisten mineraalien, erityisesti koboltin, kansainvälisten toimitusketjujen kestävyys ja vastuullisuus ongelmat. Toiminta on hyvin keskittynyttä, sillä yli puolet maailman koboltista louhitaan sivutuotteena Keski-Afrikassa, Kongon demokraattisessa tasavallassa, pääosin kiinalaisten toimijoiden hallinnan alaisissa kaivoksissa, joissa yleisesti tiedossa oleva rasite on työvoiman väärinkäytön ilmentyminen.

Edellä mainittujen ongelmien pohjalta tälle tutkielmalle on määritelty kolme päätavoitetta: selvittää taustat ja tulevaisuuden näkymät koboltin tarpeelle akkuteollisuudessa, tunnistaa koboltin toimitusketjujen läpinäkyvyyteen ja mineraalialkuperän jäljitettävyyteen liittyvät vaatimukset, standardit ja kehityssuunnat, sekä osoittaa Suomessa louhitun ja jalostetun koboltin mahdolliset logistiset kilpailuedut verrattuna Kongossa louhittuun ja Kiinassa jalostettuun kobolttiin. Tutkimuksen kohdemarkkinaksi on rajattu Euroopan sähköajoneuvoteollisuus. Tämän tutkielman case yritys on malminetsintäyhtiö Latitude 66 Cobalt Oy, jonka tavoite on tulevaisuudessa tuottaa Suomessa jäljitettävyysvaatimukset täyttävää kobolttia Euroopan sähköajoneuvomarkkinoiden tarpeisiin.

Tämä tutkielma on johtamistieteellinen tutkimus, jossa on sovellettu analyyttista päätöksentekoprosessia. Tutkimus on toteutettu kartoittamalla koboltin materiaalivirtoja ja luomalla niiden pohjalta kaksi keskenään vertailukelpoista toimitusketjuskenaariota, pohjoismainen skenaario ja kiinalaisten toimijoiden kontrolloima skenaario. Skenaariokohtainen vertailu perustuu valittuihin kuljetusten suorituskykyä mittaaviin indikaattoreihin: kuljetusaika, kasvihuonekaasupäästöt ja kuljetuskustannukset. Indikaattoreiden sisältämät epävarmuustekijät on otettu huomioon ja niiden vaikutus tutkimustuloksiin on tuotu esille Monte Carlo simulaatiolla tehdyillä herkkyysanalyyseillä.

Kirjallisuuskatsauksen löydösten pohjalta voidaan todeta, että huolimatta akkuteknologian uusista innovaatioista, koboltin kysyntä näyttää jatkavan kasvuaan vuosikymmenen loppuun päin mentäessä. Suunnitellut toimitusketjujen läpinäkyvyyden ja mineraalialkuperän jäljitettävyyden parantamisvaatimukset Euroopan markkinoille tähtääville yrityksille voivat olla haaste nykyisille päätuottajamaille, mutta toisaalta mahdollisuus suomalaiselle kobolttituotannolle. Epävarmuustekijät huomioon otettuna tutkimuksen kvantitatiivinen analyysi osoittaa logistiset kilpailuedut suomalaisen kobolttituotannon hyväksi 72–78 % kuljetusten, 77–82 % kasvihuonekaasupäästöjen ja 51–70 % kustannusten osalta.

AVAINSANAT: jäljitettävyys, koboltti, litiumioniakut, logistiikka, sähköajoneuvot, tapaustutkimus, toimitusketjut

Contents

Figures

Tables

Abbreviations

ASM	Artisanal and small-scale mining
BEV	Battery electric vehicle
CAHRA	Conflict-Affected and High-Risk Areas
CAM	Cathode active material
CCCMC	The China Chamber of Commerce Metals, Minerals & Chemicals
CO_2e	Greenhouse gases in CO_2 equivalents
DRC	Democratic Republic of Congo
ESG	Environmental, Social, and Governance
EV	Electric vehicle
GHG	Greenhouse gas
ICE	Internal combustion engine
IEA	International Energy Agency
KWH	Kilowatt-hour
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
LM	Lane metre
LSM	Large-scale mining
NMC	Nickel manganese cobalt
OECD	Organisation for Economic Cooperation and Development
PCAM	Precursor cathode active material
PHEV	Plug-in hybrid electric vehicle
TEU	Twenty-foot equivalent unit
TKM	Tonne-kilometre
TPA	Tonnes per annum

1 Introduction

This chapter introduces the basic information of this thesis. In the beginning, the background to my interest in the topic is told, and the case company's needs for this study are revealed. After clarifying the need, the reasons for concluding the selected research problems are reviewed, and the topic delimitation process is explained. Three research questions are listed in the second subchapter, and the methods for answering them are presented in the third subchapter. In the fourth subchapter, there is a summary of the thesis structure. The introduction chapter ends with the case company presentation section.

1.1 Background

Case company Latitude 66 Cobalt's need for cooperation with the University of Vaasa has its roots in a three-year project called "BATTRACE" funded by Business Finland. The case company of this thesis is one of the nine companies participating in the project. The initiative's primary purpose is to focus on sustainable battery manufacturing methods and the traceability of minerals used in battery manufacturing in Finland. The case company participation background in the project is to map out its prospects in the cobalt mining industry in Finland. My interest in applying to the project was due to the current situation in the company and in the industry. Getting involved in the development phase company in a continuously evolving industry was the challenge I was looking for the last academic year.

The selection of the research topic was based on the aim to find the approach that would be most beneficial for the case company's point of view. The debate was set in motion from the current primary producer of cobalt, the Democratic Republic of Congo, regarding supply chain sustainability, responsibility, and ethics. Although cobalt travels from the DRC via China to Europe, customers may ask whether it is more expensive to mine and refine cobalt in Finland. We started to think about the possible benefits of cobalt produced in Finland through these two issues and ended up focusing on potential logistical advantages of cobalt mined and refined in Finland compared to cobalt mined in DRC and refined in China because these differences are measurable quantitatively.

To calculate logistical competitive advantages, we had to decide target market whose end products contain cobalt. The European electric vehicle market was chosen for two reasons: firstly, the sustainability, responsibility, and traceability of the raw materials supply chains are hot topics in the European EV industry, and secondly, cobalt is one of the critical minerals in EVs lithium-ion batteries, so the EV market is thus one of the most significant single factors in the cobalt demand formation.

1.2 Purpose

This study aims to find answers to three research questions selected according to the needs of the case company. The choice of questions was also influenced by their connection, making a coherent whole of the thesis.

1. *Why is cobalt needed in the European electric vehicle market?*

2. *What are the requirements for the transparency of the cobalt supply chain and the traceability of the mineral origin in the European electric vehicle market?*

3. *Does Finnish cobalt production have logistical competitive advantages in the European electric vehicle market compared to cobalt mined in DRC and processed in China?*

The first question concerns the need for cobalt in the European EV market because it is vital for a developing company to have a market view for a mineral mined in the future. Therefore, the answer encompasses the current situation and prospects for the mineral needs of battery technology. The second question concerns traceability as it was another main point raised by the case company, and it is strongly related to the last main research question on logistical competitive advantages. The origin of the mineral, the number of actors and border crossing in the supply chain, and the total transport distance all affect the transparency of the supply chain and the traceability of the origin of the mined mineral. The more actors there are between the end-user and the primary producer of the mineral, the more complicated it becomes to determine the origin of the mineral and its movements in the supply chain because everything is based on trust about the accuracy of the information between actors. By producing comprehensive and substantiated answers to these three research questions, the case company can utilise research material to market and clarify the advantages of Finnish cobalt production and especially its own operations when customers question these issues.

1.3 Methods

The first two research questions are answered in the literature review based on primary data of previous research searched from Finna database and Google Scholar, secondary data from the internet such as publications and reports of organisations and societies researching the related industry, and expert interviews. The aim is to examine the questions critically from different perspectives, not produce one correct answer, as such is hard to find in the industry living in the middle of innovations.

The answer to the first question consists of two parts. First, the role of cobalt in lithium-ion batteries, in general, is reviewed in chapter 2.1.1. The study presents the basic principle of LIBs, the different types of batteries currently used in the automotive industry, and the possible future battery trends. Different battery types require a different amount of cobalt, which may affect the demand for cobalt in the future. The second part of the answer relates to a phenomenon called “electrification of the automotive industry”, discussed in chapter 2.1.2. The increase in the demand for electric cars directly affects the market for LIBs, which is reflected as investments of both European and Chinese players in the battery industry in Europe (see Figure 1). The study highlights regulations, laws, and initiatives that speed the electrification of the automotive industry in Europe and their consequences on cobalt demand.

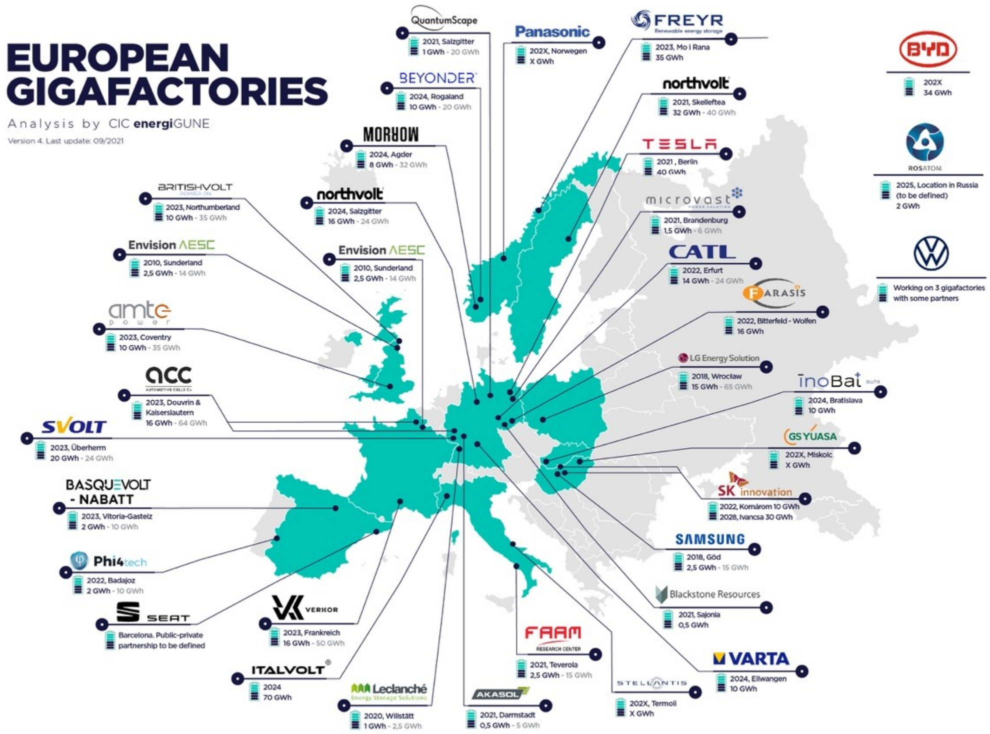

Figure 1. Analysis of the European gigafactories (CIC energiGUNE, 2021).

Chapter 2.2 reviews cobalt material refining flows at a general level to understand why supply chain transparency and mineral traceability are essential in the case of cobalt. Once the overview of material flows has been formed in chapter 2.2, the answer to the third question is obtained in chapter 2.3. The first subchapter, 2.3.1, deals with responsibility and sustainability issues that a non-transparent supply chain may contain in the worst-case scenario. The following subchapters examine the standards, guidelines, initiatives, and innovations developed to improve the transparency of cobalt supply chains and the traceability of mineral origin.

The answer to the last question is produced in chapter 4 quantitatively by collecting data and analyzing it. The study aims to create two relevant supply chain scenarios, which could be possible in the future, based on the general material flows reviewed in chapter 2.2. The first scenario concerns cobalt mined in the DRC, which is refined and used in battery manufacturing in China. The second scenario involves cobalt mined and refined in Finland and used in battery manufacturing in Sweden. Both supply chain scenarios end to the same European EV manufacturer. From these scenarios, transport routes are modelled, and the necessary data of the transport legs is collected. The three indicators used in the study are transit time, greenhouse gas emissions, and costs regarding the transport of cobalt. By comparing these three indicators calculated from the scenarios, the aim is to prove the potential logistical competitive advantages of Finnish cobalt production in the European EV market.

1.4 Structure of the thesis

The thesis is divided into five chapters, including the introduction. The second chapter is the literature review which examines the essential topics for the thesis based on previous research and the industry literature. The first two research questions are answered in the literature review. The third chapter is the methodology which introduces the methods used to provide empirical analysis and produce results related to the main research problem. The fourth chapter presents the research findings and the analysis of them. The last chapter reviews the main conclusions that can be made from research findings and considers the ideas that arise from the topic for further research.

1.5 Case company presentation

This chapter briefly introduces the case company, making it more evident why selected issues are researched in the following chapters. The topics covered are the background behind the company establishment, the mission and vision, and the outlook for the future. At the end of the chapter, there is also a summary of the case company’s current situation.

1.5.1 Background

The case company of this thesis is the Australian-Finnish mineral exploration company Latitude 66 Cobalt Oy, which was founded in 2017. Latitude 66 Cobalt (2021) operates in Finland but is 100% owned by the Australian parent company Latitude 66 Cobalt ltd. Finnish investors own 19% of the parent company. The company's objective is to specialise in mining and mineral production but is currently in the mineral exploration stage, so mining operations have not started yet. However, the company owns mining projects in Kuusamo, previously owned by Dragon Mining.

Previous projects in the same area have faced opposition by local tourism entrepreneurs and residents of the Kuusamo. Underlying this is the questioning of the environmental friendliness of the projects near the high-value nature areas important to tourism. Latitude 66 Cobalt (2021) strives to avoid these issues. The two main points of its policy are ecologic manners and social sustainability. The company emphasises that water safety solutions can be implemented safely and economically profitably due to the cobalt market price. Another essential sustainability principle is that a company requires at least 12 years of operating conditions to start mining actions. In addition, the company has defined a buffer zone of at least 10 km for all tourism activity locations.

1.5.2 Mission & Vision

Latitude 66 Cobalt (2021) emphasises that its mission is to be a socially accepted mining company made possible by well-organised exploration and mining. The company understands that it's not self-evident because the mining industry has a poor reputation in Finland regarding environmental effects to the surrounding nature. Latitude 66 Cobalt seeks to restore weak confidence in the mining industry through its actions. Open discussion and respect for other enterprisers and the environment are the means company describes essential.

Latitude 66 Cobalt’s (2021) vision is to be a mining company, not a development company. It has been typical for companies in the mining industry to develop and trade mining projects even before the mining has started. The company is constantly striving to improve its operations by utilising the newest technology, and it has a clear goal to be a mining company in the future. With the growing trend in demand and price, Latitude 66 Cobalt is focusing its interest on cobalt and not only on gold and copper like previous owners in the same areas.

Latitude 66 Cobalt (2021a) announced on their website 26.8.2021 that the company will be sold to Sun Mirror AG, a Swiss mineral exploration company. The acquisition does not affect the arrangements or the position of the personnel in the organisation, and the company intends to continue its operations the same way as a separate unit. The most significant impact will be seen in investments in mineral exploration and the opportunity to hire skilled personnel for research work. The company considers the additional resources that come with the deal necessary for developing current cobalt exploration projects and future mining operations.

1.5.3 Mining projects

Latitude 66 Cobalt Ltd (2021) has several projects in Finland and over 3000 square kilometres of holdings, which is the largest amount at the industry level for a single company in the EU (see Table 1). It means more than 16,000 tonnes of potential cobalt recourses and over 700,000 oz of gold recourses in minerals. The focus is currently in the geological area called Kuusamo Schist Belt.

Table 1. Permitting of Latitude 66 Cobalt assets 6.2.2022.

Tenure	Status	Number	Square kilometres (km2)	Municipalities
Exploration reservations	Valid	7	2407,2	15
Exploration licences	Application	49	812,3	10
	Appealed	4	22,2	2
	Valid	1	14,4	1
Mining lease	Valid	3	0,71 (71ha)	1

Latitude 66 Cobalt Ltd (2021) highlights that K-camp is the second largest not yet mined cobalt deposit in the EU. According to Sphene capital's (2021) report, K-camp has the highest estimated cobalt grade of 0.064% in the EU, and the cobalt deposit in tonnes is the fourth largest in the EU area. It is typical for the industry that cobalt is mined as a by-product, and this is also the case for Latitude 66 Cobalt; K-camp has gold reserves, and H-camp has copper reserves. Figure 2 shows the locations of these primary geological survey target areas.

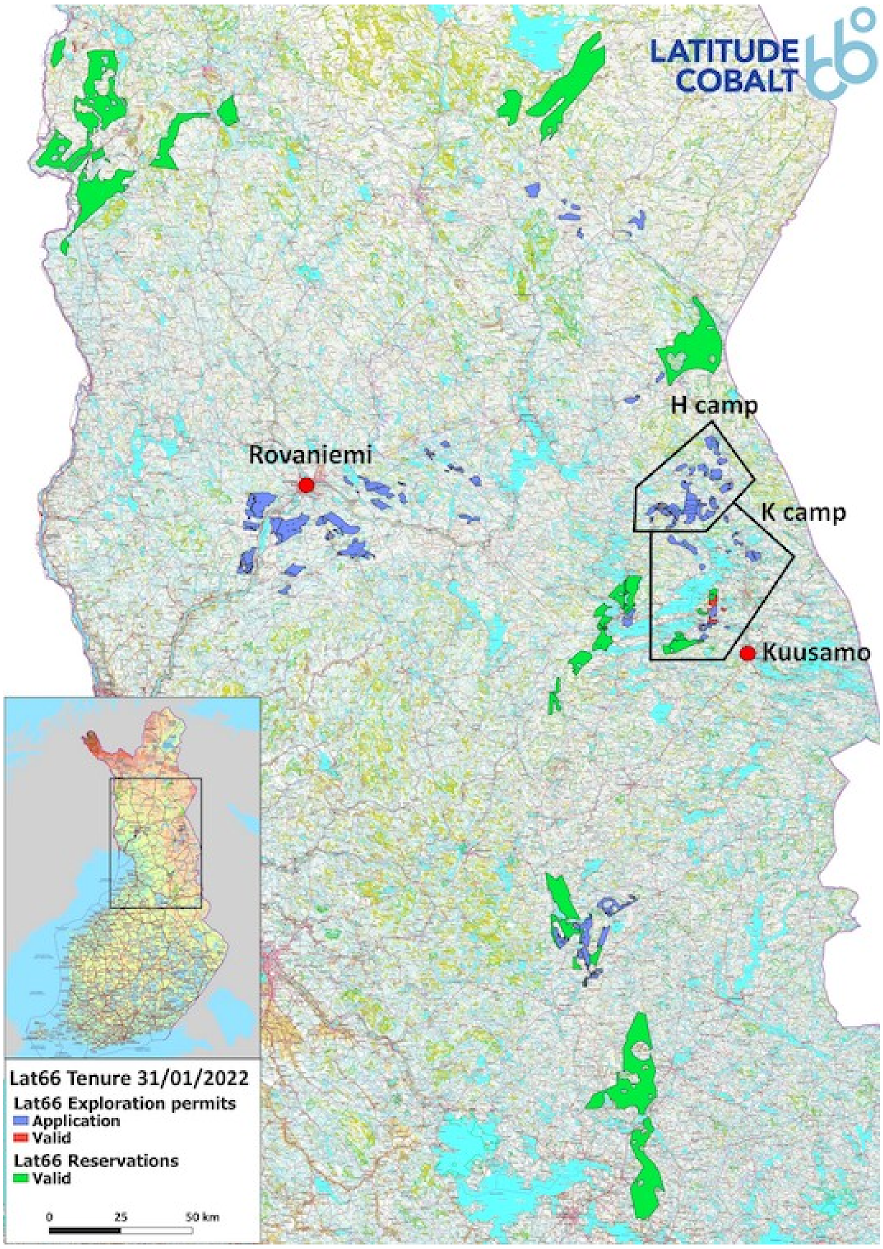

Figure 2. Target areas of the case company's geological survey.

2 Literature review

Based on previous scientific research and industry-related secondary data, this literature review answers the first two research questions and addresses the background information necessary to produce an answer to the third research question. The chapter consists of three main subjects. It begins with clarifying the application of cobalt in the European electric vehicle market. After that, the cobalt material refining flows of both the Democratic Republic of the Congo and Finland will be identified as the basis for the scenario-creating process in chapter four. In dealing with the third main topic, requirements and guidelines are determined from the perspective of the European EV market regarding the traceability of the cobalt supply chain.

2.1 Background for the need for cobalt in the EV industry

This subchapter introduces the basic principles of a lithium-ion battery to clarify the reasons behind the need for cobalt produced for the European EV market. The structure, operating principles, and minerals used in the LIBs are reviewed. Another issue addressed in this subchapter is the electrification of the automotive industry. The topics surveyed are, the reasons for the increase in the production of electric vehicles and their effects on cobalt demand.

2.1.1 The role of cobalt in the lithium-ion battery

Cobalt is used widely in many applications, but this thesis focuses on its role in lithium-ion batteries. Ellingsen et al. (2014) present the basic structure of a battery cell in their study. A lithium-ion battery cell consists of five components: a positive electrode (cathode), a negative electrode (anode), an electrolyte, a separator, and a cell container. An electrolyte is designed to isolate the positive and negative electrodes and allow lithium ions to move between the anode and cathode in the cell container. The separator's function is to ensure battery safety, preventing the contact between anode and cathode. The material of these five components underlies the price formation of the battery cell.

The principle of operation of a battery cell, described by (Ellingsen et al., 2014) in its simplest form, is based on a chemical reaction inside the cell that results in an electric current formation (see Figure 3). When the battery is discharged, energy is released. In this case, the negatively charged anode releases electrons during the oxidation reaction. The properties of electrons include movement toward a positively charged cathode, and this movement of electrons generates an electric current utilised in the electric devices. Upon arrival at the cathode, the electrons cause a reduction reaction in which the ions on the cathode receive electrons. The reactions are practically the same when charging batteries, but they happen in the opposite direction.

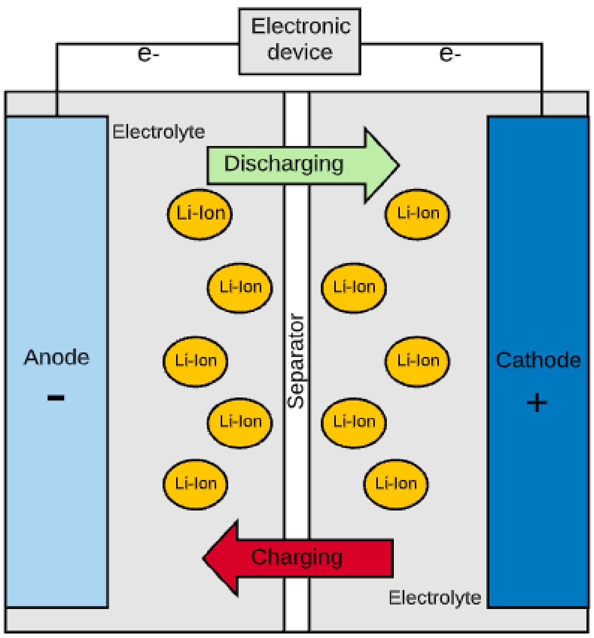

Figure 3. Lithium-ion battery chemistry.

The need for cobalt in LIBs is explained more deeply by looking at the materials from which battery cell components are made. Armand et al. (2020) and Ellingsen et al. (2014)

present the minerals used in a modern battery cell in their studies. The structure of the anode consists of two parts: Copper (Cu) made current collector covered with most often graphite made negative electrode paste. The Cathode current collector is instead made of aluminium. In addition to lithium, the composition of the positive cathode paste is, for example, a combination of manganese (Mn), nickel (Ni), and cobalt (Co) oxides, but the composition varies depending on the battery type. These oxides are called lithium transition metal oxides. The most often used electrolyte in batteries to conduct electricity in an organic solvent is lithium hexafluorophosphate ($LiPF_6$).

According to the IEA (2021a), the basic structure of EV batteries consists of several battery cells of the type mentioned above, which together form battery modules, several battery modules form battery packs, and eventually, with the rest of the parts, lithium-ion battery systems (see Figure 4). Battery cells make up most of the weight (70–85%) of LIBs and contain the largest share of the minerals required for batteries (IEA, 2021a). For this thesis, the most significant are battery cells and the minerals they contain. Therefore, the study does not further address the other parts of LIB modules.

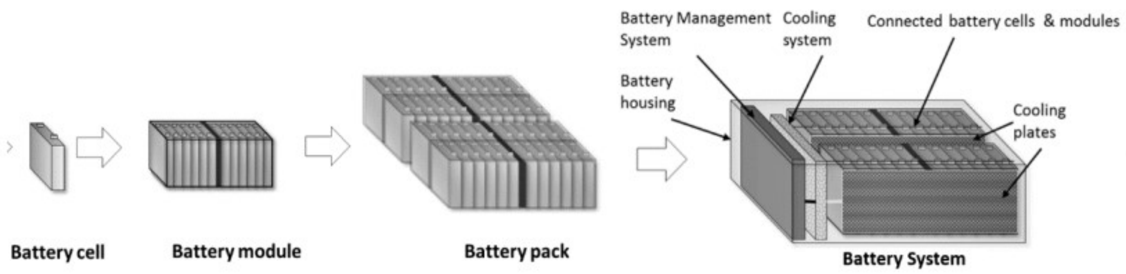

Figure 4. From battery cells to battery systems (Bielewski et al., 2021).

Different minerals have individual properties, which affect the characteristics of the battery and the EV in which the battery is placed. For this thesis, the most important minerals are the cathode minerals used in battery cells. Currently, in commercial use, there are five different combinations of minerals used in LIBs. Three of them contain cobalt: lithium cobaltite (LCO), lithium-nickel-cobalt-manganese (NCM) combination, lithium-nickel-cobalt-aluminium (NCA) combination, and the rest of the variations without cobalt oxides containing manganese or iron phosphate in addition to lithium (IEA, 2021a; Trafigura, 2018). Trafigura (2018) emphasises that although solutions are constantly being invented to replace the relatively expensive cobalt, it will continue to be needed to some extent to ensure battery safety in commercial long-range LIBs designed for EVs. The property of cobalt as a thermal stabiliser is an important safety issue, and therefore cobalt is still present in NMC and NCA batteries used in most of the EVs (Trafigura, 2018).

The cobalt content of batteries can be considered in more detail by studying the requirements for the share of different minerals in different battery types in units of kg/kWh (see Table 2). Only cobalt-containing battery types used in the EV industry are included in the table. Azevedo et al. (2018) relate that the most typical LIBs in the EV market currently are NMC and NCA battery types. NMC batteries can be further divided into three types: NMC-111, NMC-622, and NMC-811. LCO batteries are not included in the comparison because they have such a high cobalt content that the price of the battery rises too high in a commercial sense.

Table 2. Element requirements for different battery cathodes in units of kg/kWh (adapted from Olivetti et al., 2017).

Battery type	Li	Co	Ni	Mn	C
NMC-111	0,139	0,394	0,392	0,367	1,2
NMC-622	0,126	0,214	0,641	0,2	1,2
NCA	0,112	0,143	0,759	0	1,2
NMC-811	0,11	0,094	0,75	0,088	1,2

The different battery types are arranged in the table according to the cobalt content from highest to lowest. The numbers following the NMC letters reflect the number of atoms (Ni, Co, Mn) on the cathode (Azevedo et al., 2018). The order is also the order of the batteries from oldest to the newest technology, so the trend is to reduce the need for cobalt and replace it with nickel. The amount of lithium has also been slightly decreasing with development, and the same formula is repeated with manganese in batteries containing manganese. According to Olivetti et al. (2017), in NMC batteries, increasing the amount of nickel and reducing the amount of cobalt improves the battery's energy content but negatively affects the stability of the battery. So, the cobalt's mission in high-density commercial LIB batteries can be thought of as an adhesive that holds the battery together.

To clarify the differences between cobalt needs in the battery types in table 2, the most and the least cobalt-requiring battery type and, as an example, a full-electric vehicle with 75 kWh battery capacity are taken to comparison. In this case, the NMC-111 battery would contain 29,55 kg of cobalt, and the NMC-811 battery would contain 7,05 kg of cobalt, so the NMC-111 battery's cobalt need is 76% bigger than in the NMC-811 battery. As justified, the development of cathode chemistry leads to smaller cobalt needs per battery in the future, but whether it is reflected in a prominent decrease in demand will depend on demand development in the entire EV market. According to IEA's (2021a) estimates, this decrease in need per battery will be compensated by the future growth in the EV market. The problem will not likely be demand but instead meet the demand with sufficient supply (Alves Dias et al., 2018).

In addition to the lithium-ion battery variations, completely new types of batteries are also being developed for the EV market. Iclodean et al. (2017) compared lithium-ion batteries to three different battery types in a computer simulation: Na-$NiCl_2$, Ni-MH, and Li-S (see Table 3). Only one of these three other battery types contain lithium. It has been replaced by sodium (Na) or nickel (Ni). To ensure the validity of the comparison in the study, batteries of the same energy content have been used from all four battery types (Iclodean et al., 2017).

Table 3. Comparison of different battery types (adapted from Iclodean et al., 2017).

Battery type	Mass of battery (kg)	Battery price (€)	Energy consumption (kWh/100km)	Operating temperature (°C)
1. Lithium-ion (Li-Ion)	2 (318)	2 (300)	2 (14,7)	2 (33)
2. Molten salt (Na-NiCl2)	3 (457)	4 (500)	1 (12,6)	4 (270)
3. Nickel Metal Hydride (Ni-MH)	4 (500)	3 (400)	3 (15,7)	3 (36)
4. Lithium Sulphur (Li-S)	1 (173)	1 (250)	4 (17,2)	1 (30)

The mass, price, energy consumption, and operating temperature values for all four battery types are ranked in table 3. The weakest of these is battery type 3. Although battery type 2 consumption is clearly the lowest, its price is significantly higher than other batteries, and its operating temperature is nine times higher than the best-ranked in the category, battery type 4. Despite the highest consumption, the lightest and cheapest battery, according to comparison, is the battery type 4, lithium-sulfur battery. It could be an alternative as a future challenger for LIB (Iclodean et al., (2017). Iclodean et al. (2017) point out that the commercialization of a Li-S battery still requires development work related to, among other things, its lifespan and energy retention capacity. Noteworthy concerning this thesis is that Li-S batteries do not contain any cobalt, which is reflected in the weight and price of the battery. However, LIB ranks second in each category, so other battery types are not able to challenge it yet.

In 2020, the most widely used cathode material combination in the electric car market was NMC, with a 71% sales share, and most of the remaining share was for NCA batteries (IEA, 2021b). Both of these battery types contain cobalt. The third-largest percentage of sales, slightly under 4%, was for cobalt-free batteries with LFP cathode chemistry (IEA, 2021b). A few car manufacturers have reported using LFB batteries in their new electric car models. According to Wayland (2021), one of these is Tesla, which has switched to using LFP chemistry batteries because of their cost advantage and safety.

Utilising LFP batteries increases profit because they do not contain expensive critical materials such as nickel and cobalt and are therefore cheaper to manufacture. However, the disadvantages of LFP batteries are their less energy-dense and frost resistance, which is why Tesla does not use them in its long-range vehicles (Wayland, 2021). Although LFP batteries might not fully replace NMC batteries, it is expected that as more car manufacturers end up using LFP battery technology, its share of new battery sales will increase in the next few years. However, it is noteworthy that the sharp increase in demand for LFP cells has led to a rise in the price of lithium carbonate in China, which in turn has resulted in 5% higher manufacturing costs for LFB batteries than in high-nickel content NMC batteries at present (Benchmark, 2022).

2.1.2 The electrification of the automotive industry

As reviewed in the previous subchapter, one of the primary applications of cobalt is lithium-ion batteries used as a power source for electric cars. Electric vehicles are a common phenomenon on the roads today. If both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) are included in the calculations, then in 2020, more than 10 million electric cars were on the roads worldwide, while the same result in 2016 was only about 2 million electric cars (IEA, 2021b). In four years, the number has thus increased fivefold.

It is also noteworthy that in 2020, the largest number of new electric cars was registered for road transport in the European market, although China's share of electric car stock globally is still the largest (IEA, 2021b). The rapid growth of the electric car market in Europe is directly reflected in demand for batteries. As seen in figure 5, since 2016, annual demand has risen from 5 GWh to 52 GWh (IEA, 2021b). Demand is expected to grow, as a more conservative estimate by the IEA (2021b) suggests that annual battery demand in 2030 exceed 300GWh, over six times higher than in 2020. This phenomenon of electric vehicle proliferation is called electrification of the automotive industry. This chapter discusses the factors contributing to this phenomenon from the perspective of the European EV market. These factors include global and EU climate policy, national legislation, and the response of car manufacturers.

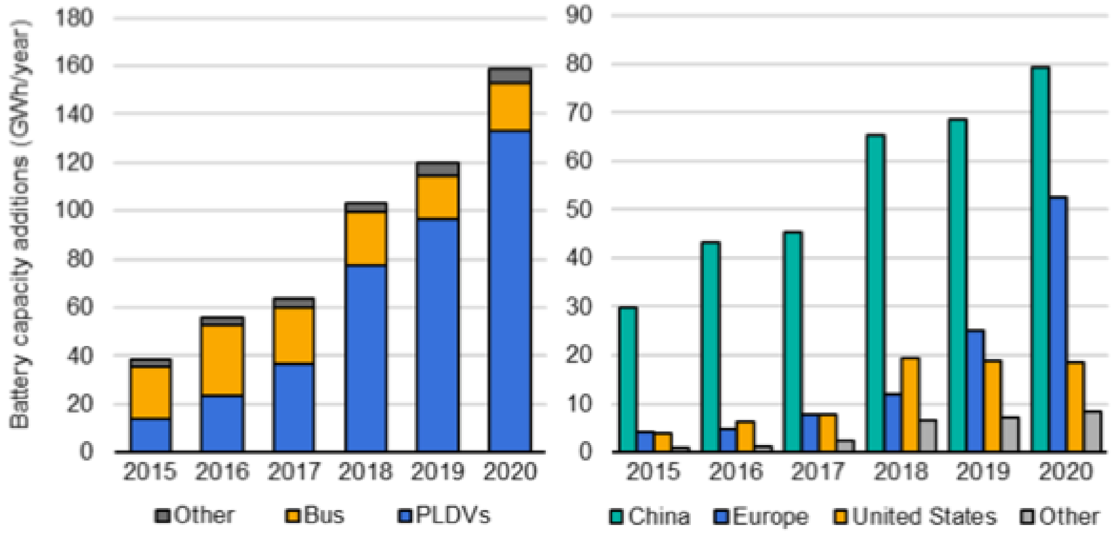

Figure 5. Automotive battery demand by mode and region (IEA, 2021b). *PLDV= passenger light-duty vehicles

One of the essential impulses towards the electrification of the automotive industry was the Paris Agreement, signed in December 2015 by 196 parties worldwide (UNFCCC, 2021). According to the UNFCCC (2021), the agreement, which entered into force in 2016, was created to commit the countries that adopted it to implement measures to combat climate change. The parties present their activities via nationally determined contributions (NDCs). The implementation of these contributions is reported and monitored through progression reviews every five years on a larger scale. New goals are placed at the end of the cycle, and the process continues incrementally with more ambitious goals. Intensified climate actions are intended to achieve the primary purpose of the Paris Agreement, to limit global warming to 1.5 degrees Celsius, compared to the pre-industrial level (UNFCCC, 2021).

However, the Paris Agreement does not give exact requirements on its adopting parties about investing in the electrification of traffic. Still, transport emissions caused by ICE vehicles are one of the major causes of increased CO_2 emissions and global warming (UNFCCC, 2015). So, the ambitious goals of the Paris Agreement will not be achieved without substantial national investments in the electrification of traffic. According to UNFCCC's (2015) declaration, to achieve the goal, it would mean that in the year 2030, there had to be over 100 million electric cars on the road. That means a 90% increase in the number of electric cars in traffic compared to 2020 levels.

European Union's actions to combat climate change have increased with the Paris Agreement. Recent regulatory framework publications that strongly accelerate the electrification of the automotive industry include the European Green Deal, the European Mobility Strategy, and the European Climate Law. The oldest of these, the European Green Deal, was published in 2019, causing a snowball effect on other publications (EC, 2021a). According to the European Commission (2021a), the Green Deal set the goal of making the EU climate neutral by 2050, which means that the net carbon footprint would be zero. The publication emphasised that transport's share of total GHG emissions in the EU is as high as 25%, indicating that 90% emission reduction is required in the transport sector to meet the Green Deal target.

The European Commission's (2021b) Mobility Strategy has set milestones for the transport sector to reach the Green Deal targets. As a shorter-term milestone, at least 30 million zero-emission cars should be on the European roads by 2030. Naturally, part of the process is to develop the infrastructure to meet the conditions for the electrification of transport. The milestones also apply to other modes of transportation, such as sea, rail, and air transport but essential for this thesis are the regulations that affect the electrification of the car industry. All in all, 82 initiatives related to the topic have been registered to the action plan. The most ambitious regulatory framework is the European Climate Law, which was entered into force in July 2021. The law tightens the targets set in the European Green Deal so that by 2030, greenhouse gas emissions should be 55% lower than in the reference year 1990 (EC, 2021c).

Strongly related to the electrification of the automotive industry, the European Commission (2021d) tightened last year the CO_2 emission limits of major car manufacturers for new cars and set targets for tightening the boundaries even more in the future. In addition, car manufacturers have been offered the opportunity to benefit from zero and low-emission car manufacturing through credit systems, and conversely get penalties for exceeding their emission targets. At a practical level, the credit system works so that when a car manufacturer sells a certain number of low-emission vehicles, the total average emissions of the cars sold are lower. If the emission level is lower than the manufacturer's target, the manufacturer will earn credit and vice versa. Another incentive for car manufacturers is the opportunity to get credits for successful eco-innovations.

As an example of the response to the electrification of the automotive industry at the national level, the Ministry of Economic Affairs and Employment (2021) has published Finland's battery strategy until 2025 on their site. The report's SWOT analysis lists Finland's strengths: comprehensive discovered and estimated mineral resources at the research level, ecology and sustainability of production, and research expertise, to name a few. Although Finland is currently mainly a producer of raw materials in terms of the European EV market, according to the national battery strategy, Finland has the potential to be a more significant player in the European battery cluster in the future. Investments in the battery sector are essential if Finland want to be carbon neutral in line with its targets by 2035 (TEM, 2021).

Car manufacturers have responded to the above-mentioned legislative changes and initiatives to promote the electrification of the automotive industry. Table 4 summarises the intentions of 13 different car manufacturers for electrification. The second column shows the date when the manufacturer will no longer make new internal combustion engines that do not use electricity as a power source at all. The third column indicates the date when the car manufacturer is not using ICE technology anymore, and the last column shows when the manufacturer aims for total carbon neutrality.

Table 4. Car manufacturer's plans for electrification (adapted from Motavalli, 2021).

Car manufacturer	Date for PHEVs/BEVs only	Date for BEVs only	Date for Carbon Neutrality
Bentley	By 2026	By 2030	By 2030
BMW	-	-	100% renewable energy by 2050
Ford	-	-	By 2050
Cadillac	-	By 2030	
GM	-	By 2035	By 2040
Honda		2022 (Europe)	By 2050
Jaguar Land Rover	100% with some electrification by 2030	By 2030	By 2039
Mazda	-	-	By 2050
Mercedes-Benz	All new platforms EV only in 2025	2030 with caveats in some market	By 2039
Nissan	-	-	By 2050
Toyota	8 Million electrified vehicles by 2030	-	By 2050
Volkswagen	-	Last new combustion platform in 2026	By 2050
Volvo	By 2025 (50% of global sales fully electric)	By 2030	By 2040

Table 4 shows that car manufacturers have different ways of presenting their electrification intentions. Some have a date for each category, others only for one or two categories. However, every manufacturer's plans for full electrification are more or less focused on 2030, which means a significant increase in EV production volumes with each manufacturer. Noteworthy is that the table includes carmakers with a completely different customer target group: British luxury carmaker Bentley, which has the tightest schedule, German premium car brands such as BMW and Mercedes-Benz, and cheaper Japanese brands such as Nissan, Honda, and Mazda.

The first research question of the thesis was "Why is cobalt needed in the European electric vehicle market?" To conclude, the demand for electric cars is affected by the electrification of the automotive industry, which began to accelerate in 2016 with the Paris agreement. The agreement's goal of curbing global warming to 1.5 degrees Celsius has led to new regulations restricting GHG emissions. Especially in Europe, a solution has been sought to reduce transport-related emissions through the electrification of vehicles, which has reflected as a multiplication of demand for electric cars within five years.

Currently, the most common power source for electric cars is a battery system assembled of battery cells containing NMC cathode. One of the minerals in an NMC battery is cobalt, the utilisation of which is essential, especially in long-range EV batteries. A well-known problem with electric cars is the shorter operating distance than in ICE cars and the time it takes to charge the battery, so there is a demand for longer range batteries. Although innovations in battery chemistry aim to replace cobalt, it will be needed to ensure a longer range of batteries, especially in countries where winters are cold and therefore challenging for LFP batteries.

2.2 The material flows of cobalt from mines to end products

In this chapter, the most relevant material refining flows for the logistical analysis of the study are modelled. The first subchapter deals with the material flow of cobalt in the supply chain from the DRC to China and from China to Europe. The second subchapter reviews the material flow of cobalt in the corresponding supply chain originating from Finland. The first material flow is modelled at a general level because identifying all supply chains from DRC to China is not possible with the schedule of this thesis. The latter material flow is described more at the company level to identify the case company's potential to be part of these supply chains in the future as a raw material producer.

The different degrees of cobalt refining studied in this chapter are divided into three categories, reviewed by Matthews et al. (2020) in their working paper. According to the Global Harmonized System (HS) breakdown, cobalt materials are coded with a 6-digit code in their respective classes (see Table 5): Unrefined cobalt ores (2605.00), refined cobalt oxides and hydroxides (2822.00), and refined unwrought cobalt metal (8105.20). The primary producer country of unrefined cobalt (2605.00) is DRC, and refined cobalt (2605.00 & 8105.20) China. Remarkable is that when cobalt sulfate, which does not have a 6-digit HS coding, is added to refined production, Finland is the second-largest producer of refined cobalt (sulfate, oxides HS 2822.00, and unwrought cobalt 8105.20) after China (Matthews et al., 2020). This thesis mainly deals with the material flows of the first two product categories.

Table 5. Cobalt products by HS subheading (adapted from Matthews et al., 2020).

Cobalt material	Degree of refining	HS Subheading	Description
Raw cobalt ores and concentrates	Unrefined	2605.00	Obtained as a by-product from nickel and copper mining
Cobalt oxides and hydroxides	Refined	2822.00	Product processed from cobalt ores and concentrates
Unwrought cobalt	Refined	8105.20	Cobalt product processed from cobalt ores and concentrates

2.2.1 The cobalt originating from DRC

According to Davenport and Moats (2014, p.625–667), nickel-cobalt ores and copper-cobalt ores are the most typical ores from which cobalt is produced by-product. In the Central African Copperbelt, upstream companies mine copper-cobalt deposits for further refining. There are two types of deposits: the top layer is called oxide surface, and below are the copper-cobalt sulfide deposits in the form of carrollite or mixed ores. Behind the operations are both large-scale industrial mining companies and artisanal miners. Artisanal miners mine cobalt by hand from the copper-cobalt oxide surface. Mined cobalt is washed and traded onwards for large-scale companies in the area for sale or refining (Schmidt et al., 2016).

Cobalt ore refined in the DRC is commercially called an intermediate product meaning cobalt chemicals (2822.00) defined in table 5. A major share of hydroxides and oxides are sold for further refining to China. Still, a noticeable amount of hydroxide is imported to Finland for further processing to Freeport Kokkola/Umicore, where it is refined to precursor material (pCAM) and sold forward for cathode active material (CAM) production abroad, where the power sources for electric vehicles, LIBs, are assembled (Tuomela et al., 2021).

In the study conducted by Schmidt et al. (2016), commercial cobalt is divided into cobalt metal and cobalt chemicals. Cobalt metal, the so-called “cobalt class I”, has a metal content of more than 99%, and its applications include magnets, high-speed steel, superalloys, and cobalt powder. Of these applications, only cobalt powder is used for battery manufacturing; other applications are not relevant for this study. Cobalt chemicals refer to cobalt with a concentration of 25–78%. This scale includes various forms of cobalt, such as hydroxides, oxides, carbonates, and sulfates. Of these cobalt chemicals, carbonates are used in other applications such as producing chemicals and chemical products. At the same time, hydroxides, oxides, and sulfates are further processed to cathode active material used in lithium-ion battery manufacturing (see Figure 6).

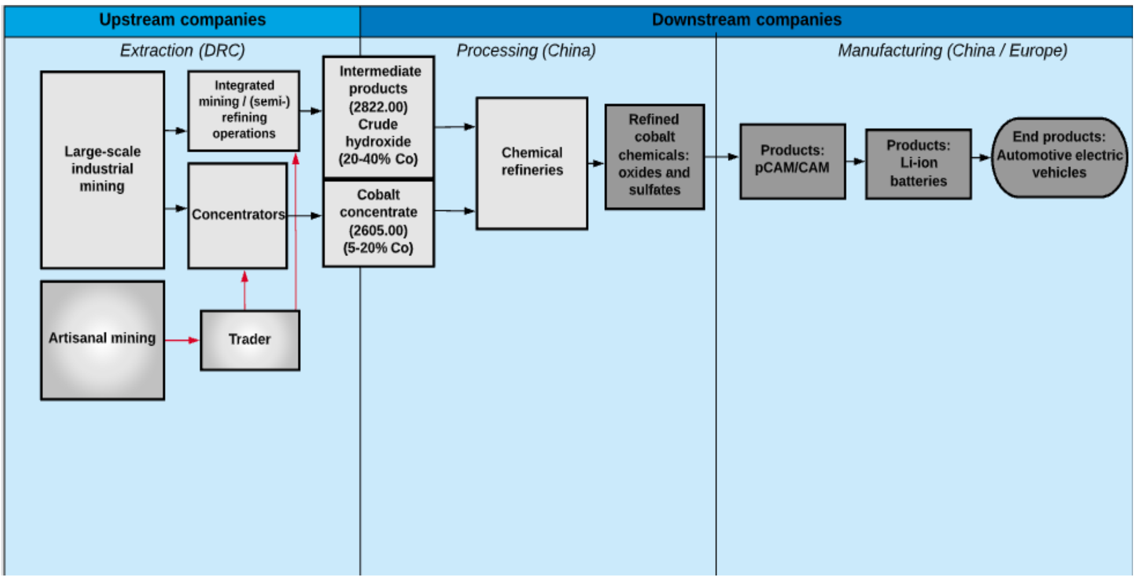

Figure 6. The cobalt material flow from Congolese mines to end products (adapted from Schmidt et al., 2016; The Faraday Institution, 2020 & Trafigura 2018).

Figure 6 summarises the most significant material flows in the DRC-derived cobalt supply chain for the European EV market. Although many other products can be obtained from cobalt, they have been left out of the figure due to the limitation of the study to the EV market. It is noteworthy that other raw materials discussed earlier are also required for LIB manufacturing. Still, these have been left out of the figure as the study focuses only on the cobalt's role as a raw material in LIB cathodes. From a logistical point of view, the most important thing is to identify the transports between the material refining processes. Total transport journeys are so long that short transport legs within production facilities will not be considered in the calculations later.

Extracted cobalt is used to make cobalt concentrate or hydroxide, most often sold to China for refining. Cathode components and lithium-ion batteries are made from cobalt refined in China, most of which remain on the Chinese market for their own electric car needs. Still, batteries are shipped to European EV manufacturers to an increasing extent, selected as the scenario for this study. The main transport route to be modelled and analysed is transporting raw materials from the DRC to China and shipping the Chinese-made batteries to Europe.

The main reason for choosing DRC to comparison is that according to Erickson (2021), almost two-thirds (68,9%) of the world's cobalt mine supply came from DRC in 2020. It means over 90 kt of cobalt which is a significant proportion considering that the total global supply is less than 140 kt. Erickson (2021) also mentioned that according to S&P Global and Cobalt institute estimate, in 2025, the same figure can be more than 70% of the estimated total supply of more than 220 kt of cobalt.

China was chosen as a part of the study for three reasons. The research conducted by Gulley et al. (2019) states that most of China's foreign cobalt ownership is in DRC, which is thus the most significant raw material producer for the Chinese cobalt refining industry and China's share of the world's production of refined cobalt in 2016 was 50%. According to Kinch (2020), Chinese investors control nearly two-thirds of DRC Mining operations. As DRC produces almost two-thirds of the world's cobalt, it can be said that the Chinese-controlled supply chains are globally the most significant cobalt supply chains. Through its operations, China can guarantee a large part of the security of supply of the global cobalt business. On the other hand, such a large concentration of activities under the control of one state is at the same time a significant risk in the event of political crises because cobalt is one of the minerals on the EU's list of critical raw materials due to the supply risk involved and its poor recycling and substitution rates.

2.2.2 The cobalt originating from Finland

Figure 7 summarises the most significant material refining flows in the Finnish cobalt production for the European EV market. Other raw materials required to produce LIBs have been excluded from this figure, like in figure 6. The cobalt material flows has been formed based on a report from the Geological Survey of Finland (Tuomela et al., 2021). Blue arrows in figure 7 indicate domestic material flows and black arrows international material flows. Process boxes marked with dashed lines describe projects under planning or construction.

The only project in the ramp-up phase is Terrafame's battery chemicals manufacturing plant in Sotkamo (Terrafame, 2021a). Under construction is one project, BASF's pCAM factory in Harjavalta (BASF, 2020). The rest of the projects are in the planning phase. Although the supply chains in the figure are not currently relevant from mines to end products, unlike in the Chinese-controlled scenario, they are included in the figure because this study addresses the potential logistical advantages of cobalt mined and refined in Finland. So, it is essential for comparison that cobalt is processed from cobalt ore to cobalt sulfate and manufactured to cathode active material in Finland.

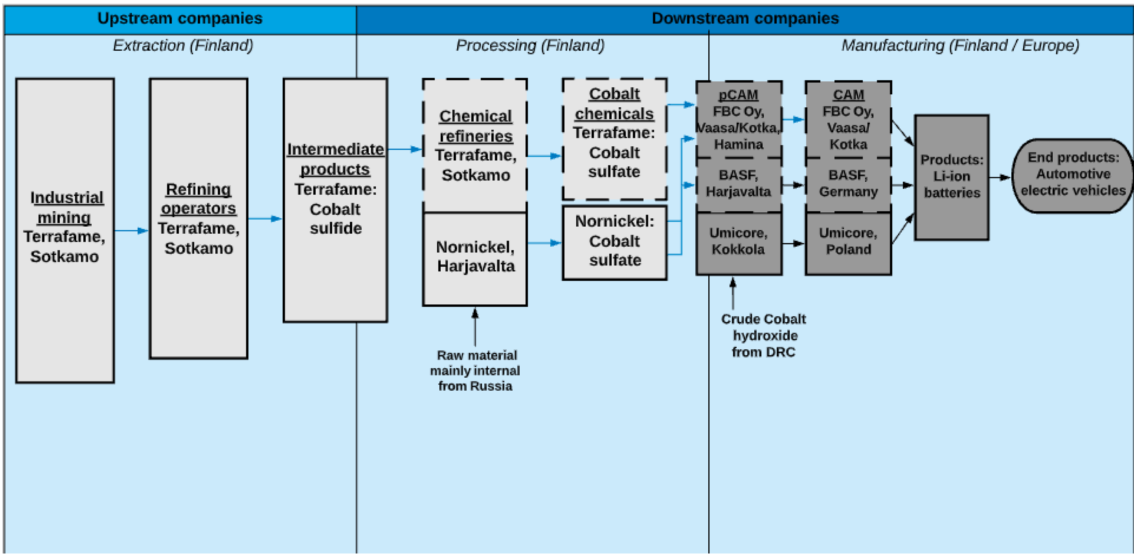

Figure 7. The cobalt material flow from Finnish mines to end products (adapted from Tuomela et al., 2021).

When the target market is the European EV industry, the case company has virtually three options to supply the mined cobalt. The first is Terrafame in Sotkamo which produces cobalt as a by-product of nickel and is thus the only company in figure 7 whose raw material is domestic. The share of Boliden, another company that mines cobalt in Finland as a by-product, has been left out of the figure because the product it refines goes mainly to different markets abroad (Tuomela et al., 2021). Another option would be Nornickel in Harjavalta, whose raw material is currently transported mainly from Nornickel's Russian plant. The third option is Umicore in Kokkola, whose raw material supplier is Glencore which sources cobalt from the DRC as refined to cobalt hydroxide (Glencore, 2019).

Figure 7 does not present the LIB manufacturer in Finland because there are no battery manufacturers in Finland who would do both, source raw material from Finland and target the European EV market. However, there is a battery factory in Finland: Valmet automotive's LIB manufacturing plant in Salo, partly owned by Chinese CATL (Tuomela et al., 2021). Of the precursor cathode active material producers, Umicore is currently the only company in Finland, but its product is transported to Poland for processing. The pCAM of the BASF's plant under construction in Harjavalta will be processed in the

BASF's plant in Germany. So, the only option is to utilise the Finnish Minerals Group pCAM/CAM plant project plans in the scenario.

2.3 Transparency of cobalt supply chains and the traceability of mineral origin

This chapter addresses the essential issues considering cobalt supply chain transparency and the traceability of the mineral origin. The problem of traceability is related to corporate value propositions. ESG factors increasingly influence consumers' purchasing decisions (Fraser et al., 2020). Still, a company cannot market its products as environmentally friendly and ethically produced if the origin of the raw material contained in the final product is unclear even to the company itself. In these cases, there are gaps in the transparency of the supply chain. On the other hand, why would battery and car manufacturers voluntarily pay more for guaranteeing the traceability if not required and no one else is doing that? Topics included in this chapter are concerns with responsibility and sustainability in current supply chains, requirements and guidelines related to cobalt supply chain traceability, and innovations developed to improve supply chain transparency and the traceability of the mineral origin.

In their study, Fraser et al. (2020) detailed what traceability means. In practice, traceability refers to the overall transparency of the mineral origin and branches of the mineral supply chain from the mine to the final product. However, the study emphasises that traceability is actually one of the six transparency information, meaning that traceability alone does not guarantee supply chain transparency. The other five factors of supply chain transparency information are: transaction, policy and commitment, effectiveness, and impact information (Fraser et al., 2020).

Fraser et al. (2020) investigated the number of actors operating at different tiers in the selected downstream company's cobalt supply chain. The used method in the study is referred to as the multi-tier transparency approach. The study results showed that the information suggested by the case company on the number of actors (28) is almost three times smaller than the actual number (79) found during research. The number of actors may be even higher due to uncertainty in the research results. From the perspective of this thesis, Fraser et al. (2020) showed both issues, challenges in guaranteeing the transparency of the cobalt supply chains and a need for traceability improvements.

Because the study found that the supply chain contained more actors than the case company informed, the implementation of traceability systems and innovations in the supply chain management is not the first step in ensuring the traceability of the supply chain. Fraser et al. (2020) remind that it is essential first to identify all the different actors in the supply chain and the processes that the raw material goes through. Without holistic supply chain transparency, the promise of downstream companies' compliance with ESG requirements is based solely on trust in previous tier suppliers. If supply chain transparency would be achieved successfully, Fraser et al. (2020) point out that companies may still face challenges implementing tracking systems with the following factors: capabilities, complexity, lack of standards, and costs.

For the purposes of this thesis, the above information indicates that EV manufacturers need to know where LIB manufacturers source their raw materials from, and raw material refiners need to inform battery manufacturers about their raw material sources, etc. In addition, sustainability, and ethics of operations, especially for upstream companies, must be considered. Thus, the most important thing is not only to strive for supply chain transparency but also to guarantee the ethics and the sustainability of the supply chain, especially in CAHRAs. In fact, the use of the term "traceability" is suggested in the Fraser et al. (2020) study to be replaced by speaking about "Transparency for sustainability".

2.3.1 Concerns with responsibility and sustainability

Going deeper into the "Transparency for Sustainability" perspective, the real issues emerge at the beginning of the cobalt supply chain in DRC. The problems underlying supply chain responsibility and sustainability are related to previously mentioned artisanal miners' operations. The problem in the operations compared to, for example, mining in Finland is how the mining activities are implemented. In Finland, cobalt ore mining is exclusively under the responsibility of industrial mining companies, which produce cobalt mainly as a by-product. The situation is different in the Democratic Republic of Congo. In addition to industrial operations, many people from poor backgrounds extract cobalt manually from surface deposits in hazardous working conditions with a minimum wage (Banza Lubaba Nkulu et al., 2018).

In terms of production volume, the largest share of the world's cobalt ores and concentrates originate from the DRC's Katanga Copperbelt (Banza Lubaba Nkulu et al., 2018). How this relates to Finland and the European EV market is explained by the fact that cobalt mined in the DRC, or mined in the DRC and refined in China, is also used as a raw material in Europe (Banza Lubaba Nkulu et al., 2018; Mancini et al., 2021). It is estimated that 15%–30% of mining still takes place by artisanal miners, although there have been developments in the region's mining activities over the years. In 2009, the same percentage was estimated at 60%–90% (Delve, 2021).

The operation of ASMs is one of the core reasons for the problematic tracing of the origin of cobalt. According to the data from Delve database (2021), although cobalt mining is estimated to be 70%–85% by large-scale mining, there is no guarantee of transparency in this share either, as part of the LSM companies' cobalt raw material is originated from ASMs. LSM companies mix cobalt from ASMs into their production (see Figure 6), making it difficult to determine the origin of the refined cobalt. Most of the DRC's cobalt production activities occur in the Haut-Katanga and Lualaba regions. The cities of Likasi and Lubumbashi in Haut-Katanga and Kolwezi in the Lualaba region are the most significant artisanal mining areas, where are also several large industrial mining companies (Delve, 2021; Mancini et al., 2021).

According to a study by Baumann-Pauly and Cremer (2019), it is difficult to define the exact number of ASMs in DRC. Still, it has been estimated that of the 2 million Congolese artisanal miners, up to 200,000 people are working with cobalt mining in the previously mentioned areas, and according to UNICEF, an estimated 40,000 of these workers are children. The study shows that despite the Congolese mining code that contains requirements for ASM operations, the youngest children working in the areas are only five years old. In addition to the utilisation of child labour, the problems are poorly or not at all organised occupational safety measures, health risks related to the manual extraction of minerals, such as cobalt, and numerous accidents that have been occurred in the areas (Baumann-Pauly and Cremer, 2019).

In addition to the issues associated with work performance, Baumann-Pauly and Cremer (2019) state that the level of wages is low, there are recurring armed conflicts in the country, and the activities of the state are highly corrupt. The word “democratic” in the name of the state is a bit misleading, as the DRC is found in the 2020 Democracy Index in the second last position just above North Korea (EIU, 2021). Addressing these issues is important because, despite mentioned challenges, it is the livelihood of hundreds of thousands of people, so pushing ASMs out of the supply chain is also a bad solution (Mancini et al., 2021).

2.3.2 Requirements and guidelines

One possible solution to the traceability challenges mentioned in the previous chapters is creating industry-specific standards that include supply chain transparency, traceability of mineral origin, responsibility, and sustainability requirements. When a company has adopted the standard, it demonstrates to consumers that it has tackled these issues via its operations and policy. This chapter discusses supply chain transparency and traceability standards and guidelines, their application, and their implications for managing international cobalt supply chains.

GS1 is an organisation that develops standards for supply chain management. The GS1's (2017) traceability standard is familiar from the retail industry in ensuring the transparency of the supply chain, widely used, for example, in fresh food supply chains management. GS1 provides guidance for industries with a need for improving supply chain traceability. For companies, GS1 has developed solutions to help create traceability systems that meet industry requirements. At a practical level, this means, for example, identifying objects based on an ID at different tiers to verify the origin and monitor the movements of the tracked object. GS1 (2017) emphasises that the system developed for the company, in addition to traceability, can increase the efficiency of the supply chain through optimisation and a common language, operational reliability and security, and compliance with international laws and requirements.

According to GS1 (2017), ensuring supply chain traceability requires collecting traceability data from the processes of all partners in the supply chain who impact the object to be tracked. The exact definition of the data to be collected depends on what is relevant to the industry in question. The data collected from supply chain organisations includes answers to five questions which contain information on the processes of these organisations and their impact on the activities of other stakeholders (see Figure 8). The questions are used to determine: the external activities affecting the organisation's operation, the information about the processed object and its previous handler, the location where the organisation's actions occur, when processes were performed, how long processing took, what and how it was done, and who was the following operator to take responsibility of the object (GS1, 2017).

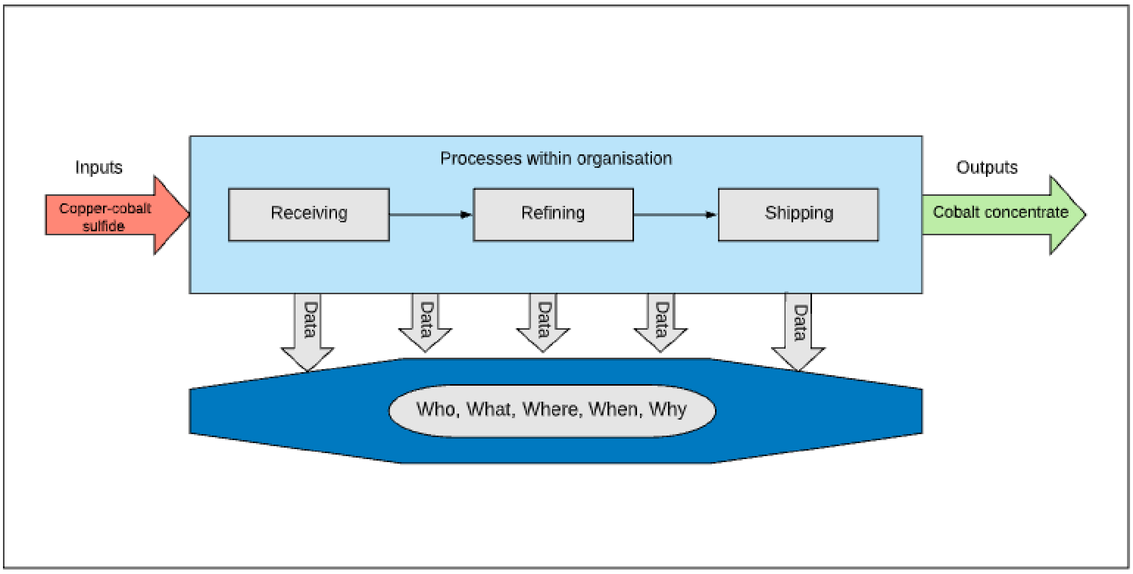

Figure 8. Generation of traceability data – single company view (adapted from GS1, 2017).

Figure 8 shows an example of a single organisation's traceability data collection process. However, traceability data from a single organisation does not guarantee transparency throughout the supply chain. To enable traceability of the entire supply chain requires that data collection systems must be implemented as part of the operations of each organisation so that the downstream company receives corresponding data from all actors in the supply chain (GS1, 2017). Figure 8 shows that the upstream and downstream actor in the supply chain also affects the data collected by the current actor. For example, the company that processes cobalt from cobber-cobalt sulfide to cobalt concentrate must receive accurate traceability information from the previous handler to send its outputs forward as a traceable product. Data collection aims at automation to minimise errors, for example, by utilising RFID coding, and should cover not only processors but also logistics functions, retailers, the afterlife of the product etc. (GS1, 2017).

There are already a few frameworks for managing the minerals supply chains. According to Mancini et al. (2020), the best known of these are OECD (2021) due diligence practices underlying requirements recorded in the EU Conflict Minerals Regulation, which currently only applies to tin, tantalum tungsten, and gold, not cobalt. Many other standards and certificates have been created based on OECD due diligence practices. The OECD provides guidance to the company to ensure the sustainability and responsibility of the supply chains of the raw materials it sources via supply chain information transparency. The ultimate purpose of OECD due diligence practices is to address problems in mineral supply chains such as corruption, human rights abuses, tax evasion, and money laundering (Mancini et al., 2020).

For cobalt, this means that downstream companies in China, such as refiners and LIB manufacturers, ensure that the operations of upstream companies in DRC comply with the requirements. The OECD has created a five-step framework (see Figure 9) that is generalisable to many sectors but has been widely adopted in connection with the EV industry initiatives because it is well known that there are responsibility issues in the supply chains of DRC-derived minerals.

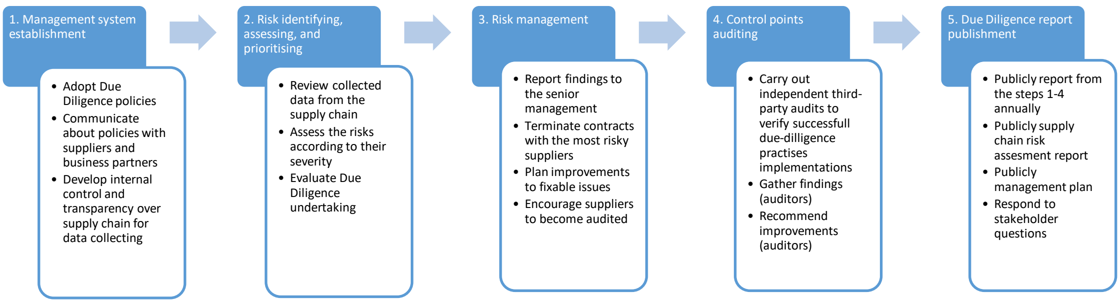

Figure 9. The OECD five-step framework (adapted from OECD, 2021).

Figure 9 presents the activities included in the five-step process established by the OECD. The intention is to implement due diligence practices for all parties in the supply chain. The process created by OECD (2021) thus works from the top down, which means that downstream companies adopt due diligence practices and seek to adopt the practices into the operations of upstream companies. Therefore, all suppliers are assessed and categorised based on whether there are preconditions for implementing due diligence practices and, if so, what measures it requires. Compliance with the requirements is monitored, and data is collected. It is essential that suppliers agree to be audited. Efforts will be made to respond to the findings of the audits, and a public report will be made annually. The whole process aims to end up in a situation where the supply chain is transparent from start to finish, and all selected suppliers can commit to meeting the responsibility requirements.

In their report, Mancini et al. (2020) present two more frameworks for responsible sourcing. CCCMC Guidance is practically a Chinese version of OECD Guidance. It is based on the OECD and operates on the same formula by setting requirements and guidelines for supply chain responsibility management. However, unlike the OECD, its focus is more on environmental aspects and respect for indigenous rights. Like the OECD, it is intended to serve as a basis for new initiatives for Chinese operators in CAHRAs such as DRC, which is China's largest cobalt supplier.

The International Finance Corporation (2021) has a different approach to the problem. It has created performance standards for its customers in eight categories as a prerequisite for business financing. These categories are Risk Management, Land Resettlement, Labour, Biodiversity, Resource efficiency, Indigenous people, Community, and Cultural heritage. The IFC's (2021) customer financing decision process is divided into five parts, as in the OECD five-step framework (see Figure 9). In the process, the company is introduced to IFC standards, and the development needs of its current operations are identified to meet the requirements of the standards. If the company is seen as developable, it will receive financing, the keys to developing its operations in line with required ESG values and thus the potential to arouse interest among new investors.

International human rights organisation Amnesty International (2017) have researched the above-mentioned due diligence practices implementation at the organisational level. At the heart of the research has been Zhejiang Huayou Cobalt., Ltd., whose operations as China's largest cobalt refiner is reflected in the supply chain transparency and responsibility of several downstream organisations in connection with the mineral industry supply chains. Huayou Cobalt's primary raw material producer is Congo Dongfang International Mining (CDM), which according to Amnesty, is the largest artisanal miners' user in the DRC.

The problems listed by Amnesty (2017) highlight the uncertainty of companies. Some companies do not admit their connection to Huayou Cobalt, and some of those who admit to acquiring from Huayou Cobalt claims that the cobalt they receive is not from the DRC or, if it is from the DRC, it is not from the CDM. Another recurring issue in the responses is the avoidance of responsibility. Amnesty International (2017) found that downstream companies rely intentionally or unintentionally too much on their suppliers complying with due diligence requirements.

The easy way to avoid responsibility is to hide behind certificates without clarifying the implementation of practices at a practical level in the DRC. According to Amnesty's (2017) study, 43% of the companies surveyed have taken only minimal action for compliance with practices. However, the study also found a positive change, as out of the 28 companies surveyed, seven companies' efforts to comply with due diligence practices were noteworthy. The problem is that the situation of the company's registered workforce does not tell the whole truth. Pattison (2021) states that a remarkable part of the industrial mines artisanal miners have been employed through subcontractors, in which case responsibility is not with the mine but with the subcontractor.

An example of a successful sustainable sourcing initiative from another industry is a joint initiative between coffee capsule producer Nespresso (2018) and mining company Rio Tinto for responsible aluminium sourcing. Rio Tinto mines and processes aluminium at its mine in Australia, from where it is sent for processing to Quebec in Canada. The operation complies with ESG standards because aluminium production is certified with the Chain of Custody Standard, guaranteeing 100% supply chain traceability. The certificate tells the consumer that the production is designed with respect for nature and human rights. The standard is based on The Aluminium Standards Initiative (ASI), whose founding members include Nespresso and Rio Tinto. A similar example is Neste's (2021) certified and 100% traceable palm oil that the company sources from Malaysia and Indonesia. The company emphasises that it obtains its certified palm oil directly from producer companies and does not purchase separate certificates from the world market. EU legislation on the biofuels industry requires operators to prove that the biofuel they use is responsibly produced.

2.3.3 Traceability initiatives

Some regulations affect the operation of the entire market. Halleux (2021) presents the EU's new battery regulatory framework in the European Parliament Research Service report. The new regulations concern both the characteristics of batteries and the responsibility and sustainability of their raw material supply chains. If enacted, the regulatory framework would repeal the earlier directive. Upon entry into force, the new regulations defined in the framework would apply both to the manufacture of LIBs in Europe and LIBs imported from other markets into the European EV market.

Halleux (2021) reminds that, although the regulations apply in practice to the European market, they also impact international markets. The supply chains of non-EU companies targeting the EU market must comply with EU regulations. Figure 10 summarises the regulations and targets that affect the supply chains of LIBs divided into three main categories: carbon footprint requirements, recycling targets, and due diligence obligations. According to Halleux (2021), the requirements for batteries' life cycle carbon footprint would be tightened, impacting the sourcing of raw materials, the manufacturing of batteries, and actions at the end of their life cycle. Recycling targets apply to both the battery components and the minerals they contain during the manufacturing phase and at the end of their life cycle. In addition, the due diligence practices mentioned earlier would become mandatory for all supply chains of companies entering the European market, and implementation of the practices would be audited on behalf of a third party.

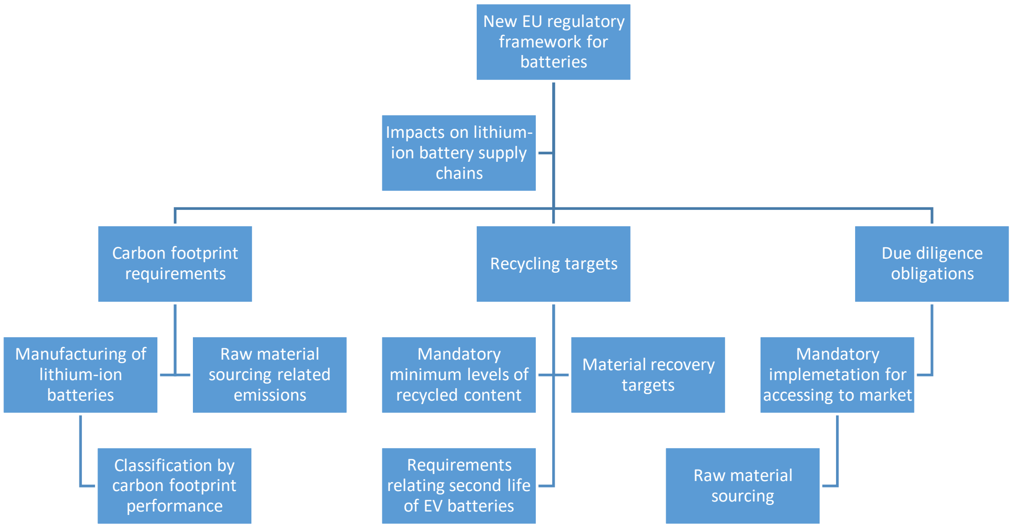

Figure 10. Impacts of the new EU battery regulatory framework on LIB supply chains (adapted from Halleux, 2021).

One possible direction in striving for the sustainability of LIB manufacturing would be to classify batteries into different categories according to their carbon footprint (Halleux, 2021). The classification would set a target for battery manufacturers to minimise the carbon footprint associated with battery manufacturing. If categorisation would affect the pricing of batteries, it might increase the demand for batteries and battery raw materials from the EU internal market. The problem is that the current supply of critical raw materials within the EU will not be enough if forecasts come true and for example, demand for cobalt will increase 15-fold by 2050 (Halleux, 2021).

One solution to reduce the internal supply gap for raw materials is the battery regulatory targets concerning LIBs and LIB raw materials recycling to support the EU's Circular Economy Action Plan, which aims to extend the life cycle of raw materials used in the market (EC, 2021e). However, due to the technological challenges and operational costs, Halleux (2021) states that the recycling rate for lithium is currently low. The situation with cobalt is better, and the goal is to increase its recycling rate from 68% to 90% by 2025.

Despite good recycling rates, the reuse of recycled minerals is still a challenge. For example, the share of recycled cobalt in new LIBs is only about 22% at present (Halleux, 2021). Therefore, the future challenges are improving the recycling rates and the use of recovered metals and finding new sources of raw materials in the internal market. Nevertheless, raw materials and LIBs are likely to continue to be sourced, at least to some extent, from the Chinese market. The question is whether non-European operators are prepared to bring their measures into line with EU rules or whether stricter regulations will lead to a noticeable reduction in supplies from other markets.

2.3.4 Traceability innovations

According to Hastig and Sodhi's (2020) study, one possible solution to issues regarding cobalt supply chains traceability is to apply the blockchain technology familiar with cryptocurrency bitcoin to collecting transaction data. For example, in the case of minerals, the blockchain has been used to increase the diamonds supply chains' transparency and traceability of the mineral origin. The basic idea is the same as the generation of GS1 traceability data discussed in the previous chapter (see Figure 8). The advantages of the blockchain include the speed and accuracy of data transfer (Hastig and Sodhi, 2020).

By utilising blockchain technology, the responsibility no longer lies solely with the EV or LIB manufacturers but with every supply chain member who enters transaction data into the blockchain. The study finds out that blockchain technology is still under development regarding cobalt supply chains because, unlike diamonds, cobalt undergoes a 12-step process in the supply chain in which the mineral is processed into various compounds (Hastig and Sodhi, 2020). Thus, tracing cobalt is not as simple as tracing diamonds or other items where a concrete object can be tracked throughout the supply chain.

How blockchain helps tackle supply chain ESG issues relates to transaction data collection. Hastig and Sodhi (2020) demonstrate that it is possible to track cobalt movements in the supply chain by analyzing the inputs entered the blockchain. The data will show whether the cobalt has travelled through forbidden areas, whether it originates from banned operators, and whether there are exceptions in production volumes that could indicate LSM company mixing artisanally mined cobalt into its production. The importance of trust is emphasised in operations, as ensuring traceability is based on entering the correct information into the system. The study has identified six critical success factors for implementing blockchain technology (see Figure 11).

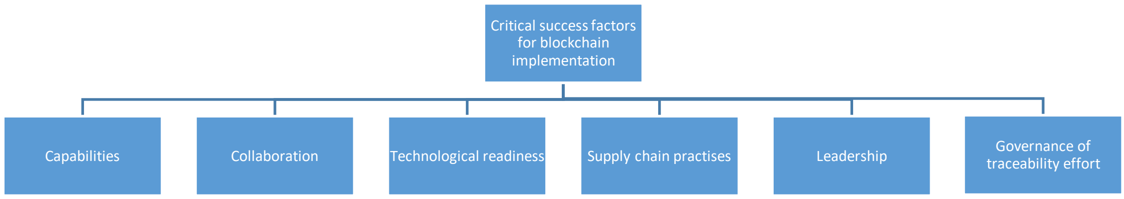

Figure 11. Critical success factors for blockchain implementation (adapted from Hastig and Sodhi, 2020).

The pressure from increasing customer awareness to find out the origin of a mineral is on focal companies, not upstream companies. In this case, the need to implement blockchain technology starts from the top down for commercial reasons. Hastig and Sodhi (2020) emphasise that through collaboration, upstream companies in the supply chain need to be made clear why they should adopt blockchain technology. Therefore, it is the responsibility of downstream companies to highlight the benefits of technology and identify the required practices and capabilities. In addition, leadership must be shared so that the management of each supply chain partner is committed to change, and through it, guaranteeing the reliability of operations.

Particularly in cross-border supply chains where upstream companies are located at CAHRAs, the most problematic factors are capabilities, technological readiness, and governance of traceability effort. Even if the upstream company is a prosperous Chinese-owned mine, it can be staffed by locals whose technical skills are insufficient to operate the new systems. Another big problem is the lack of standards and successful implementations of traceability systems, making it challenging to create a standardised system with a similar language of use for each party (Hastig and Sodhi, 2020). On the other hand, the lack offers the opportunity to be a pioneer in exploiting the blockchain.

Lastly, activities must comply with laws and regulations, which is a big challenge in implementing new technology in highly corrupted countries (Hastig and Sodhi, 2020). In addition, Hastig and Sodhi (2020) point out in their study that an industry-wide issue is to decide on how traceability can be commercialised. For example, would there be a different market for traceable and untraceable batteries in the future? Commercialisation would act as an incentive to develop traceability but would possibly put the market in an unequal position in the same way as the EU battery regulation discussed earlier.

The first signs of utilising blockchain to improve traceability of the international cobalt supply chains in the EV industry came from Volvo. Volvo (2019a) began cooperating at the same time with LG Chem, Korea's largest battery manufacturer, and Contemporary Amperex Technology Limited (CATL), China's largest battery manufacturer. Although traceability is seen mainly as a problem in supply chains from developing countries, supply chain transparency and traceability of mineral origin are current issues in other supply chains also. The first steps in utilising blockchain have also been taken in Finland, for Circulor has entered into an agreement with Finnish Minerals Group to trace Terrafame's nickel and cobalt production (Trafigura, 2021).

However, it is noteworthy that, as mentioned earlier, the blockchain is also based on the correctness of the input data. It can only guarantee the transparency of the value chain and the origin of the mineral if the data entered in the system is not distorted. A solution to this problem has been sought in the "BATTRACE" project. By looking at the repetitive properties of a mineral at different stages of the processing chain, the aim is to be able to trace the origin of the mineral. This technique is called mineral fingerprinting. In the best-case scenario, the technology would guarantee the correctness of the input data at different stages of the supply chain, allowing to prove the origin of the mineral to the end customer. (Kaikkonen, 2021.)

The second research question of the thesis was "What are the requirements for the cobalt supply chain transparency and the traceability of the mineral origin in the European electric vehicle market?" To conclude, as noted in section 2.2, cobalt mining is highly concentrated in Central Africa in the Democratic Republic of the Congo, where operations are controlled mainly by Chinese operators. At the same time, the processing of cobalt and its utilisation in the cathode chemistry of electric vehicle lithium-ion batteries is concentrated in Asia, especially China.

Although cobalt mining, refining, and battery manufacturing are already taking place in Europe, the supply chains controlled by Chinese players are crucial for the European electric car market currently and in the future as demand for cobalt continue increasing. The impact of Chinese players in Europe is also directly reflected in investments in the LIB and EV industries. Given the above, the traceability challenges addressed in section 2.3 and its subchapters focus mainly on the supply chains controlled by the Chinese operators targeting the European EV market.

More attention has been paid to the traceability of the mineral origin due to increased consumer awareness. Publications on the ethics of cobalt mining and the sustainability of supply chains have increased as demand for cobalt has grown due to the electrification of the automotive industry. It is the responsibility of downstream companies to ensure the responsible and sustainable implementation of the operations of upstream companies. International guidelines, such as the OECD five-step due diligence framework mentioned earlier, offer companies the opportunity to eliminate all non-compliant activities from their multi-tier supply chains.

Applying supply chain standards and traceability innovations to promote supply chain transparency and traceability for cobalt is still ongoing. Compared to cobalt from Finland, which is exploited in the European EV market, transport distances from the DRC and China are considerably longer. Those supply chains include more border crossings on different continents, which naturally poses regulatory challenges. In addition, developing countries' attitudes, capabilities, and resources pose an additional challenge to adopting standards and related systems. Due to reliability problems in implementing due diligence practices and the concentration of activities in the DRC and China, both LIB and EV manufacturers have begun to look for new alternatives for sourcing critical raw materials to ensure the security of supply.

According to Hampel (2020), BMW has announced it has signed a $100M contract with a Moroccan mine for cobalt supplies for five years. However, this agreement covers only about one-fifth of BMW's needs. With the solution, BMW seeks to eliminate the need to utilise DRC-derived cobalt, as the rest of the company's cobalt needs come from Australia. BMW also emphasises that it will procure its cobalt directly from the mines and supply it to battery manufacturers to ensure the supply chain's transparency. In addition, BMW intends to use blockchain technology to increase the transparency of its cobalt supply chains. However, BMW does not rule out the possibility of exploiting Congo's cobalt reserves in the future. The company emphasises that this will only be the case if cobalt is sourced from certain mines in which BMW has been involved in improving the responsibility and sustainability of the production activities and the transparency of supply chains.

3 Research methodology

This chapter reviews the implementation methodology of this research step-by-step. The chapter is divided into two parts: data collection and data analysis. The data collection section introduces the data sources and the calculations performed to convert the data to a comparable format. The data analysis section describes how the research results have been visualized and the actual comparison performed to produce research results.

This thesis is a management science study that applies an analytical decision-making process. The study method used is a scenario-based comparison. Anderson et al. (2012, p.4) divide the decision-making process into five steps:

1. Define the problem.
2. Identify the alternatives.
3. Determine the criteria.
4. Evaluate the alternatives.
5. Choose an alternative.

The research problem and the main goal of the thesis is to prove the logistical competitive advantages of Finnish cobalt production when the target market is the European EV market. Alternative a) is that Finnish cobalt production has logistical competitive advantages in the European EV market compared to Chinese-controlled supply chains, and option b) is that there are no logistical competitive advantages. The problem is solved using quantitative methods first by creating two comparable supply chain scenarios: The Chinese-controlled scenario and the Nordic scenario. Production and processing occur on different continents, but the end customer is the same in both scenarios. The case company Latitude 66 Cobalt is part of the Nordic scenario as a raw material producer. The scenario evaluation is done by calculating the transit time, GHG emissions and costs of all transport legs from the scenarios. These three indicators are compared between the scenarios.

3.1 Data collection

Supply chain scenarios need to be created before the actual data collection can begin. Cobalt material flows in both cases have been identified at a general level in chapter 2.2. Companies need to be selected for different stages of the cobalt supply chain, and the locations of these production facilities need to be determined to calculate transport distances between the facilities. In both scenarios, actors need to be selected for six different activities:

1. Cobalt sulfide/oxide mining and extraction company.
2. Company refining cobalt to hydroxide/sulfate
3. Precursor cathode active material producing company (pCAM)
4. Cathode active material producing company (pCAM)
5. Lithium-ion battery cells and modules manufacturing company
6. Full-electric vehicle manufacturing company

More detailed information on the scenario creating process can be found in chapter 4.1., which deals with both scenarios step-by-step. However, in the Chinese-controlled scenario, the starting point was to find a mining company in the DRC whose cobalt is being refined in China. It was also important for comparison that the battery manufacturer is Chinese. The aim was to keep the supply chain simple by selecting well-known players whose cobalt business covers processing operations on a wide scale with large operating volumes. In the Nordic scenario, the starting point was the extraction and processing of cobalt into cathode active material entirely in Finland. Another limiting factor was the integration of the case company into the supply chain. The scenarios have been created based on my suggestions and approved in meetings with the case company.

Once the scenarios have been decided and the locations of the selected companies are known, it is possible to determine the transport distances between the companies. Only logistic activities to or from production plants are considered, so the scenarios do not consider the impact of transport or production activities within production facilities. Determining the distance first requires selecting a mode of transportation for each transport leg. Scenarios have been formed using two options for a single transport leg: truck freight or sea freight.

In some transportations between the production facilities of supply chain companies, the mode of transport changes, for example, from truck freight to sea freight when the goods are shipped to another country. In these cases, the transports legs are divided into sections containing only one mode of transport per leg to simplify calculating. The transport of goods by a combination of modes of transport is called intermodal transport (Ghiani et al., 2013, p.323). In intermodal transport, it is possible to change modes of transport during deliveries because goods are loaded into containers, which is the basic loading unit in intermodal transport (Ghiani et al., 2013, p.323).

In truck freight, it is mentioned separately whether the transport is with containers or not. However, the default for all transports is to utilise the full load capacity of the trucks. Prices in freight quotes are for 40 ft standard containers, and the thesis defines a standard payload of 21 t as the cargo of containers to harmonize the calculations. The gross weight of one container is 25 t rounded because the 40 ft standard container's tare weight is 3,7 t (iContainers, 2022). These container loads are of the full container load (FCL) type meaning the entire contents of the container are reserved for the use of the supplier, in which case the price does not depend on the weight of the contents of the container (SeaRates, 2022).

The data used in the thesis has been collected in an excel file, where the necessary calculations have also been made. Table 6 summarises the comparative data for the Chinese-controlled scenario. All transport legs in the supply chain from mine to car manufacturer have been listed in the second column, and the third column shows the mode of transport associated with each leg. The row-level number in the third column refers to the definition table below, which identifies each mode of transport's GHG emissions conversion factors.

Table 6. Chinese-controlled scenario's data for competitive advantage analysis.

ID	Transport leg	Mode of transport	Cobalt concentration	Length (km)	Transit time (d)	CO2e (kg/t) 100% Co	Freight rate ($)	Cost ($/t) 100% Co
1	CDM, DRC –> Port of Durban, South Africa	1 (Container truck)	30 %	2734	7,0	382	2500	397
2	Port of Durban –> Port of Shanghai	3 (Container ship)	30 %	13128	30,5	744	1169	186
3	Port of Shanghai –> Huayoy Cobalt	1 (Container truck)	30 %	157	3,0	22	336	53
4	Huayou Cobalt –> CATL	1 (Container truck)	100 %	170	2,0	11	353	17
5	CATL –> Port of Shanghai	1 (Container truck)	100 %	257	3,0	17	437	21
6	Port of Shanghai –> Port of Antwerp	4 (Container ship)	100 %	19433	40,5	253	14765	703
7	Port of Antwerp –> Volvo Car Gent	2 (Container truck)	100 %	67	3,0	3	735	35
			Total:	35946	89	1431		1411

ID	Mode of transport	CO2e (g/tkm) Highway driving	CO2e (g/tkm) Urban driving	CO2e (g/tkm) Ocean freight	Source
1	GVM 40t, pay load capacity 25t (EURO III)	39	68	-	(Lipasto, 2017)
2	GVM 40t, pay load capacity 25t (EURO VI	35	66	-	(Lipasto, 2017)
3	Container ship, 3000-4999 TEU	-	-	17	(GOV.UK, 2021)
4	Container ship, 8000+ TEU	-	-	13	(GOV.UK, 2021)

GHG emission calculations in this thesis have been made by applying the standard **SFS-EN 16258: 2012**, which provides guidelines for GHG emission calculation in transport services (Lipasto, 2017). Because the study would include so many transport service providers from different countries to gain exact information, average emission factors have been used due to the limited time. The conversion factors for truck freights are from the Technical Research Centre of Finland's Lipasto (2017) unit emission database, and the conversion factors for sea freight are from GOV.UK's (2021) unit emission database.

Grams per tonne-kilometre (g/tkm) were chosen as the unit for the emission factor, as the study aims to determine emissions per 1-tonne of cobalt (100%) transported for each leg. Truck freights have CO_2e (g/tkm) conversion factors for both highway driving and urban driving, as in the calculations have been assumed that 10% of each leg is urban driving and 90% highway driving. $KgCO_2e$ per tonne emissions in column seven have been calculated multiplying the definition table value with the length of the transport leg in column five.

The fourth column in table 6 contains information on cobalt concentration during the transport in question. The lower the concentration is, the greater the negative effects for total GHG emissions and costs per tonne are because the calculated CO_2e and cost values have been divided by the concentrations in the fourth column. So, the results for each leg in columns seven and nine are per tonne of cobalt (100%) transported. As emissions are determined per tonne of cobalt transported, the study does not consider transports emissions with empty loads. In addition, costs per tonne values have been obtained by dividing the total costs of each transport in column eight by the net weight: 21 t in container transports and 40 t in other transports. More detailed information on cost sources can be found in chapter 4.1.

The classic.searoutes.com online distance calculation tool has been used to calculate the lengths of sea voyages, and the classic-maps.openrouteservice.org online distance calculation tool has been used to calculate the lengths of transports on the mainland. Both sea voyages have the exact transit times from the shipping company schedules, and transit times of the other transport legs are estimates rounded to the nearest day. Transit time also includes the time it takes to load or unload the goods (Ghiani et al., 2013, p.320). The default loading time has been determined to be two days in the Chinese-controlled scenario and one day in the Nordic scenario. The reason for the difference is the larger ports and ships in the Chinese-controlled scenario. Information of the estimated production volumes is mentioned in chapter 4.1.1.

Table 7 presents the corresponding data for the Nordic scenario. The same assumptions as in the Chinese-controlled scenario have been used to calculate GHG emissions to validate the comparison. The same tools have also been used to determine the distances. At the time of the calculations, the exchange rate was $1.13. Since the exact information can be found only for the fourth shipment, other transit times in column six are assumptions. The information on the estimated production volumes can be found in chapter 4.1.2.

Table 7. Nordic scenario’s data for competitive advantage analysis.

ID	Transport leg	Mode of transport	Cobalt concentration	Length (km)	Transit time (d)	CO2e (kg/t) 100% Co	Freight rate ($)	Cost ($/t) 100% Co
1	Lat66, Kuusamo –> Terrafame, Sotkamo	1 (Truck)	9 %	320	2,0	97,8	904	251
2	Terrafame –> Battery Chemicals Plant, Vaasa	1 (Truck)	21 %	403	2,0	54,1	1140	136
3	Battery Chemicals Plant –> Port of Vaasa	1 (Truck)	100 %	16	1,5	0,5	45	1
4	Port of Vaasa –> Port of Umea	2 (RoRo Ferry)	100 %	99	1,5	3,0	339	8
5	Port of Umea –> Northvolt, Skelleftea	1 (Truck)	100 %	156	2,0	5,1	442	11
6	Northvolt –> Port of Skelleftea	4 (Container truck)	100 %	11	1,5	0,4	31	1
7	Port of Skelleftea –> Volvo Car Gent	3 (RoRo Ferry)	100 %	2598	11,5	130,4	2930	140
			Total:	**3604**	**22**	**291**		**548**

ID	Mode of transport	CO2e (g/tkm) Highway driving	CO2e (g/tkm) Urban driving	CO2e (g/tkm) Ocean freight	Source
1	GVM 60t, payload capacity 40t (EURO VI)	30	55	-	(Lipasto, 2017)
2	RoRo-Ferry 0-1999LM	-	-	31	(GOV.UK, 2021)
3	RoRo-Ferry +2000LM	-	-	50	(GOV.UK, 2021)
4	GVM 40t, pay load capacity 25t (EURO VI)	35	66	-	(Lipasto, 2017)

3.2 Data analysis

Data analysis of this thesis has been performed by visualizing the data collected in the excel file. Scenario-specific diagrams have been created for every three indicators to identify the most significant bottlenecks of the supply chains. Chapter 4.2 discusses the underlying causes of these observed bottlenecks. After scenario-based analyses, the calculated total transit time, GHG emission and costs values from tables 6 and 7 are compared between the scenarios. The study’s primary output is the indicator-specific differences between the scenarios, expressed as percentages.

All the indicators examined and calculated in the thesis include uncertainty. Transport delays are affected due to varying weather conditions, equipment breakdowns, the choice of transport routes, and waiting times at borders and ports. GHG emissions are affected by the age and size of the transport equipment and the fuel used. The variation in the concentration of cobalt transported and the routing of the transport service provider also have a significant effect on emissions variation. In addition, transport costs are affected by the current fuel price, container rent prices, and customer-specific pricing based on volume. These are just to name a few examples of sources of variation.

A Monte Carlo simulation method has been applied in the thesis to demonstrate the effects of uncertainty. Historically, Monte Carlo simulation was used to prove the expression of repetitive features of different models when the model is repeated several times (Anderson et al., 2012, p.557). The trial results are not related in the simulation, meaning that each trial affects the outcome but not the previous or forwarding trial (Anderson et al., 2012, p.557). Today, the Monte Carlo simulation is a generic name for this type of sensitivity analysis, which is utilised in various software that automatically performs the simulation based on the given inputs. This thesis uses Oracle Crystal Ball software, which can be installed as an add-in to Excel (Anderson et al., 2012, p.557). The simulation process in this thesis consists of six steps:

1. Define the input values as assumptions to simulation software
2. Select the probability distribution for each input
3. Set the minimum and maximum value or the standard deviation to the distribution
4. Define the total value of the inputs as the simulation forecast
5. Set the number of trials
6. Perform a simulation and analyse results

The assumption and forecast values used in this study's Crystal Ball simulations are from tables 6 and 7. Appendix 7 tabulates the probability distributions used with the inputs, minimum and maximum values set for the triangle distributions, and standard deviations set for the normal distributions. In all simulations performed, the number of trials is set to 100,000. The software generates random input values based on the defined probability distribution and calculates the output. The simulation repeats 100,000 times with different random inputs, and the software visualizes the outputs as a histogram from which the variation of the forecast values of the indicators from tables 6 and 7 can be reviewed.

4 Results & analysis

This chapter has been divided into three subchapters. The first subchapter models both scenarios utilising map images of the transport routes between production facilities. In the second subchapter, the modelled scenarios are compared quantitatively to identify potential logistical competitive advantages of Finnish cobalt production in the European EV market. The last subchapter deals with the validity and reliability of the research findings. Figure 12 below models the supply chain scenarios to be compared in this chapter on a large scale.

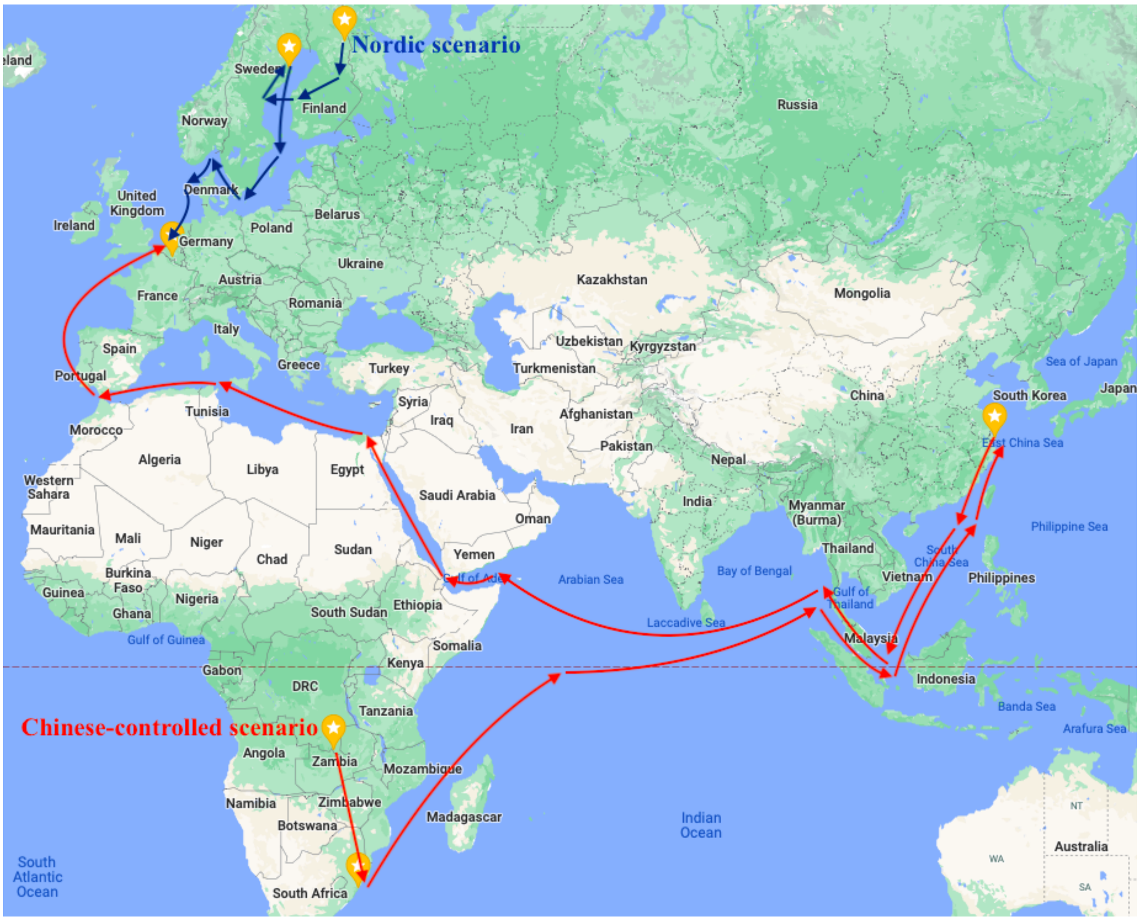

Figure 12. Comparable supply chain scenarios on the map.

4.1 Modelling of supply chain scenarios

This chapter details the cobalt supply chains, studied in chapter 2.2, at the enterprise level. Both scenarios are explained step-by-step to provide a connection to the values used in the comparison calculations in chapter 4.2. The chapter also gives background information on why these organisations were selected for the created scenarios.

4.1.1 Chinese-controlled scenario

The number of supply chains formed by Congolese cobalt mines and Chinese cobalt refiners is many times higher compared to the number of alternatives in creating the Nordic scenario. The simple reason is that, as mentioned earlier, almost 2/3 of the world's cobalt is originated from the DRC, and China is the world's largest cobalt refiner, sourcing most of its raw material from the DRC. It is not possible to explore all the different options of a modellable supply chain on the schedule of this study. One mine can act as a raw material producer for several refiners, and the material produced by one refiner can be a raw material for several different battery manufacturers. However, the basic principle in supply chains from DRC to China and from China to Europe is the same. Still, for example, the transport routes within China between different companies in the scenario are assumptions due to a lack of public information.

In contrast to the Nordic scenario, all actors in this supply chain have ongoing production. The modelled supply chain is a scenario created with internet sources, as accurate information on the current connections of companies in the supply chain is not available. According to sources, there are connections between companies, but it is difficult to determine which of the companies' plants are related to which customers with the public information. However, the main point was to model a scenario where cobalt ore is mined in the DRC, refined in China, and are used as a raw material in Chinese made LIBs. From China, LIBs are shipped to Europe. In this way, it is possible to compare the potential logistical advantages of the Nordic scenario to the most significant supply chains controlled by Chinese players. It is noteworthy that neither scenario is intended to accurately describe the current situation, as the case company's mining activities are still in the planning stage. So, scenarios describe potential supply chains within five years.

Huayou Cobalt, one of the largest cobalt refineries in China, was selected as the cobalt refiner for the scenario. In addition to the volume of operations, the reason for the choice was that Huayou's cobalt business covers everything from the extraction of cobalt to the production of cathode active material (see Figure 13). For a comparison between the two scenarios to be valid, the last link in the supply chain, the European electric vehicle manufacturer, must be the same in both cases. For this reason, had to be found an EV manufacturer operating in Europe with an agreement with both a European and a Chinese LIB manufacturer. Volvo (2019b; 2021b) has a supply agreement for battery cells with Swedish Northvolt Ett and Chinese CATL. Volvo's first battery assembly line is in Ghent, Belgium, where Volvo's fully electric vehicle XC40 is manufactured. Therefore, the modelled supply chains in both scenarios end at Volvo's manufacturing plant in Belgium.

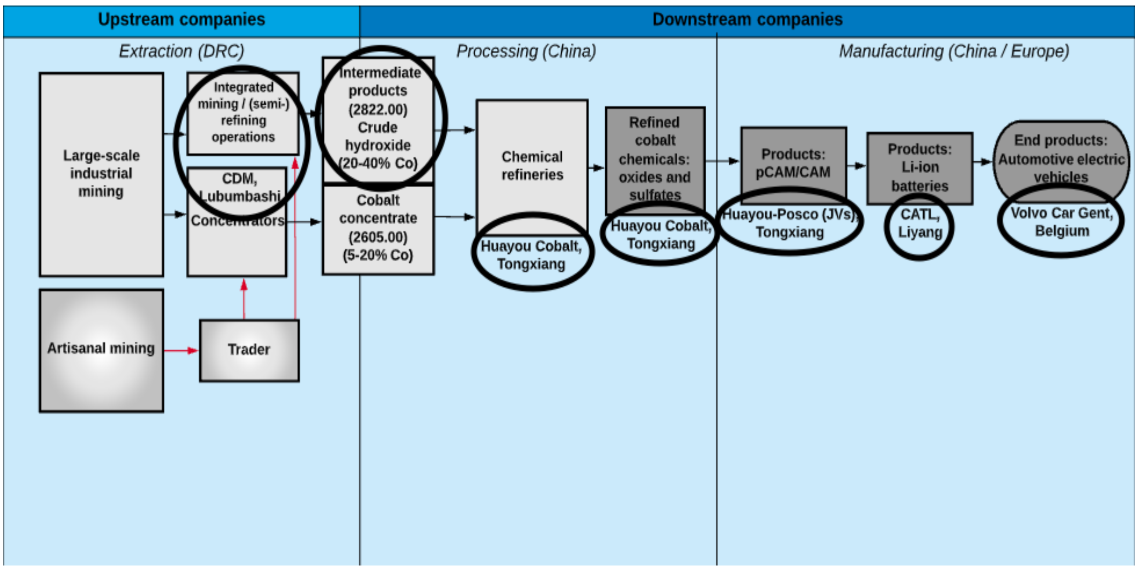

Figure 13. Companies in the Chinese-controlled scenario supply chain.

Figure 14 presents Huayou Cobalt's supply chain for cobalt production. The cobalt to be processed in China originates from several sources. Of these, Huayou Cobalt (2020) has named in its social responsibility report only its cobalt smelters in the DRC: CDM and Mikas. The report does not differentiate these smelter's raw material sources, so the origin of the mineral is not fully traceable with this information. CDM was chosen as the first actor in the scenario because it is the primary source of Huayou's cobalt hydroxide, and on the other hand, the report does not reveal the raw material sources of CDM.

Huayou Cobalt (2020) is headquartered in Tongxiang City, Zhejiang Province, less than 150 kilometres from Shanghai. The company's production facilities are also in the same area, a refinery 100% owned by Huayou Cobalt and joint ventures with the South Korean POSCO Chemicals company. Precursor production is 60%, and cathode active material production is 40% owned by Huayou Cobalt (see Figure 14). According to Choo and Chen (2021), construction work will begin this year to increase the Tongxiang plant's pCAM and CAM coproduction volume to 60 ktpa from 10 ktpa. The exact locations of these production facilities were not publicly available, so the address of Huayou Cobalt's head office has been used in the calculations. Choo and Chen (2021) also point out that CATL's plant is located near Tongxiang and is a potential customer for Huayou Cobalt at present and in the future. It was also one reason to choose CATL as part of the scenario.

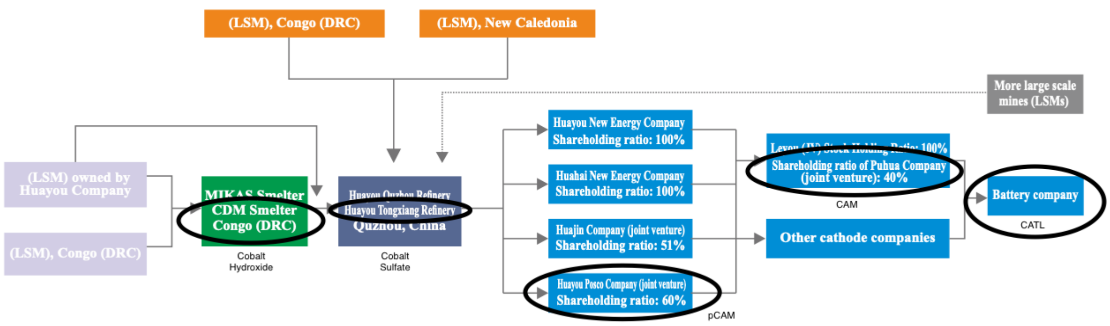

Figure 14. The cobalt supply chain map of Huayou Cobalt (adapted from Huayou Cobalt, 2020).

The cobalt acquired by Huayou Cobalt becomes mainly from the CDM smelter, the south-eastern part of the DRC, from the city of Lubumbashi, known as the DRC's Mining Capital. According to the personal conversation (16.12.2021) with the experienced metal trader, under normal circumstances, the most used port for cobalt shipments to China is the Port of Durban in South Africa. Due to the lockdowns caused by the Covid-19 pandemic, the Port of Dar es Salaam in Tanzania and the Port of Maputo in Mozambique have also been in use. These changes during the Covid-19 pandemic have hampered logistical operations, as customs clearance at borders takes more time when the destination is an exceptional port.

The distance travelled by truck from Lubumbashi to Durban is more than 2,700 km (see Figure 15). The trucks used in Africa are equivalent to EURO III trucks in Europe, so the calculations are based on a EURO III semi-trailer combination with a gross vehicle mass of 40 t and payload capacity of 25 t. Usually, the journey from Lubumbashi to Durban takes about 5–7 days, depending on the smoothness of border checks and weather conditions. The main roads are in moderate condition, but the condition of smaller roads in Lubumbashi, for example, can vary depending on weather conditions. The price of one shipment is approximately $2,500, and there are several departing shipments daily (Metal trader, personal conversation, 16.12.2021.) According to Trafigura (2018), DRC-derived crude cobalt hydroxide has an estimated cobalt content of 20–40%, so the average (30%) has been used as a working number in the calculations of the first three transport legs.

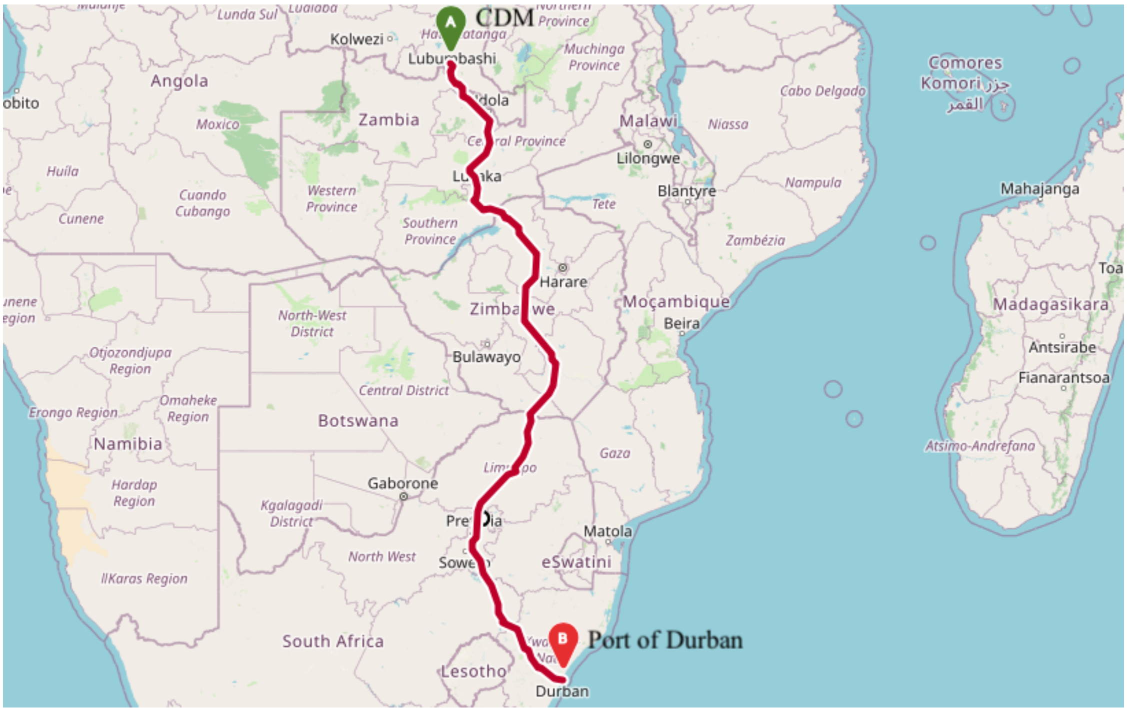

Figure 15. Transport from the DRC to the Port of Durban.

In Lubumbashi, cobalt is usually loaded into containers, but during Covid-19, the availability of containers has been weak. As a result, cobalt is also packed in 1-tonne bulk bags, which are loaded onto a truck and transferred to containers at the port if containers are available. Poor availability of containers and vessels has affected container prices and the security of supply. In the worst-case scenario, the goods may have to wait in port for several months. As a result, the Port of Durban, for example, is suffering from a lack of storage space. Delivery problems are also reflected in companies' cobalt warehouses. World's largest cobalt-mining company Glencore, for example, has had a record amount of cobalt on African soil during the crisis. (Metal trader, personal conversation, 16.12.2021.)

In this scenario, cobalt is shipped from the Port of Durban to the world's largest cargo and container port, Shanghai (see Figure 16). The destination is the Port of Shanghai because the production bases of Huayou Cobalt and CATL are in its vicinity. The sea distance from port to port has been calculated with the classic.searoutes.com online distance calculation tool (13,128 km). The freight quote is from SeaRates.com, which reviews current container freight prices. The poor container availability is indicated by the fact that there was only one freight quote available for this leg (see Appendix 1). The shipping company, in this case, was Evergreen.

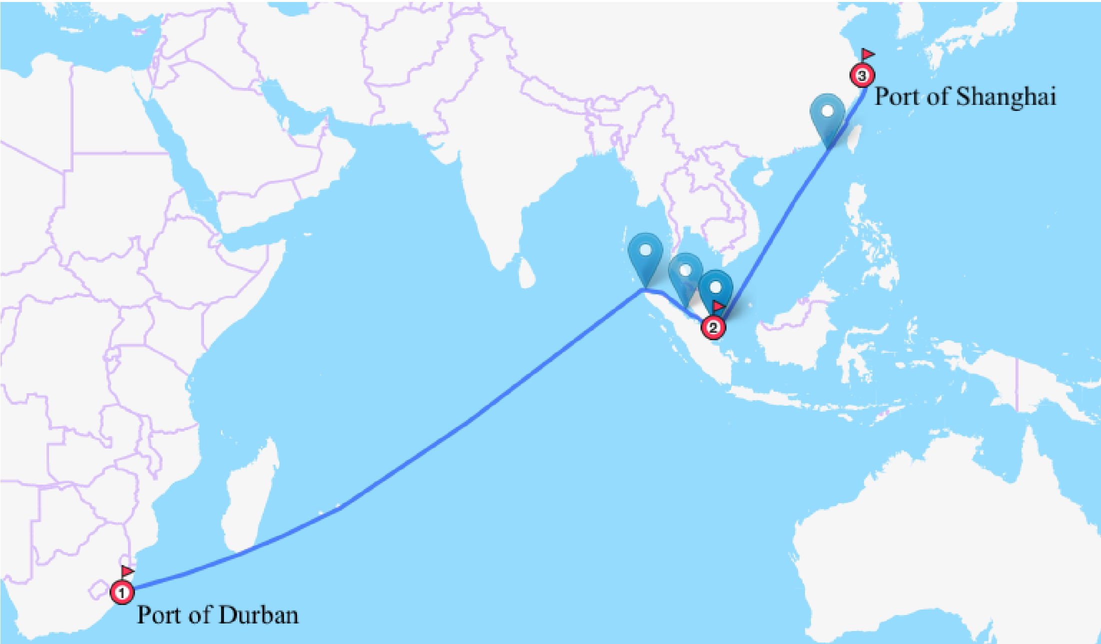

Figure 16. Shipping from the Port of Durban to the Port of Shanghai.

Evergreen's routing network between Durban and Shanghai is called Far East-Africa Express (see Appendix 2). Vessels operating on the line arrive in Shanghai in an average of 27 days and sail this leg every seven days in a normal situation. The ShipmentLink (2021a) website schedule includes the names of the operating vessels. With the name, it is possible to search for more detailed information from the vessel on MarineTraffic.com. In this scenario, the Cosco Wellington container vessel with a cargo capacity of 4,253 TEU has been used as a benchmark in data collection. The information has been utilised to determine the (gCO2e/tkm) conversion factor.

All shipments on mainland China have been assumed to be carried by container trucks. EURO III and trucks of the same size as previously used in this scenario have been utilised as the emission category. The distance from the port of Shanghai to Tongxiang to Huayou

Cobalt's refinery is 157 km (see Figure 17), and the price of transport is specified in Appendix 1. In the absence of precise information on the location of the different production facilities, the scenario assumes that all processing activities will take place in the same area at the Huayou Cobalt's plant. Transport of cobalt between different stages of processing within the Tongxiang borders is therefore not differentiated. By Huayou Cobalt and POSCO Chemicals, cobalt is processed and used as one of the raw materials for the cathode active material (see Figure 10). As previously mentioned in chapter 2.1.1 in the cathode active material of NMC type lithium-ion batteries, cobalt is one of the three minerals in addition to manganese and nickel.

Figure 17. Transport from the Port of Shanghai to the Huayou Cobalt's refinery.

The CAM, manufactured in Tongxiang, is transported 170 km (see Figure 18) to the CATL´s Liyang production base, located closest to Tongxiang (CATL, 2021). The transport cost for this leg has been obtained from SeaRates.com, which also offers price estimates for land transports. CATL (2021) has published plans to build a new production base in Shanghai, which is also well located from the perspective of Huayou Cobalt. In addition, according to Bolduc (2019), CATL will start manufacturing LIBs in Germany at its first European plant, where production is expected to begin in 2022. However, Bolduc (2019) reminds there is no certainty that the LIBs to be manufactured will be supplied to Volvo, as deliveries will start with BMW first. Therefore, it is very likely that the CATL batteries supplied to Volvo's plant in Belgium are from one of the Chinese plants. It is also noteworthy that since CATL is a Chinese battery manufacturer, some of the raw materials for the Europe-plant in the future may also be supplied from China.

Figure 18. Transport from Huayou cobalt to the CATL's Liyang production base.

The last truck transport of containers on Chinese soil is a 257 km journey to the Port of Shanghai (see Figure 19). CATL manufactures battery modules delivered to Volvo's assembly line in Ghent, where they are assembled into battery packs (Automotive Logistics, 2020). As mentioned in chapter 2.1.1, these battery modules consist of several battery cells manufactured by CATL. An article in Automotive Logistics (2020) states challenges associated with transporting LIBs because they have been classified as class 9 dangerous goods by UN Model Regulations. According to the article, in Europe, the International

Electrotechnical Commission has set standards for the transportation of batteries. The suitability of batteries for transport must be tested before transport, and there are also specific rules for their packaging and labelling.

Figure 19. Transport from CATL to the Port of Shanghai.

DB Schenker's (2020) report on battery shipments presents specific measures related to battery shipping. Batteries must not be transported in a standard container or placed in the same container as other metal goods. Because batteries are classified as dangerous goods, their shipment takes place in reefer containers whose temperature can be adjusted. The special handling of the batteries and the need for reefer containers increase the transportation costs. Due to poor container availability, there were no freight quotes available for reefer containers, so a standard 40 feet container rent price has been used in both scenarios.

In this scenario, the longest shipment is from the Port of Shanghai to the largest port in Belgium, Antwerp (see Figure 20). The length of the journey is 19,433 km when the vessel sails through the Suez Canal. Due to poor containers availability, only Evergreen’s freight quote on SeaRates.com (see Appendix 3) was available for this shipment, like in the Durban–Shanghai sea freight. The rent price of a 40 feet standard container for this journey was over $14,000. Cheng's (2021) publication on the CNBC website reports that container prices have risen fivefold from approximately $3,000 to $15,000 during the covid-19 pandemic. The effects are also reflected in a significant increase in delivery times due to the poor availability of both containers and space in vessels. As a result, companies are considering new modes of transport to deliver their goods to Europe. The problem, in this case, is the unsuitability of certain goods for carriage by different modes of transport. (Metal trader, personal conversation, 16.12.2021.)

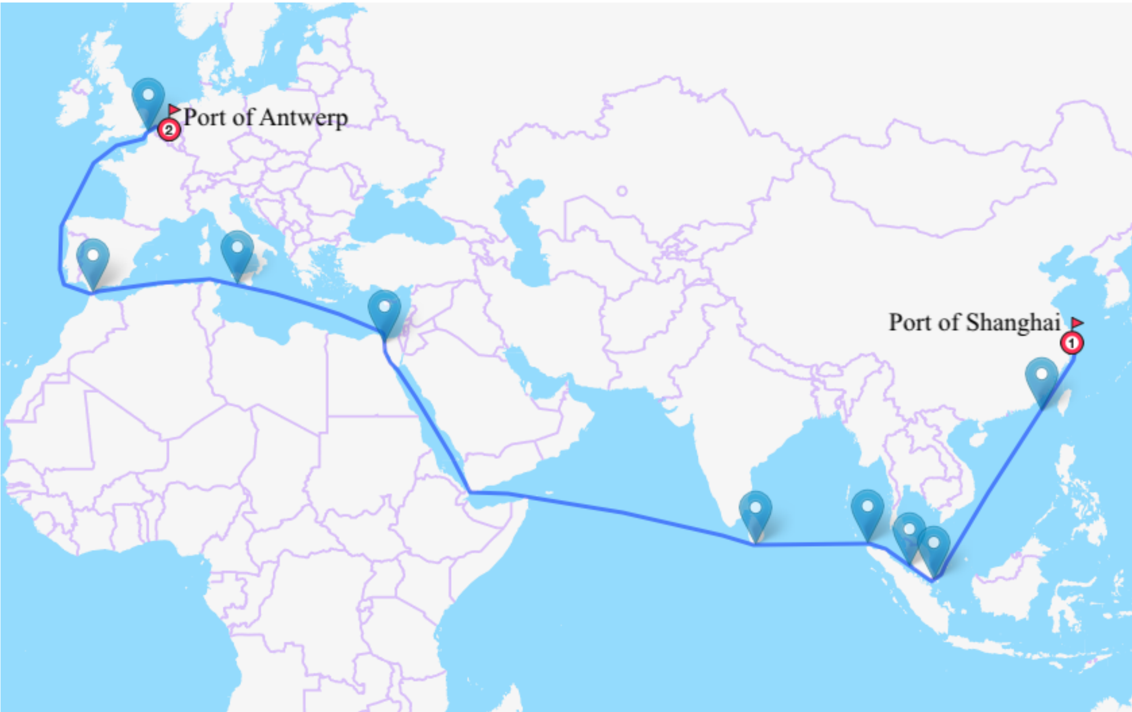

Figure 20. Shipping from the Port of Shanghai to the Port of Antwerp.

Evergreen's routing network (see Appendix 4) between Shanghai and Antwerp is called French Asia Line 3 (ShipmentLink, 2021b). Vessels operating on the line arrive in Antwerp in an average of 37 days and sail this journey every seven days in a normal situation. As in the Durban–Shanghai shipping, a vessel operating on the line has been selected to define CO2e emissions for this leg. The CMA CGM Kerguelen container vessel with a cargo capacity of 17,554 TEU has been used as a benchmark in GHG emission calculations. The last shipment in the Chinese-controlled scenario is 67 km transport by truck from the port of Antwerp to Volvo's plant in Ghent (see Figure 21). The transport costs for this leg can be found in Appendix 3.

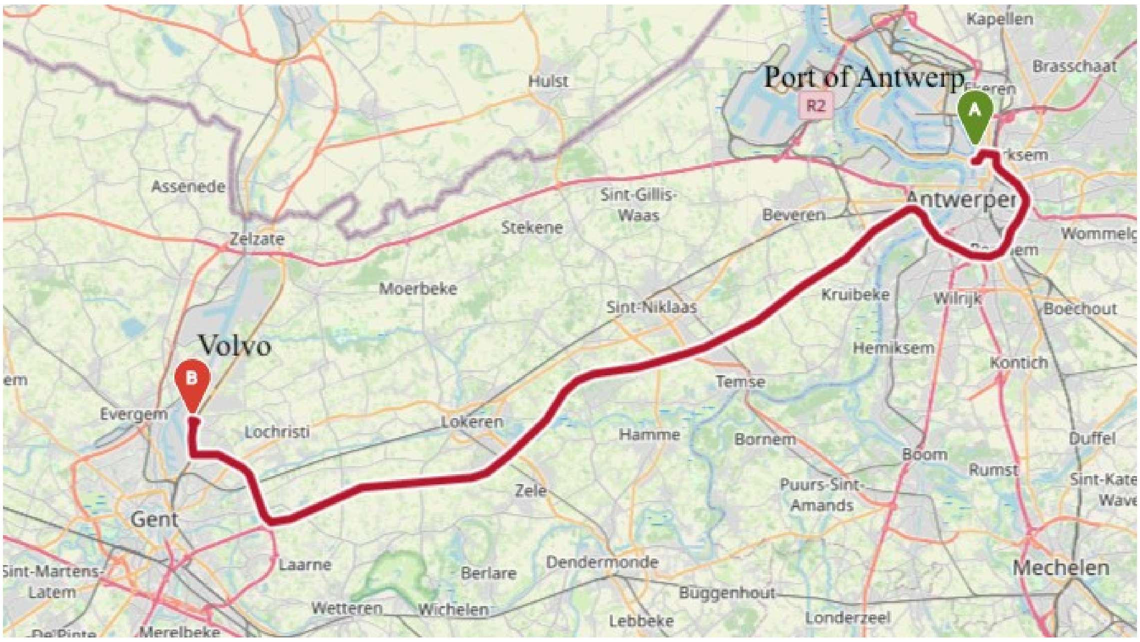

Figure 21. Transport from the Port of Antwerp to Volvo Car Gent.

There are also other ways to transport goods from China to Europe. The International forwarding association (2019) has reviewed the pros and cons of different modes of transport in international freight forwarding. The benefits of air freight are related to speed and safety of delivery. However, the weakness of air freight are the highest cost and emissions of all modes of transport. The strengths of rail freight are low costs and emissions. Weaknesses in rail freight are inflexibility and delays caused by several border crossings. The advantages of sea freight are the largest cargo capacity and the developed infrastructure of the ports, but the weakness is the long delivery times.

The report commissioned by Nurminen logistics from Gaia Consulting (2020) on the carbon footprint of rail transport compared to other modes of transport in freight forwarding from China to Europe deals with the issues mentioned above in the numerical form (see Figure 22). The report confirms that air freight is clearly the most climate polluting, and railway freight is more climate-friendly than sea freight. On the other hand, on the

Narvik–Shanghai route, the inflexibility of rail freight is emphasised when the last section of the route from Helsinki to Narvik must be implemented by road freight. As a result, the overall emissions gap is only 4% in favour of rail freight. The calculations in the report have been performed according to the same standard, and emission conversion factors are taken from the same sources as in this study.

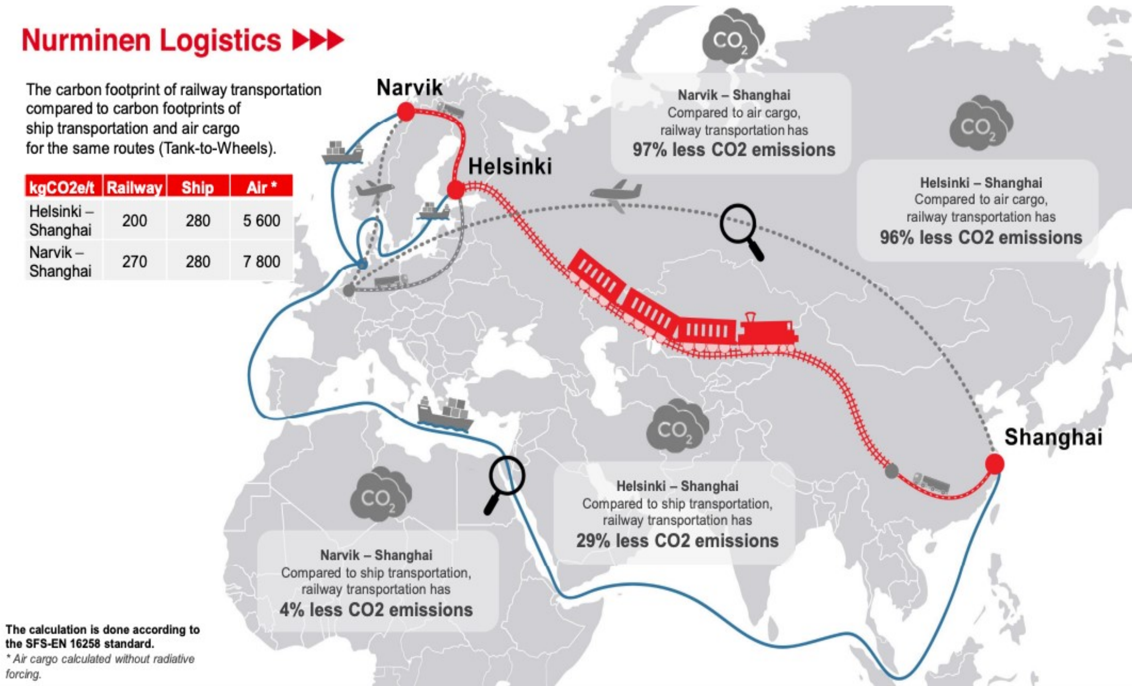

Figure 22. The carbon footprint of railway transportation in comparison (Gaia Consulting, 2020).

4.1.2 Nordic scenario

In chapter 2.2.2, it was concluded that Terrafame is the most logical alternative to be a cobalt refiner in the Nordic scenario, given the domesticity of cobalt production and the European EV market. It is also a logistically sensible option due to the shortest distance to the assumed mine location in Kuusamo (320 km). The scenario assumes that Latitude 66 Cobalt will produce 1,500 t of cobalt for Terrafame annually if the quality requirements for the cobalt they produce are met. The battery manufacturer in the scenario is Northvolt, which, as mentioned earlier, has a planned battery supply agreement with Volvo. The Northolt’s factory is in Skelleftea, Sweden, 156 km north of the Umea harbour.

From the Port of Vaasa is a daily ferry connection to the Port of Umea. Because of this, Vaasa was chosen as the manufacturing site for the pCAM/CAM to the scenario (see Figure 23).

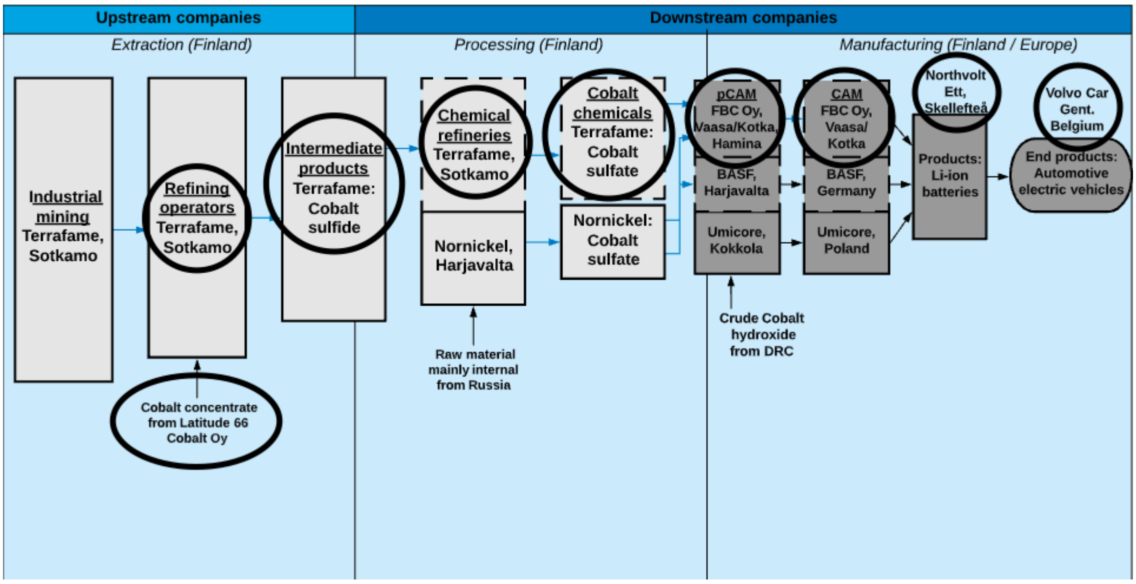

Figure 23. Companies in the Nordic scenario supply chain.

The first transport in the Nordic scenario departs from the assumed Latitude 66 Cobalt mining site from Kuusamo (see Figure 24). The distance to Sotkamo, to the Terrafame mine, is 320 km. Due to the lack of a direct rail connection, the cobalt concentrate will be delivered by trucks. Cobalt is assumed to be packed in 1-tonne bulk bags which are loaded onto trucks. By utilising the large full trailer combination, more concentrate can be transported at once, which means that GHG emissions and costs per tonne of transported cobalt are lower.

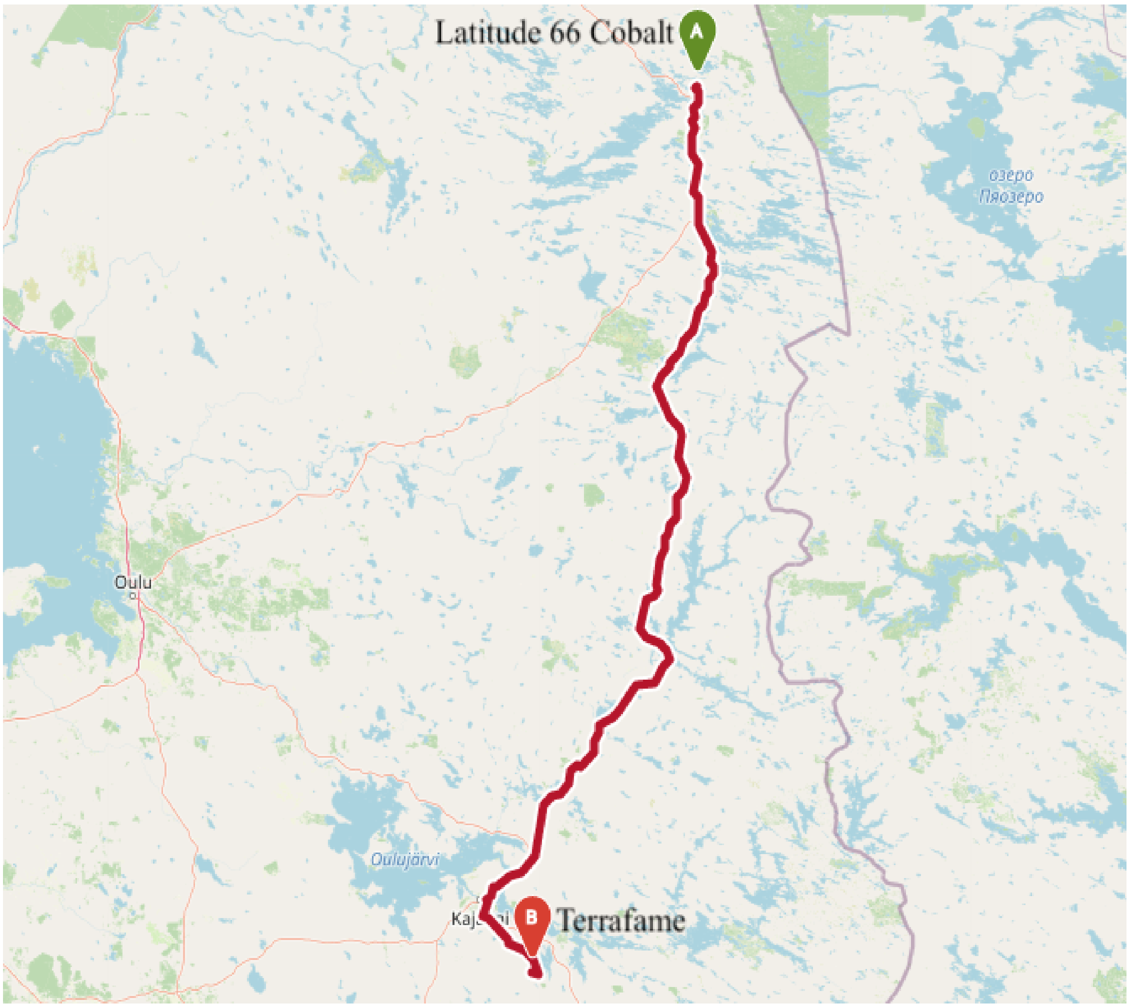

Figure 24. Transport from Latitude 66 Cobalt to Terrafame.

According to Lipasto (2017), the EURO VI emission standard has been in use in Finland since 2014. The emission factor of a truck with a gross vehicle mass of 60 t and a payload capacity of 40 t is used as a benchmark in the calculations. Latitude 66 Cobalt will supply cobalt for Terrafame, which is assumed to be approximately 9% concentrate. It means that the company will have to produce and transport more than 16,000 t of concentrate for Terrafame to reach the 1,500 t annual target for 100% cobalt. The price for one 40t delivery with defined volume is €800 (Local transport company CEO, personal conversation, 20.12.2021). The reason for the high cost is the lack of freight traffic between Kuusamo and Sotkamo. The return will most likely be driven on the empty truck.

Terrafame extracts and refines nickel sulfate ($NiSO_4$) and cobalt sulfate ($CoSO_4$) from the nickel-cobalt sulfide (NiCoS) they produce. These products are raw materials for the precursor cathode active material (pCAM). The sulfate transported from Terrafame for further processing is assumed in the scenario to have 21% cobalt content. Terrafame (2021b), in cooperation with VR Transpoint, utilises the Finnish railway network to transport its end-product to harbours in Finland. According to VR Transpoint (2021), this means that about 170,000 t of battery chemicals are transported by rail annually. Daily, it means 25-30 train cars. Transports take place in sealed sea containers loaded onto a train. Shipments are uninterrupted and 100% traceable due to the VR tracking system. VR also points out that during the transport, the train is entirely reserved for the customer's use, utilising the maximum capacity of the train. The shortest route by rail from the Terrafame mine to Vaasa is 528 km, marked with black arrows to figure 25. (Väylävirasto, 2021a).

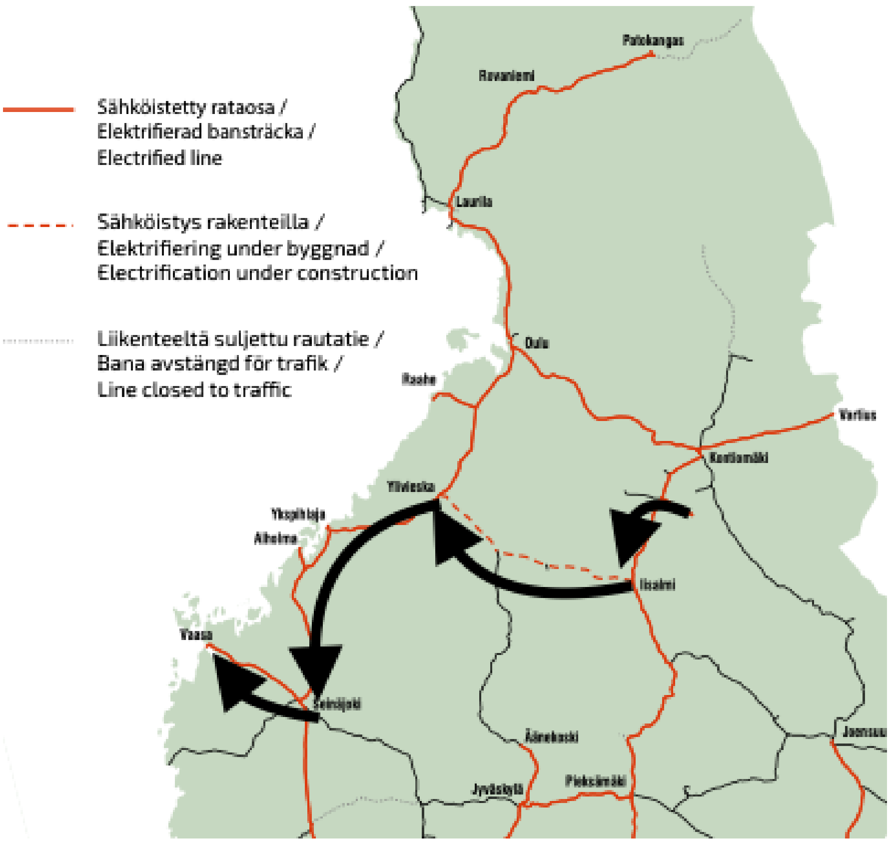

Figure 25. Transport from Terrafame to Vaasa by rail (adapted from Väylävirasto, 2021a).

When running, an electric train does not generate CO_2e emissions (Lipasto, 2017). VR Group's (2021) sustainability report tells that the electricity purchased by VR is originated from renewable energy sources, so there are no emissions from electricity generation either. Only the Iisalmi–Ylivieska leg of this route has not been electrified (see Figure 25), but a project to electrify it is underway and scheduled to be completed by December 2023 (Väylävirasto, 2021b). If the volumes of the battery chemicals plant increase to such an extent that the deliveries by rail will be justified in the future, the benefits related to emissions will be significant, despite that transport distance by rail is longer.

However, the personal conversation (20.1.2022) with the experienced mining industry logistics engineer confirmed the assumption that if the refining operations would take place in Finland, the volumes from Terrafame would most likely be so small that, at least initially, transports would be carried out by trucks. Therefore, the goods of this leg (403 km) are also assumed to be transported by the similar 60 t trucks as on the first leg (see Figure 26).

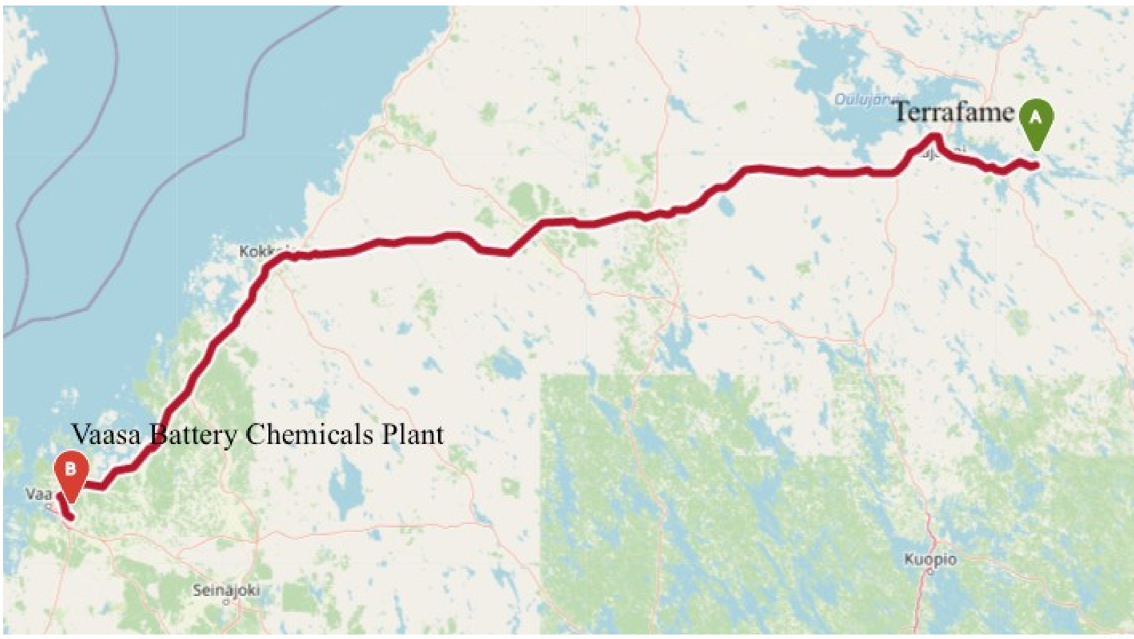

Figure 26. Transport from Terrafame to Vaasa Battery Chemicals Plant by road.

One possibility also at this point is to pack sulfate in 1-tonne bulk bags and load them onto the trucks (Mining industry logistics engineer, personal conversation, 20.1.2022). Transport costs for this leg, as well as other truck transports in this scenario, are derived from the costs of the first leg. The total cost of €800 has been divided by the leg's transport distance (320 km), so the price is 2,5 €/km. The price is affected by the assumption of the empty return loads. The final stop of this leg is the Laajametsä industry area (see Figure 27), which is one of the possible pCAM/CAM plant construction locations planned by the Finnish Minerals Group (FMG, 2020). Both the precursor and the NMC cathode active material would be produced in the vicinity of the Laajametsä, so transports between these stages are not considered in the scenario.

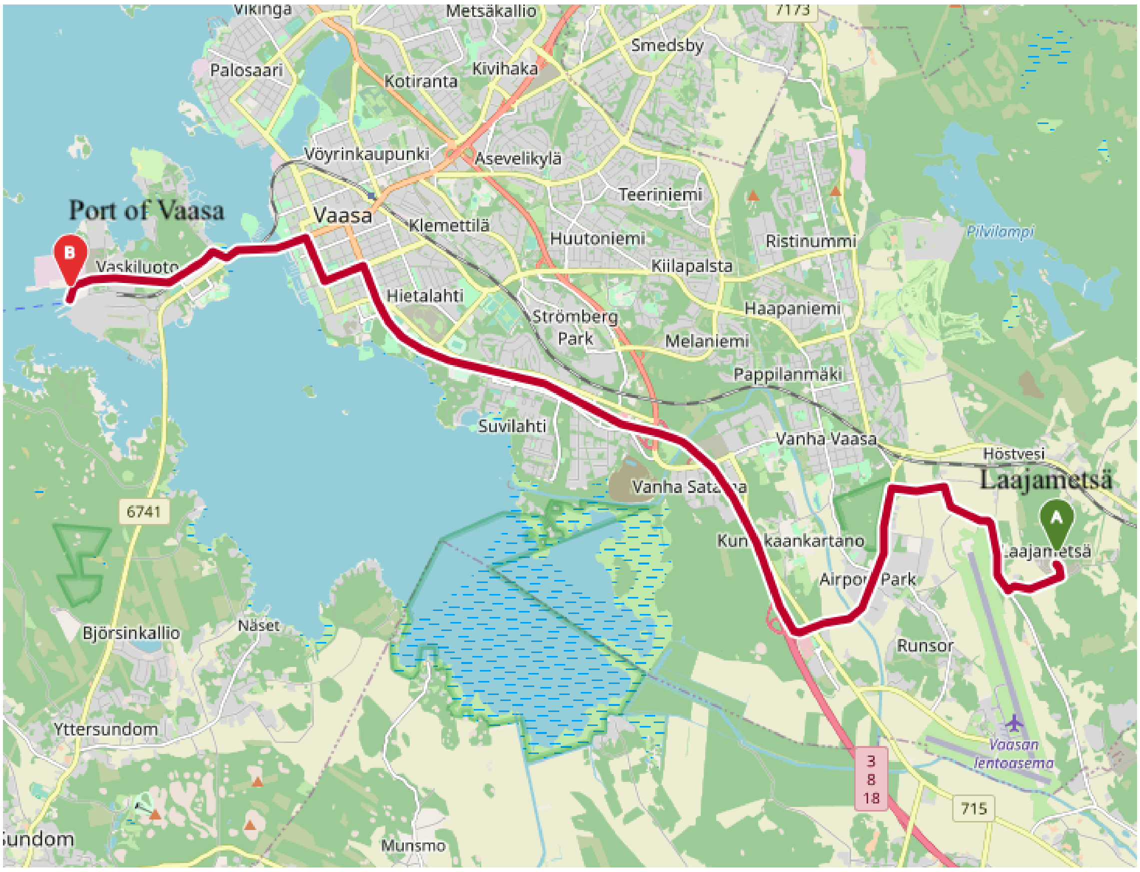

Figure 27. Transport from the Battery Chemicals Plant to the Port of Vaasa.

The scenario assumes that the truck transports the cathode active material from the Laajametsä industry area to the port (16 km). In the harbour, the truck is driven to RoPax vessel sailing to Umea (see Figure 28). At this point of the supply chain, cobalt is 100% refined as it is no longer a separate raw material requiring processing but one of the minerals of the NMC cathode active material. Therefore, cobalt's concentration is no longer reflected in emissions or costs per tonne. Noteworthy is that above the route simulated in figure 28, a railway bypasses the Laajametsä industry area and ends in the port of Vaasa. So, it would practically be possible to utilize container traffic by rail all the way from Terrafame to the port of Vaasa in the future.

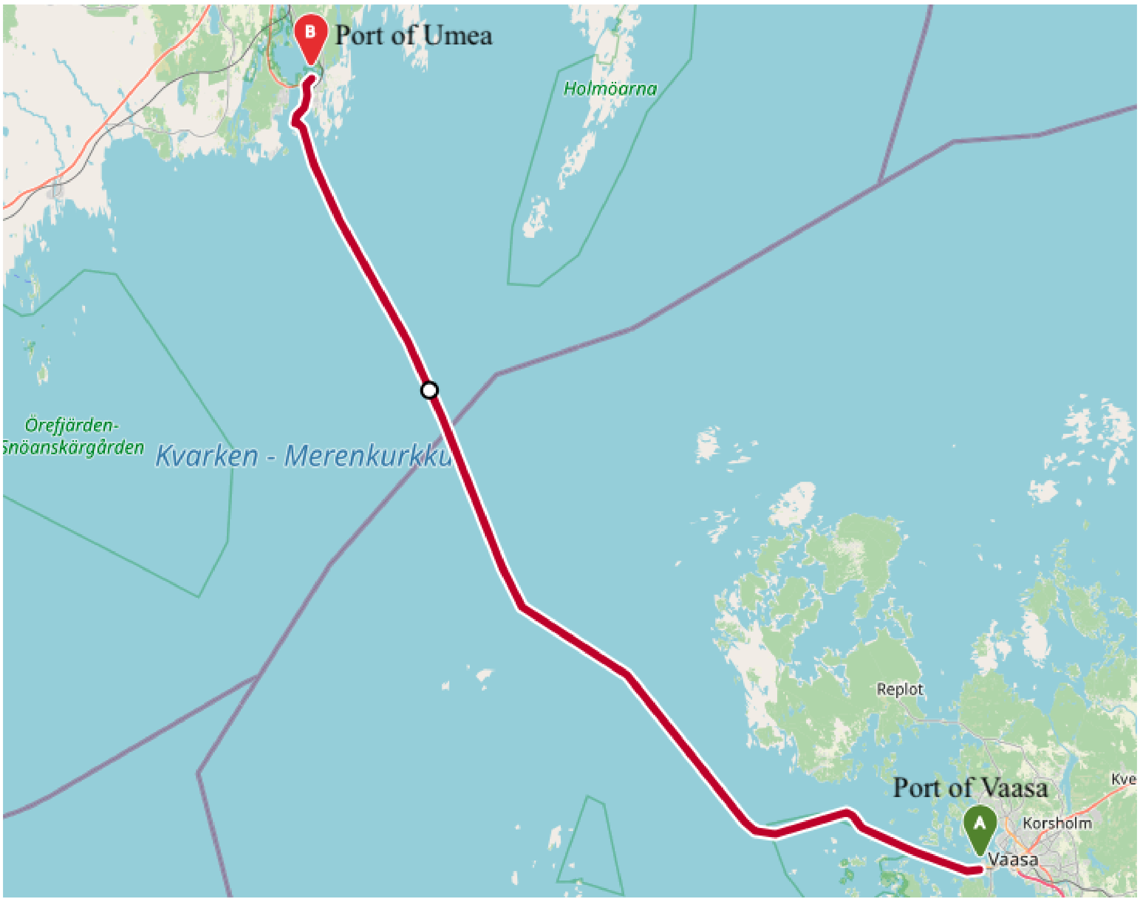

Figure 28. Shipping from the Port of Vaasa to the Port of Umea.

The transport of trucks to Sweden is assumed to take place by Wasaline's RoPax vessel, Aurora Botnia, marketed by Wasaline as the world's most environmentally friendly RoPax vessel, with a CO2 footprint per tonne of cargo loaded more than half smaller than similar vessels (Wasaline, 2021). The ship sails this 100 km voyage in 3,5 hours 2-4 times a day and has a cargo capacity of 1,500 lane meters (Wasaline, 2021). The GOV.UK (2021) conversion factor for 0-1,999 lane meters capacity ferry has been used in the emission calculations, and this figure has been halved better to reflect the vessel's (gCO2e/tkm) emissions. Transporting the truck to Umea by Wasaline costs about €300 (Wasaline cargo, personal conversation, 13.12.2021).

From the Port of Umea, the truck continues its journey along the east coast of Sweden 156 km to the Northvolt's battery manufacturing plant in Skelleftea. The route runs on the left side of the green arrow added to figure 29 on highway E4. There would also be an opportunity to utilise the railway network in Sweden. The railway from Umea to Skelleftea runs on the right side of the black arrow added to figure 29, and it has been electrified (Trafikverket, 2019a). Emissions at this leg would be zero because the electricity produced for the rail traffic in Sweden also comes from renewable energy sources (Trafikverket, 2021). According to Trafikverket (2019b), there is under construction a railway along the coast between Umea and Skelleftea called North Bothnia Line. It will significantly reduce the length of this leg by rail. The construction work of the railway is expected to be completed in 2030.

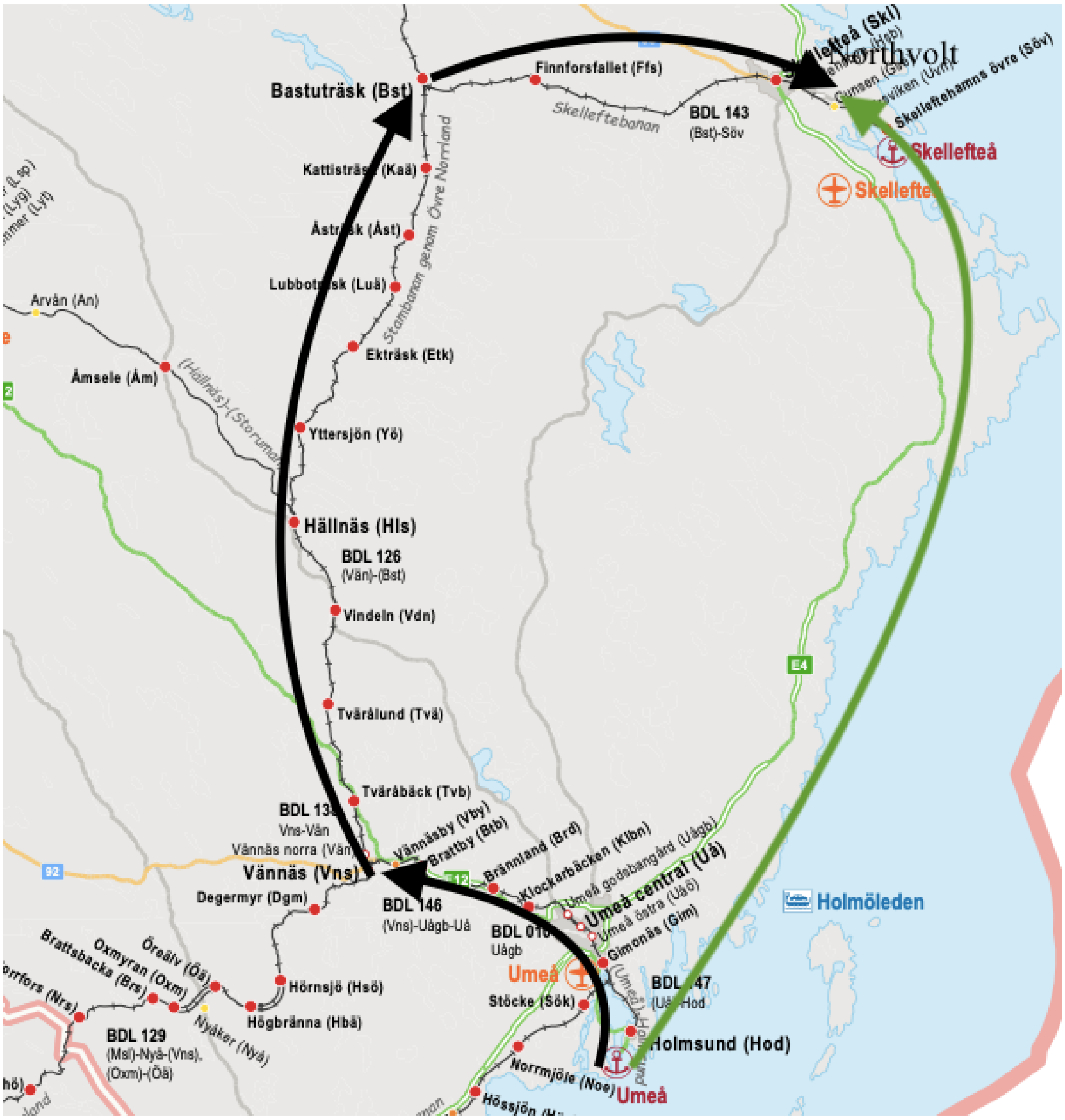

Figure 29. Transport from the Port of Umea to Northvolt (adapted from Trafikverket, 2019a).

The news published on Northvolt's (2020) website tells that the company intends to use the Port of Skelleftea, 11 km from the plant, to deliver its end products to customers. The port will be upgraded utilising electrified solutions in terminal operations to minimise CO_2e/t emissions. The company also intends to electrify the traffic between the manufacturing site and the harbour in the future. However, in this scenario, lithium-ion batteries are assumed to be loaded into sea containers and transported by truck to the Port of Skelleftea (11 km). In the harbour, containers will be loaded onto a vessel (see Figure 30).

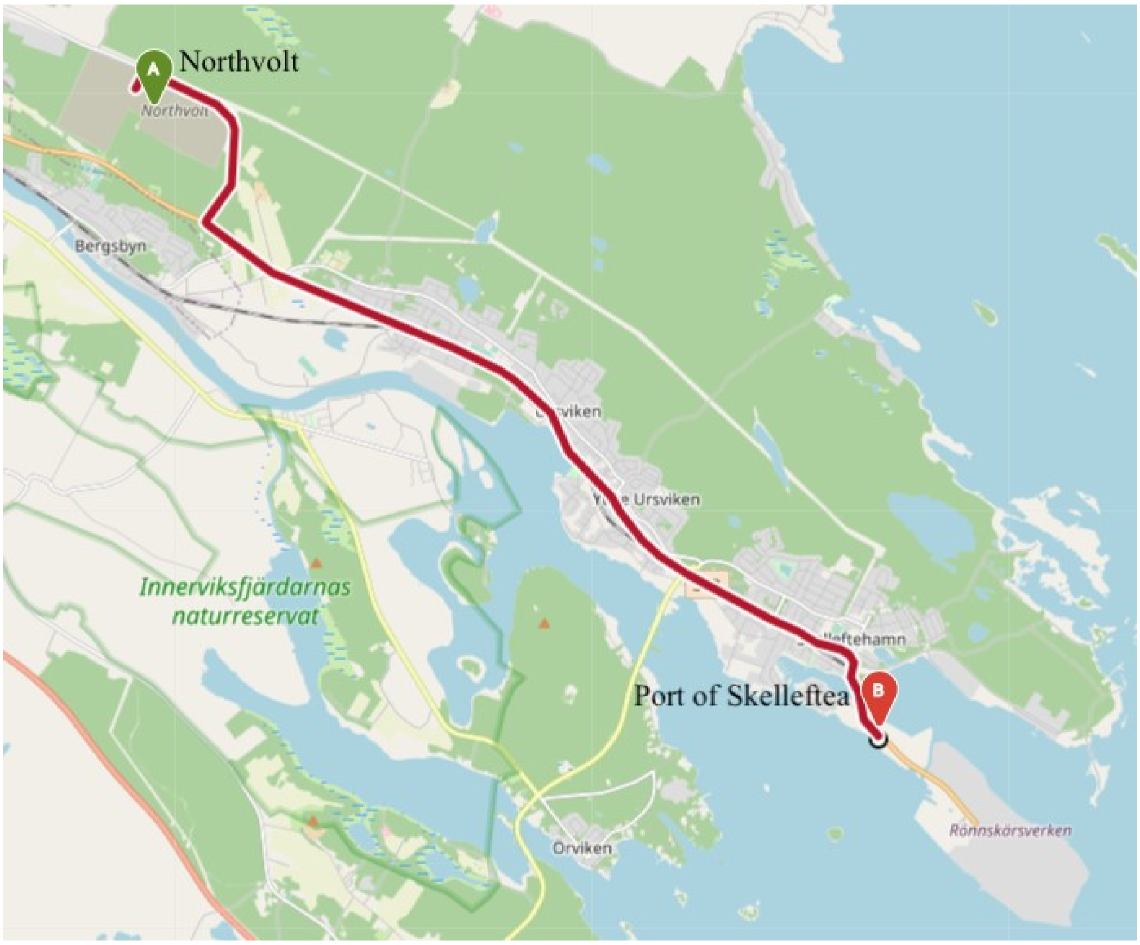

Figure 30. Transport from the Northvolt plant to the Port of Skelleftea.

As Northvolt's deliveries from Skelleftea to Volvo begin only in 2024, the scenario will proceed through assumptions (Volvo, 2021b). Wallenius Sol (2021) shipping company's weekly routing network includes Skelleftea Harbour (see Appendix 6). The journey from Skelleftea to Antwerp (see Figure 31) has been scheduled to be eight days. However, the scenario assumes that when deliveries begin, the ship will sail via the North Sea Port, Ghent, because it is in the vicinity of Volvo's manufacturing plant.

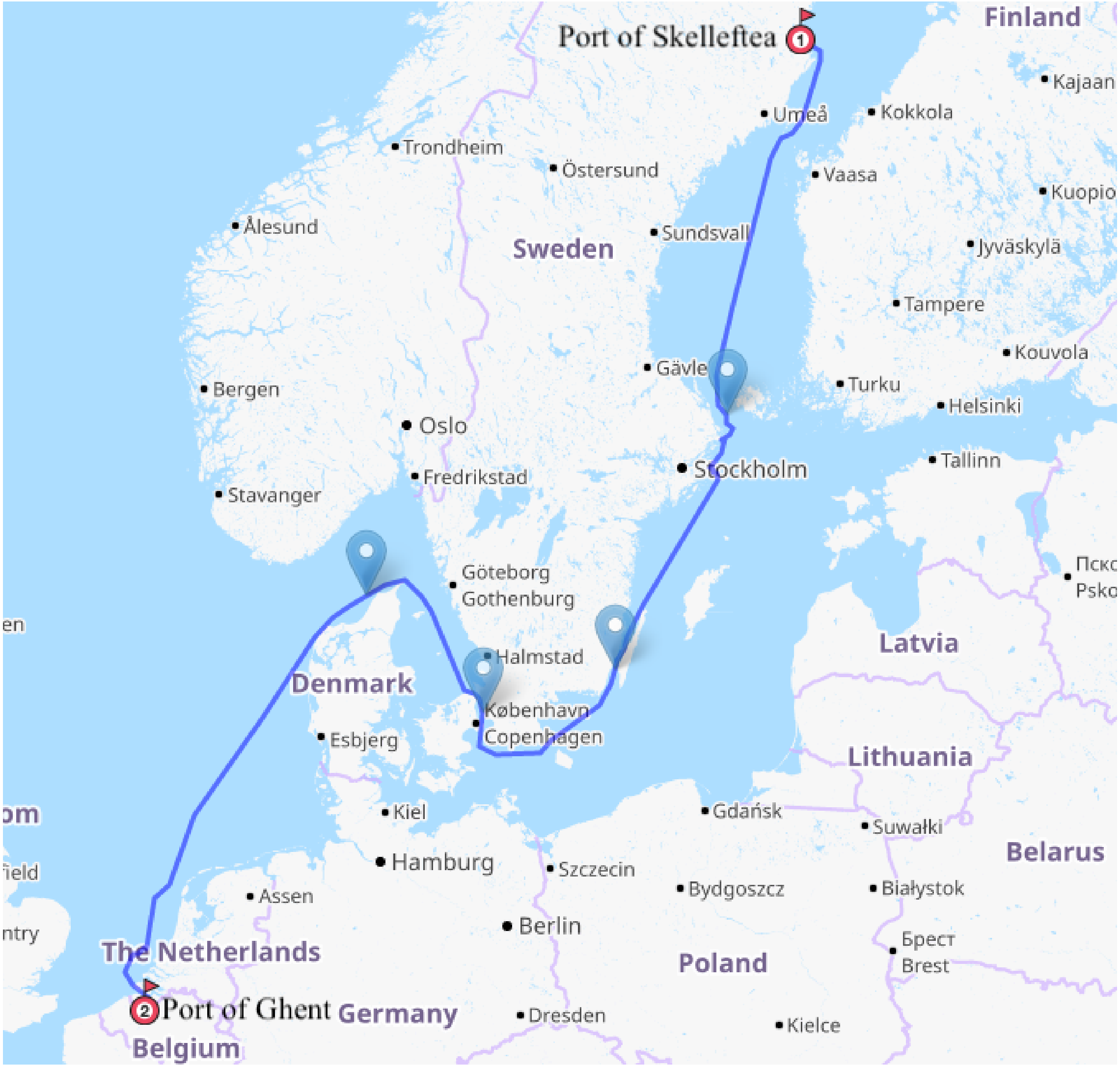

Figure 31. Shipping from the Port of Skelleftea to the Port of Ghent.

The distance from port to port has been calculated by classic.searoutes.com online distance calculation tool (2,598 km). Jutlandia Sea RoRo vessel, which operates on the route, has been used as a benchmark in the emission calculations. The vessel's capacity is 3,321 LM (Wallenius Sol, 2021). The conversion factor used is for the 2,000+ LM RoRo ferry (GOV.UK, 2021). There is no freight quote available for this route from SeaRates.com, so the freight price for the Kotka–Rotterdam route has been used to determine the costs for the shipment (see Appendix 5).

4.2 Comparison of scenarios

This chapter compares the scenarios described in the previous section. In addition to the three defined indicators: transit time, GHG emissions, and costs, the section first presents the transport distances in each scenario to show the difference in scale between supply chains. The chapter also highlights and discusses the transport legs of each scenario, which have the most significant negative impact in each category. At the end of each subchapter, the uncertainty of the results, utilising Monte Carlo simulation, is also examined.

4.2.1 Total transport distances

Figure 32 shows the transport distances of all legs in the Chinese-controlled scenario relative to each other. Two ship voyages of more than 10,000 km stand out from the figure, scaling the other bars effect on the total transport distance appealing to be very small, even though they would stand out in the scale of the Nordic scenario in figure 33. Only the first leg is remarkable long from road transportations, as the transport distance from Central Africa to South Africa is over 2,700 km.

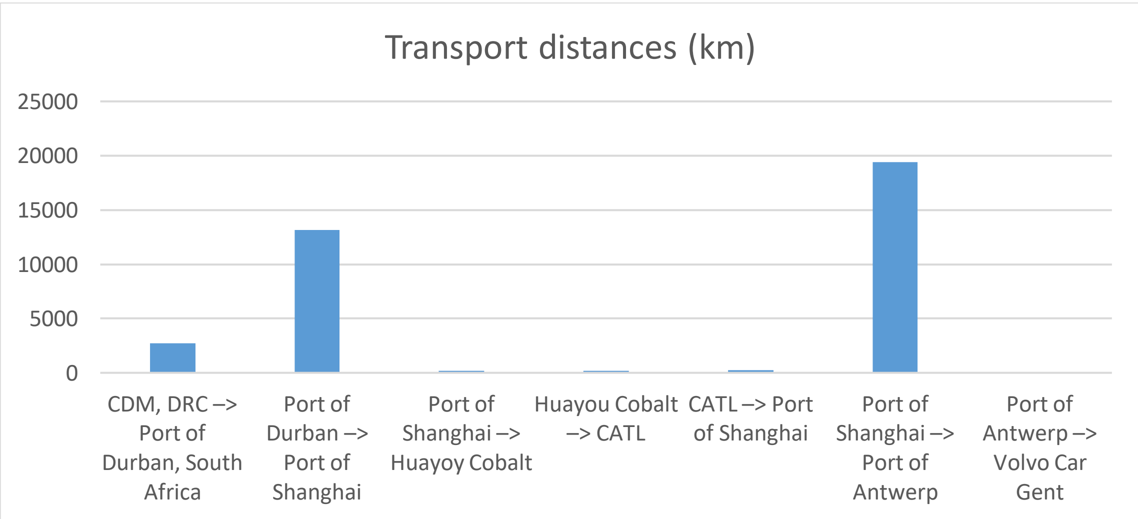

Figure 32. Transport distances in the Chinese-controlled scenario (total: 35,946 km).

The longest transport leg in the Nordic scenario is the last one, where LIBs are shipped from Skelleftea to the Port of Ghent near Volvo's plant (see Figure 33). The second-longest leg is cobalt sulfate transport from Sotkamo to Vaasa. Case company's operations add one transport to the beginning of the supply chain, and it is the third-longest transportation in the entire supply chain. Although the number of transport legs is the same as in the Chinese-controlled scenario in figure 32, the difference in total transport distances can already be deduced from the scales on the vertical axis of the figures.

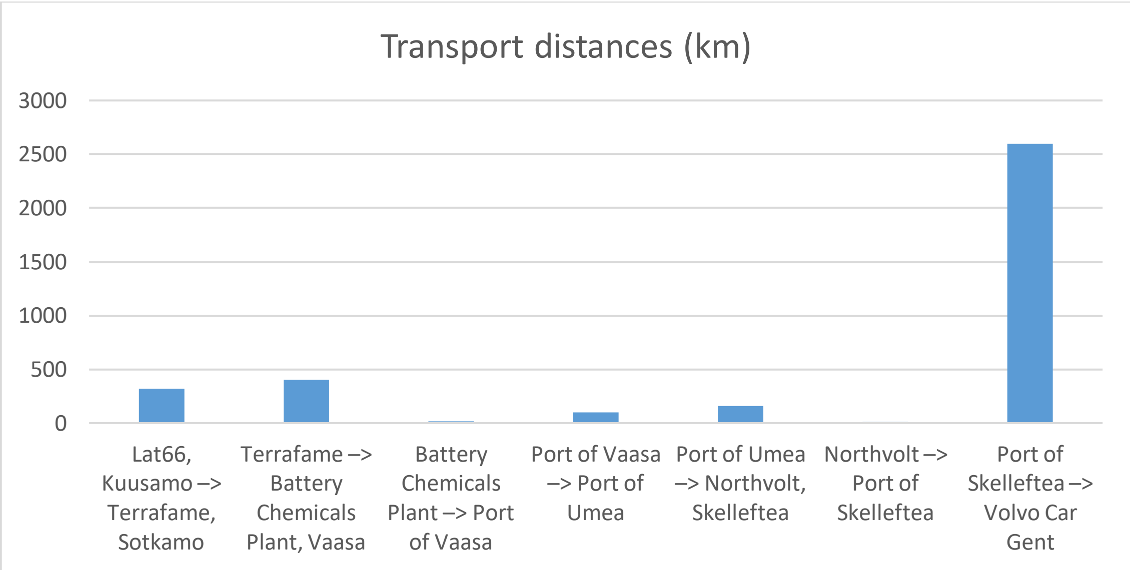

Figure 33. Transport distances in the Nordic scenario (total: 3,604 km).

The total transport distance in the Chinese-controlled scenario is 35,946 km (see Table 6), which is a prominent figure considering that the circumference of the earth is 40,000 km. The Nordic scenario's total transport distance is 3,604 km (see Table 7). Therefore, the difference in the total transport distances between the scenarios is 90% (32,342 km). Such a significant difference in the transport distances of the supply chain scenarios gives a preconceived notion of differences in the indicators to be examined.

4.2.2 Total transit times

Figure 34 shows that, in the Chinese-controlled scenario, the effect of previously mentioned longest transports on the total transit time is the largest. Truck transport in China has been assumed to be daily due to the large production volumes of the actors in the supply chain. In addition, longer loading times caused by large cargo volumes in the scenario's ports have been considered for shipments leaving ports.

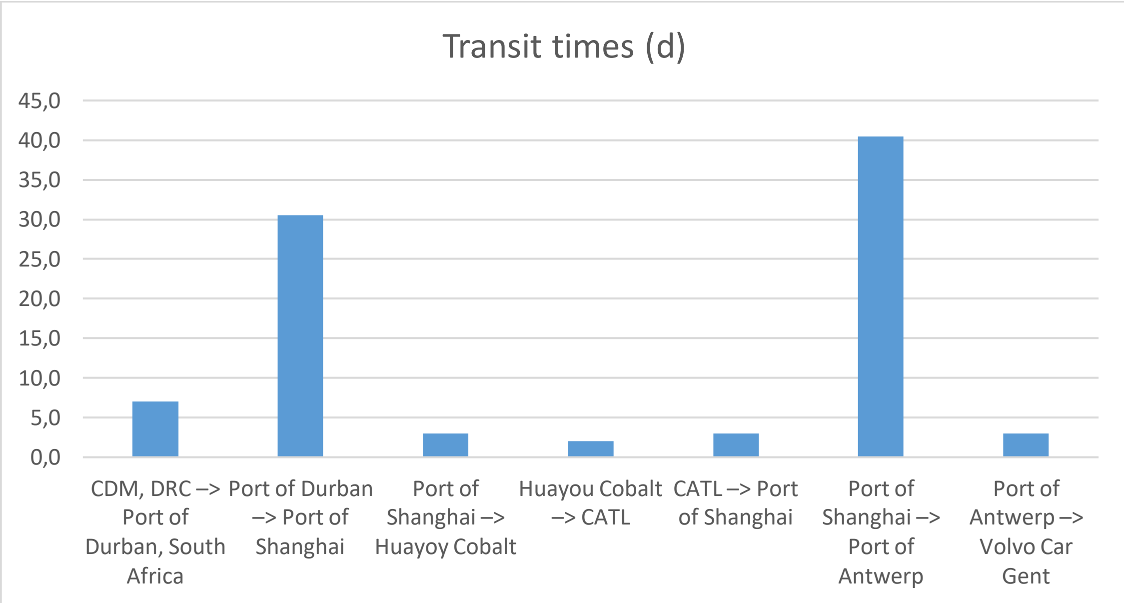

Figure 34. Transit times in the Chinese-controlled scenario (total: 89 days).

Figure 35 is very similar to figure 33, highlighting only the last shipment of more than 2,500 km. Because the annual volume from Northvolt to Volvo from 2024 onwards has been estimated to be 15 GWh, the scenario assumes that the ship will sail from Skelleftea to Ghent mainly once a week (Volvo 2021b). Delivery time seems long as it contains an average waiting time of 3,5 days. For other transport legs, transports have been assumed to take place daily.

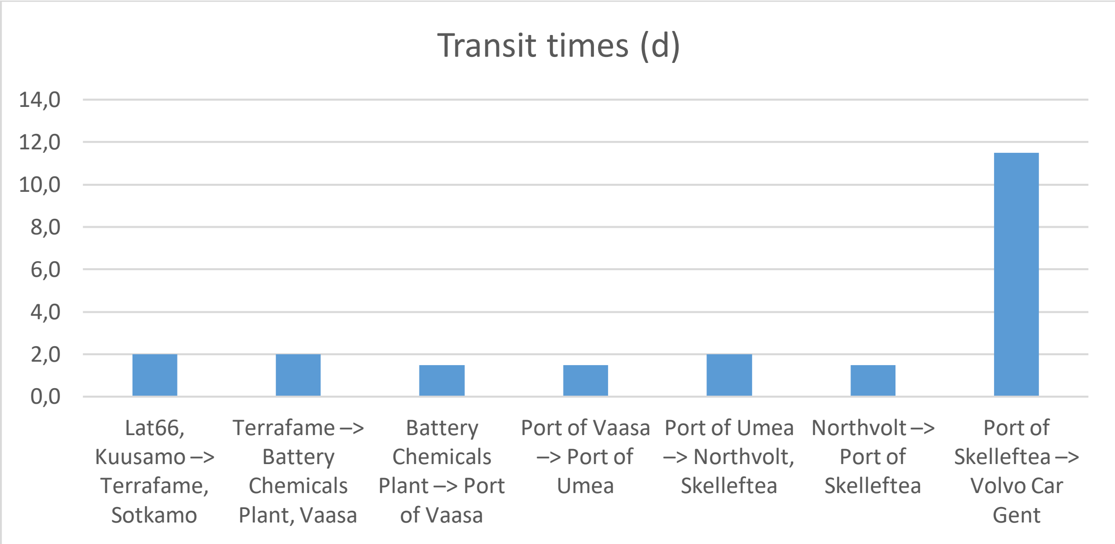

Figure 35. Transit times in the Nordic scenario (total: 22 days).

The total transit time of the Chinese-controlled scenario is 89 days (see Table 6), which is 67 days longer than in the Nordic scenario (see Table 7), so the difference is 75%. Long international sea shipments from South Africa to Asia and from Asia to Europe in the Chinese-controlled scenario are the main reasons for this significant contrast. For example, the longest transport in the Nordic scenario is 29 days shorter than the longest transport in the Chinese-controlled scenario, and this difference is longer than the total transit time in the Nordic scenario.

In the sensitivity analysis of the Chinese-controlled scenario, the most significant causes of uncertainty are the Durban–Shanghai and Shanghai–Antwerp shipments. The initial values of these shipments have been set for a triangular distribution, which allows a sufficiently large range to be defined between the minimum and the maximum values (see Appendix 7). The values of transit times have been determined considering the poor availability of containers and the variation in transit times caused by carriers' routes. The range is thus 69–109 days (see Figure 36).

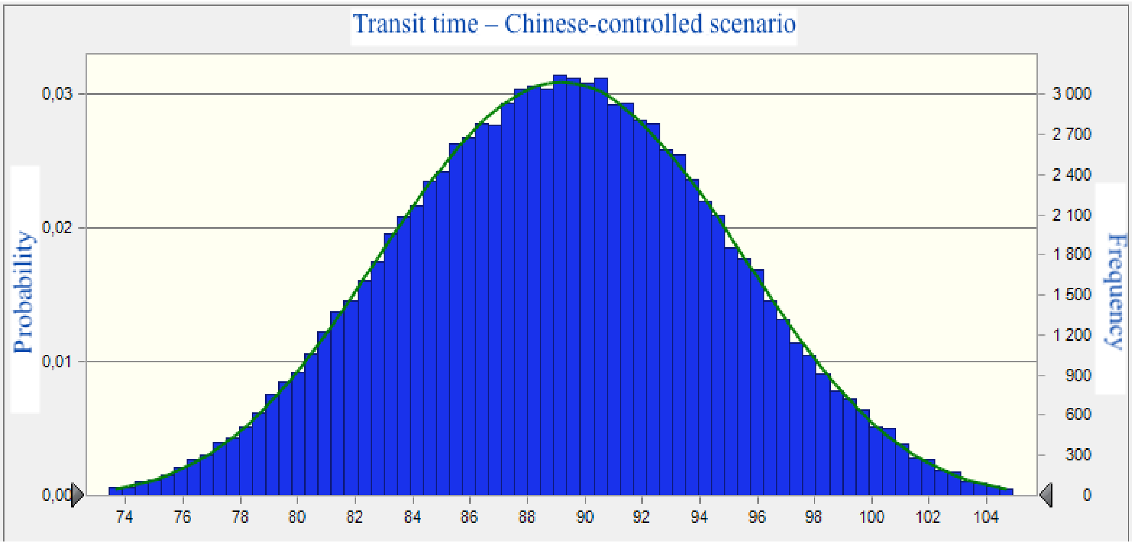

Figure 36. Sensitivity analysis of the Chinese-controlled scenario transit time (forecast: 89 days).

The horizontal values in the sensitivity analysis are random values generated by the simulation increasing from left to right in figure 36. The vertical values on the right side of the histogram indicate the frequency of random value expression during the 100,000 simulations. The vertical values on the left side of the histogram represent the frequency-related probability of the random value.

Most of the histograms in this thesis settle near the form of a normal distribution, so its laws have been used as a benchmark in the analysis. The standard deviation distance in either direction from the centre of the distribution includes 68% of all values (see Appendix 8). For example, the standard deviation of the histogram in figure 36 is 6. Thus, values 83–95 are included in the distance between one standard deviation, most of which have a frequency greater than 2,000. The same clarification applies to all the following sensitivity analyses in this thesis.

In the Nordic scenario, the variation is much smaller (16–24 days) because the longest transport from Skelleftea to Ghent is only a fraction of the length of the Shanghai-Antwerp shipment. In the scenario, the uncertainty is caused chiefly by the last delivery, so it has been set to have the highest variation possibility (see Appendix 7). Other transports are relatively short, averaging one day, so the variation's effect on the total transit time is small. Few carriers are operating on the Skelleftea–Antwerp line, so at this point, it is impossible to say which service provider Northvolt will use in the future or whether the transports will be carried out with its own fleet. However, it is more likely that the delivery time will be shorter in the future, explaining the shape of the graph (see Figure 37).

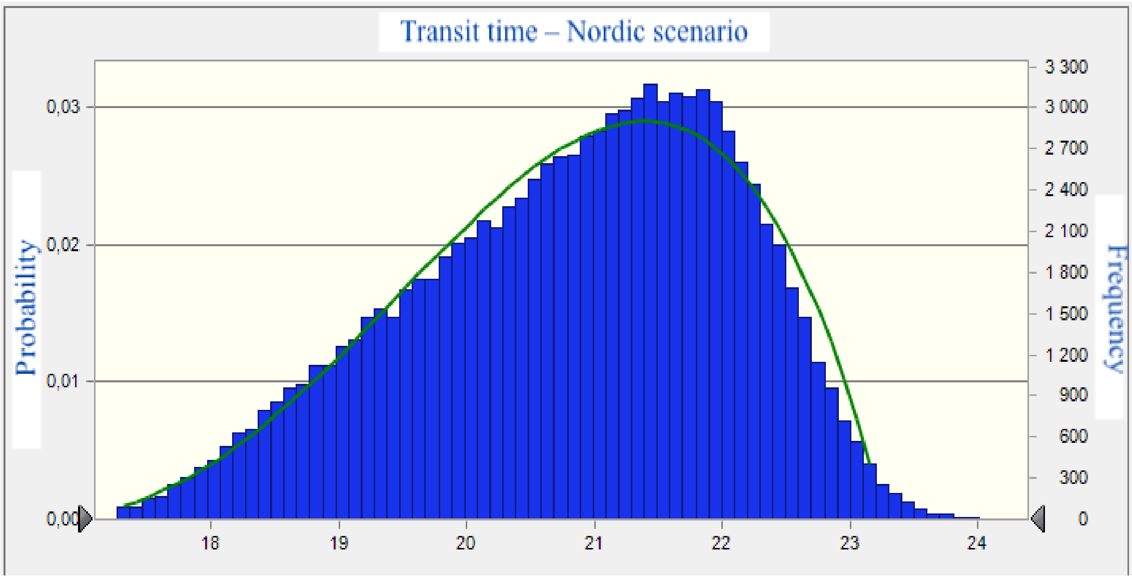

Figure 37. Sensitivity analysis of the Nordic scenario transit time (forecast: 22 days).

Despite the uncertainty of transit times, the difference between the two scenarios is large, as the transport distance in the Chinese-controlled scenario is several tens of thousands of kilometres longer regardless of route choices. In the Nordic scenario, all transports occur in Europe, but in the Chinese-controlled scenario, transports take place in Africa, Asia, and Europe. Even in the worst extreme case, the difference in favour of the Nordic scenario is 65%, and in the best extreme case, the difference is 85%. To conclude, the Nordic scenario has a clear logistical competitive advantage in transit time despite the uncertainties.

4.2.3 Greenhouse gas emissions

In the Chinese-controlled scenario, emissions from the longest transport are not the highest per tonne of cobalt transported (see Figure 38). Shipping from Durban to Shanghai is more than 6,000 km shorter than shipping from Shanghai to Antwerp but causes almost four times the emissions because the cobalt to be shipped is assumed to be 30% concentrate. For the same reason, emissions from truck freight from the DRC to Durban are also higher than in the longest shipment. Significant impact also arises because truck freight's emissions (g/tkm) are considerably higher than the +8,000 TEU container ship's emissions.

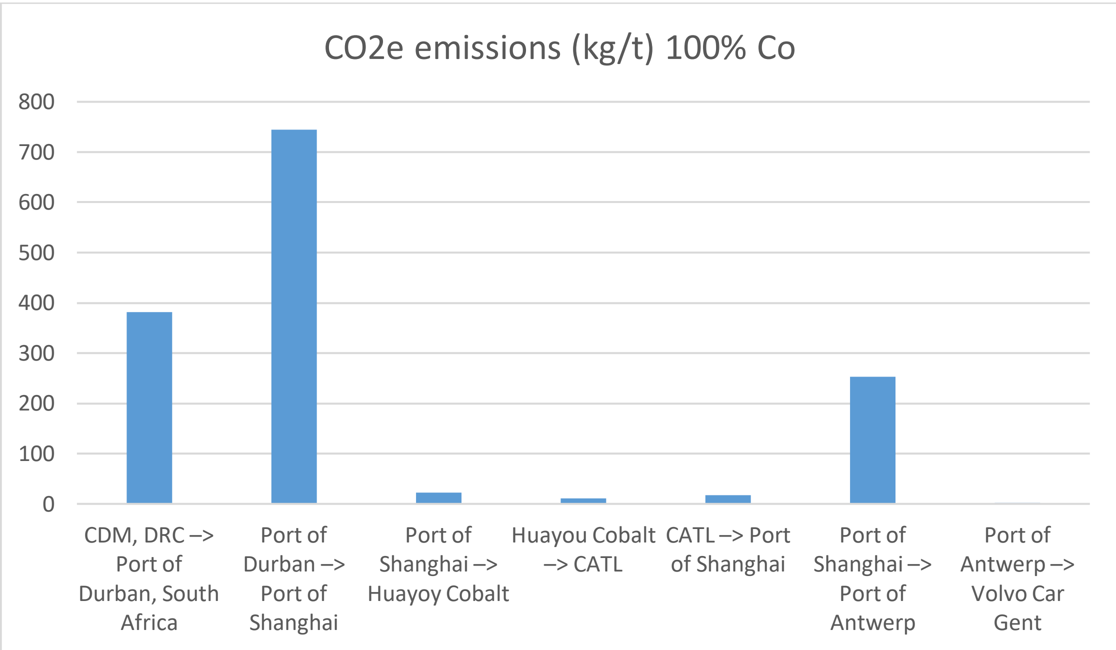

Figure 38. GHG emissions generated in the Chinese-controlled scenario transports (total: 1,431 kgCO2e/t).

The highest greenhouse gas emissions per tonne of cobalt transported in the Nordic scenario occur during shipping from Skelleftea to Ghent (see Figure 39). It was expected because the leg is clearly the longest. However, almost equal emissions arise from the first shipment, which is approximately one-eighth of the last shipment´s length. The high emissions are because a cobalt concentrate of 9% is transported in the first leg, and in the final leg, the cobalt has been fully refined. The same problem is repeated in the second leg when the cobalt content is about 21% of the load during transport. For this reason, the alternative modes of transport discussed in section 4.1.2 should be considered in the future if it is economically viable as production volumes increase.

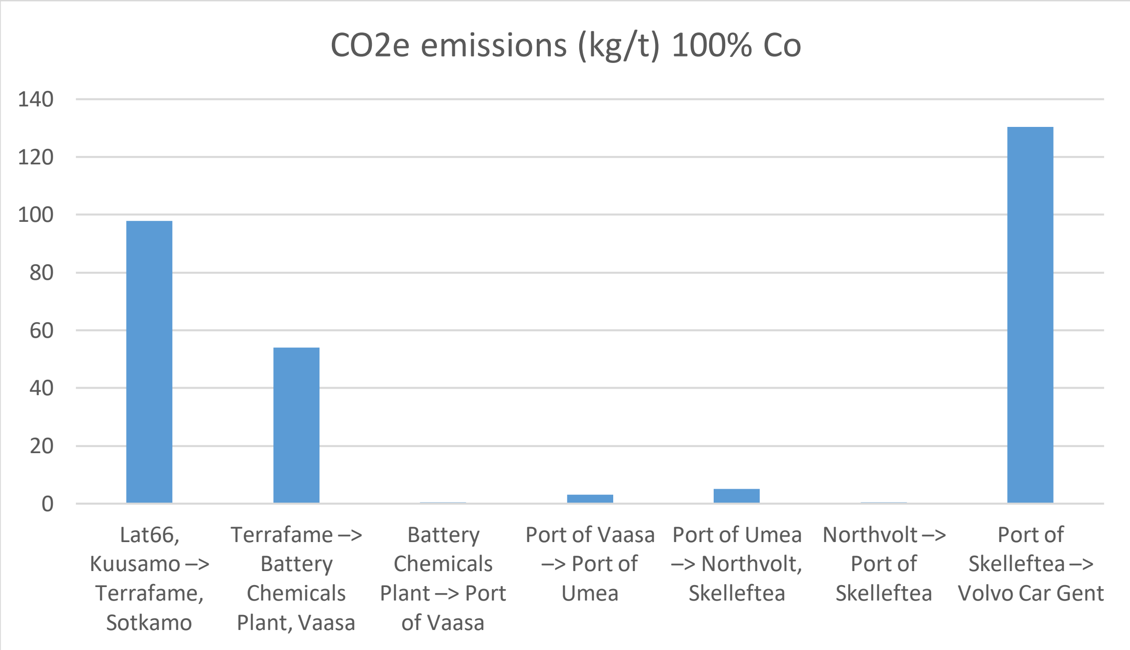

Figure 39. GHG emissions generated in the Nordic scenario transports (total: 291 kgCO2e/t).

In the Chinese-controlled scenario, the total GHG emissions kilograms per tonne of transported cobalt (100%) are 1,431 (see Table 6). The corresponding figure is 291 in the Nordic scenario (see Table 7). Due to the two long international shipments and the effect of cobalt hydroxide transporting, the total difference between the scenarios is 80% (1140 kg/t) in favour of the Nordic scenario.

For GHG emissions, the most considerable uncertainties in the Chinese-controlled scenario are the first three transport legs, which are affected by the transported product's cobalt content and the emission factor from the mode of transport (see Appendix 7). The extreme values for the triangular distributions of these transports have been determined by giving different values for both concentration and emissions in excel table 6. The high uncertainty can be seen in figure 40 as a wide range (1,218–1,948 kgCO2e/t).

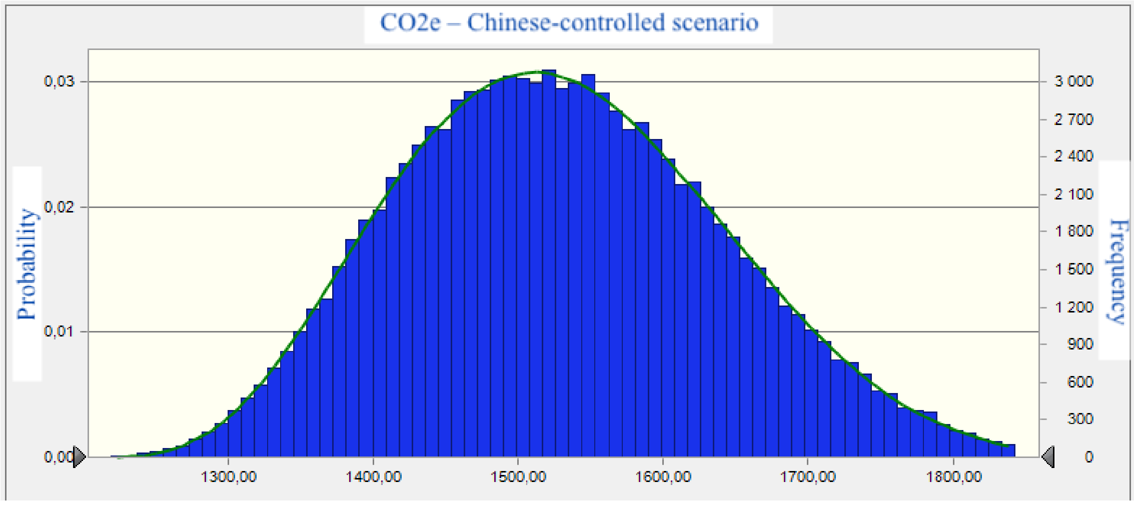

Figure 40. Sensitivity analysis of the Chinese-controlled scenario GHG emissions (forecast: 1,431 kgCO2e/t).

In the Nordic scenario, the emissions from the first two transportations contain the most considerable uncertainty due to the possible variation in the cobalt content of the transported goods and the uncertainty of the transport equipment emission factors as in the Chinese-controlled scenario. Highlighting the effects of variation has been accomplished by setting a larger standard deviation for the first two legs (see Appendix 7). However, the total range (232–349 kgCO2e/t) is moderate compared to the Chinese-controlled scenario (see Figure 41).

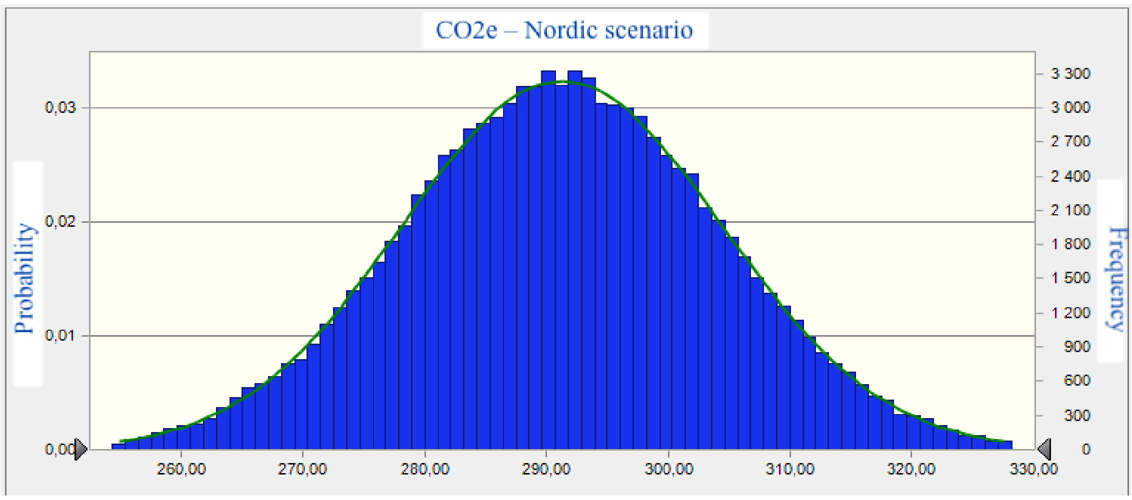

Figure 41. Sensitivity analysis of the Nordic scenario GHG emissions (forecast: 291 kgCO2e/t).

Despite the uncertainty shown by the sensitivity analyses, the logistical competitive advantage in favour of the Nordic scenario is still 71% in the worst extreme case. In the best-case scenario, the difference can be as much as 88%. Radical results are due to differences in the scale of supply chains noted in section 4.2.1. To conclude, the Nordic scenario has a clear logistical competitive advantage in GHG emissions despite the uncertainties.

4.2.4 Transport costs

The situation with costs is the same as with GHG emissions, as costs have also been calculated per tonne of cobalt (100%) transported. However, in figure 42, the shipping costs from Shanghai to Antwerp are the highest, although the cobalt concentration no longer affects costs at this stage. The reason for this is the problem with high container prices highlighted in chapter 4.1.1.

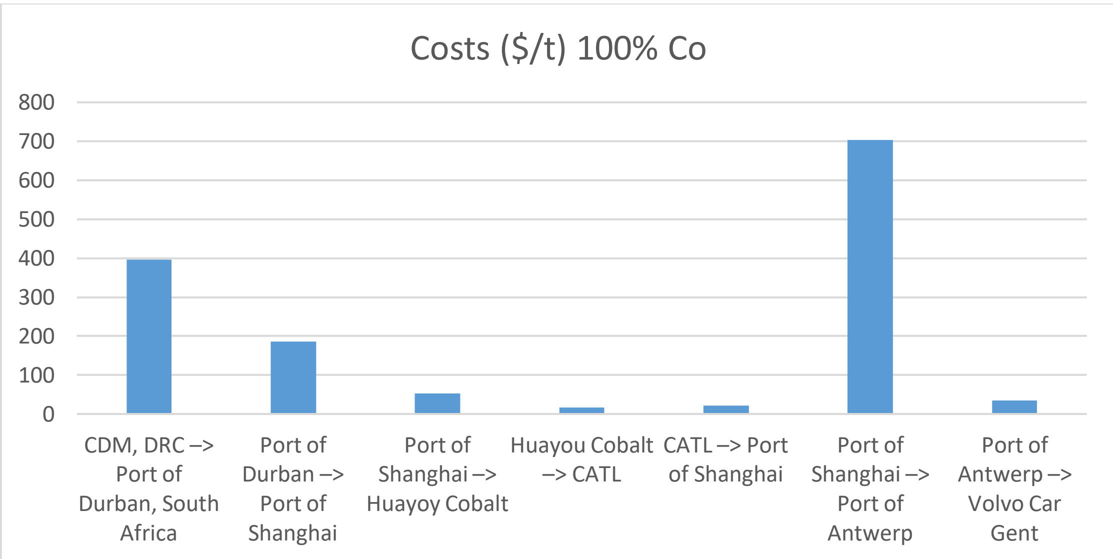

Figure 42. Transport costs in the Chinese-controlled scenario (total: 1,411 $/t).

It can be seen from figure 43 that the effect of the cobalt concentration in transport is reflected in the relatively high costs of the first two transportations in the Nordic scenario. In addition to this, the high price of the first transport is affected by the previously mentioned information that the return to Kuusamo will probably have to be carried out with an empty truck. Except for the last shipment, the impact of shipments of refined cobalt on total costs is minimal.

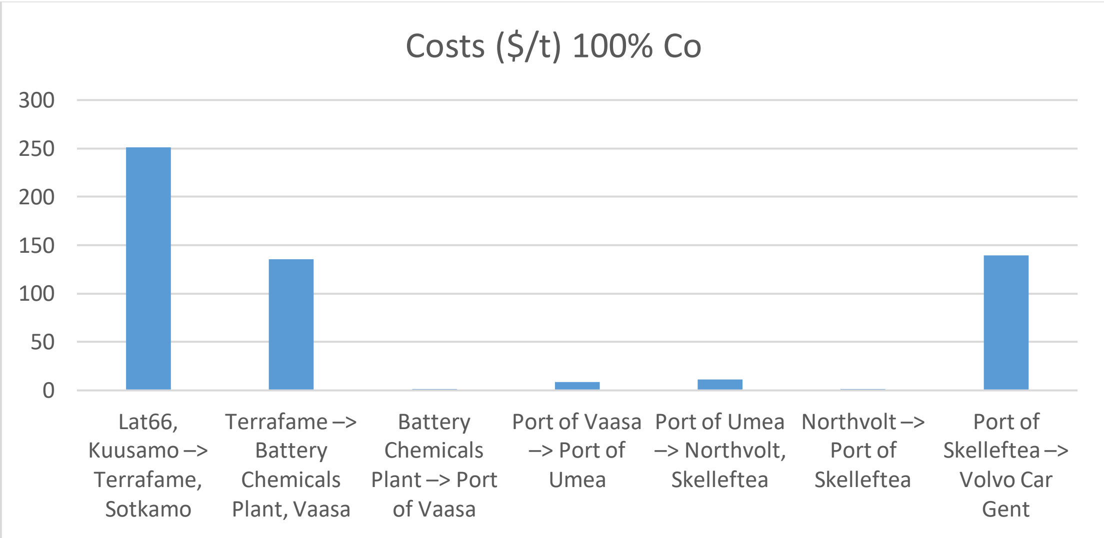

Figure 43. Transport costs in the Nordic scenario (total: 548 $/t).

In the Chinese-controlled scenario, the total costs per tonne of transported cobalt (100%) are 1,411 (see Table 6). The corresponding figure is 548 in the Nordic scenario (see Table 7). Due to the high container prices and the effect of cobalt hydroxide transporting in the Chinese-controlled scenario, the total difference between the scenarios is 61% (863 $/t) in favour of the Nordic scenario.

The uncertainty of transport costs in the Chinese-controlled scenario is affected mainly by the same factors as GHG emissions. The initial values for the Durban–Shanghai and Shanghai–Antwerp shipments have been set for a triangular distribution, which allows a sufficiently large range to be defined between the minimum and maximum values. For example, in the case of Shanghai–Antwerp shipping, the minimum value is well below average due to the exceptionally high prices for containers now. At lower container prices, the costs ($/t) for sea shipping can be relatively small concerning the transport distance. Mainly due to the uncertainty of container prices, the range in figure 44 is wide 739–2,155 ($/t).

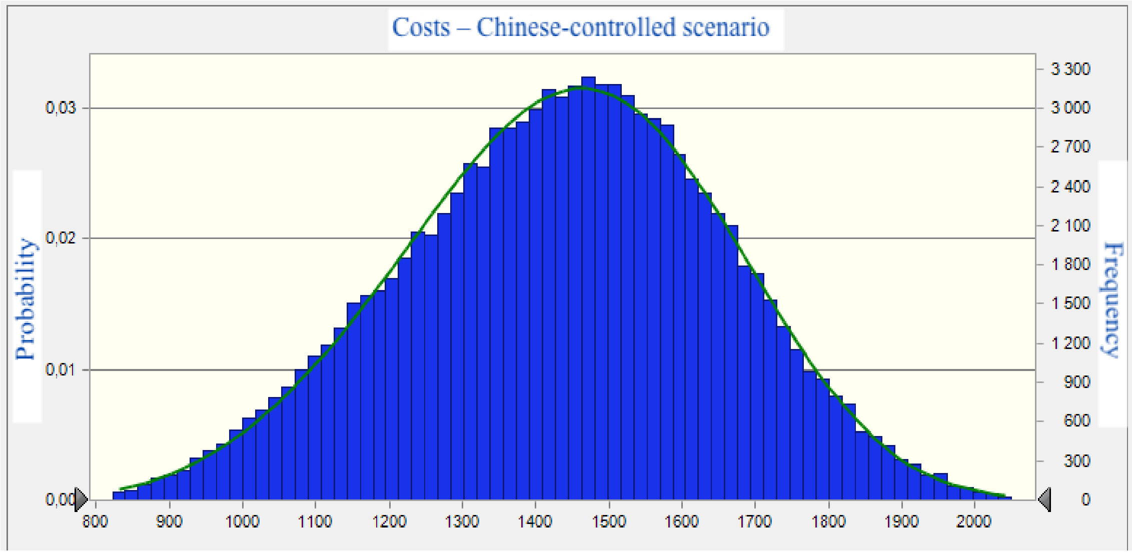

Figure 44. Sensitivity analysis of the Chinese-controlled scenario costs (forecast: 1,411 $/t).

The costs of the Nordic scenario are also affected by the same factors as emissions. However, there are no equally significant individual uncertainties in this scenario. Even changes in container prices over short distances have not caused variation of several thousand dollars as in the Chinese-controlled scenario. The range between the minimum and maximum values in figure 45 is 388–707 ($/t).

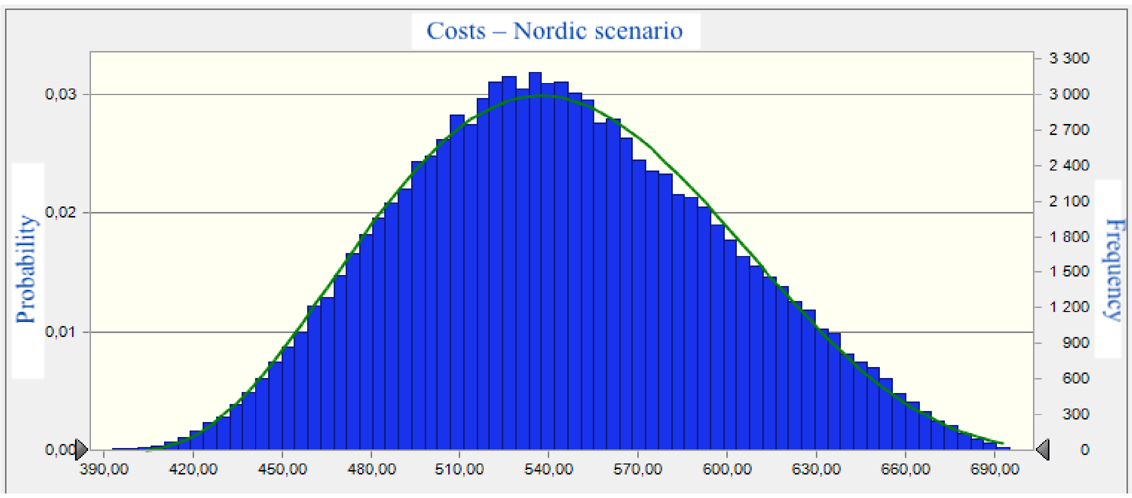

Figure 45. Sensitivity analysis of the Nordic scenario costs (forecast: 548 $/t).

If container prices in China would fall and the other costs of the scenario were minimal, the difference to the maximum total value of the Nordic scenario would be only 4% in favour of the Nordic scenario. Still, narrowing the gap would also require an increase in the costs of the Nordic scenario. However, compared to the forecast value of the Nordic scenario, the difference, in this case, would still be 26%, and if container prices rose further, the difference would be 75% compared to the forecast value, and 82% compared to the minimum value. Exceptional container prices and uncertainty about the direction of the situation development in China make cost comparisons currently challenging. Still, it can be said that it is extremely unlikely, unless impossible, that the costs in the Nordic scenario would be higher than in the Chinese-controlled scenario. To conclude, the Nordic scenario has a logistical competitive advantage also in the last category despite the uncertainties.

4.2.5 Summary of the research findings

Table 8 summarises the findings of the scenario-based comparison in chapter 4.2. The most relevant values obtained from the Monte Carlo simulations of all three indicators can be found at the row-level after the scenario name. These values are the minimum and maximum values of the histogram defining the result range, the forecast value used to perform the simulation, and the figures calculated by adding/reducing the standard deviation figures, obtained by the simulations, from the forecast values.

Table 8. Analysis of the research findings.

	Transit time (d)					CO2e (kg/t) 100% Co					Costs ($/t) 100% Co				
	Min	St.dev-	Forecast	St.dev+	Max	Min	St.dev-	Forecast	St.dev+	Max	Min	St.dev-	Forecast	St.dev+	Max
Chinese-controlled scenario:	69	83	89	95	109	1218	1319	1431	1543	1948	739	1192	1411	1630	2155
Nordic scenario:	16	21	22	23	24	232	278	291	305	349	388	494	548	602	707
Competitive advantage in favour of the Nordic scenario:															
Difference between forecast values:	75% (67 days)					80% (1140 kg/t)					61% (863 $/t)				
Range, min-max values:	65%–85% (45-93 days)					71%–88% (869-1716 kg/t)					4%–82% (32-1767 $/t)				
Range, +- standard deviation:	**72%–78% (60-74 days)**					**77%–82% (1014-1265 kg/t)**					**51%–70% (590-1136 $/t)**				

Based on the values mentioned in the previous paragraph, the logistical competitive advantages of the Nordic scenario compared to the Chinese-controlled scenario have been calculated in table 8. These values are also indicator-specific and can be found under the bold heading in the middle of the table. The values in the first row indicate the percentage advantage without the possibility of variation due to uncertainty. These values have been calculated based on forecast values. The percentage ranges in the second row have been calculated based on the minimum and maximum values of the histograms. It is noteworthy that such an extensive range is practically impossible because the realisation of the minimum and maximum values is very unlikely.

The most important figures for the decision-making of the thesis can be found bolded in the last row of table 8. These results consider the uncertainty and, at the same time, exclude extreme cases as the range has been calculated with figures based on standard deviation. Thus, random values that make up both ends of the distributions, totalling 32% (see Appendix 8), do not affect the magnitude of the range. To conclude, the advantage of the Nordic scenario is 72%–78% in transit time, 77%–82% in transport-related greenhouse gas emissions, and 51%–70% in transportation costs.

4.3 Validity and reliability of the study

This chapter reviews the validity and reliability of the empirical analysis of this thesis. Three different approaches are most used to evaluate the validity of a quantitative case study: construct validity, internal validity, and external validity. In addition, the implementation of the research and its results are examined from the perspective of reliability. The construct validity evaluation concerns the ability of the research method used to measure the studied phenomena. The review of internal validity considers factors that may influence the conclusions reached in the analysis phase of the study. External validity instead assesses the significance and generalisability of research results. Finally, reliability is evaluated through the reproducibility of the research process. (Riege, 2003).

The primary purpose of the research was to evidence the possible competitive advantages of Finnish cobalt production from the perspective of logistical factors compared to the most crucial international supply chains. Most of the published studies deal with cobalt trade flows at a general level, for example, in total annual deliveries, such as Schmidt et al. (2016) conducted in their research, which was helpful information while creating the Chinese-controlled scenario. Of course, there are studies commissioned by LIB or EV manufacturers on their critical mineral's supply chains, but the problem is the possible subjectivity of the research results and the lack of publication of the calculations performed.

As the indicators to be compared in the study were transport-related transit times, GHG emissions, and costs, it is impossible to identify several supply chains and calculate the averages of the indicators from them in the schedule of this study. Therefore, the analytical decision-making process conducted by using a scenario-based comparison is a structurally appropriate research method for solving the research problem. The indicators used in the study provided a clear answer to the research question. The findings would have been even more plausible if more case companies were included in the study, providing more detailed information on the indicators to be examined. In this case, the use of average conversion factors could have been minimised. However, it would require a significantly longer schedule and more resources because it takes a lot of time to get and conduct interviews and analyse the interview materials.

Many factors affect the internal validity of this study. Their effects were sought to be minimised by considering uncertainties in the indicators studied. Utilising the Monte Carlo simulation, the input values used in the calculations were given ranges based on an appropriate probability distribution so that the results were not tied to single initial values. The inputs and predictions used in the simulations have been summarised in appendix 7, and the rationale for all methods and figures used can be found in chapter 4. Nevertheless, the creation of scenarios and data collecting, for example, depends partly on the assumptions the author of the study makes. The timing of the data collection also affects the results. If a similar study had been carried out, for example, five years ago, it would be unlikely that the author would have been able to consider that container rental rates for shipments from Asia to Europe could be fivefold after five years.

Considering the study's external validity, the research method used can also be generalised to other industries. If the research results evidence the research hypothesis in a positive sense, this type of research can be useful, for example, in the marketing of a case company. Although this study is based on scenarios, its results can be considered significant because the supply chains created in the study are justified and, regardless of the creator of the scenarios, the primary material flows from Africa to Asia and Asia to Europe follow the same pattern. Deciding which companies to choose for supply chain scenarios causes variation, but in the big picture, its significance is minor because the material flows between different continents are default.

This study can be repeated by following the instructions in the research methodology section on how to carry out the research. After creating scenarios and collecting related data, it is possible to end up with the same values. These values are used as inputs in the Monte Carlo simulation stage, which is performed because of the uncertainty of the input values of the indicators. So, if the study's objective is the same as in this thesis, the simulation results and the percentual comparison are likely to be of the same order of magnitude.

5 Conclusions and further research suggestions

This chapter reviews conclusions that can be drawn from the research findings. Real-life examples have been used to support the conclusions. A study commissioned by Volvo in 2020 compared the life cycle emissions of the XC40 internal combustion engine and electric versions produced at the Ghent plant in Belgium. The same production plant was also addressed in this thesis. The study's calculations included all emissions from the vehicles' manufacturing and operating phases to recycling. The car's life cycle had been set at 200,000 km in the study. The research commissioned by Volvo is relevant to this research, as the emissions from the production phase of the EV also included the logistics emissions from the procurement of critical minerals and the emissions from their processing. Most of the emissions from the EV were generated during the procurement of raw materials and the manufacture of the vehicle, as the energy consumption of the EV while driving is low. In the case of the ICE car, the situation was the opposite. (Egeskog, 2020.)

In Volvo's research, emissions from refining and producing raw materials and manufacturing the car were approximately 37% higher with the EV than the ICE version. When the car comes out of the factory assembly line, the advantage in favour of the ICE car is considerable. The break-even point in terms of emissions comes at 146,000 km due to higher emissions from the operating phase of the ICE car. On the other hand, emissions can cross much earlier if renewable electricity is used to charge the electric car. Using electricity generated by wind power alone, the break-even point will reach 47,000 km. (Egeskog, 2020.)

Volvo's research some of the issues addressed in this thesis. Currently, Volvo's battery module suppliers are Chinese CATL and South Korean LG Chem (Egeskog, 2020). One reason for the significantly higher emissions from the manufacturing phase of electric cars is the sourcing of critical minerals. Volvo's report does not address these issues in more detail. Still, it can be assumed that the battery modules were supplied to Volvo from non-European markets during the research period. Thus, minerals used by the battery manufacturers in question may be derived from DRC. Emission figures could be significantly lower in the future if battery deliveries from Northvolt start and the company would utilise Finland's mineral reserves, for example. In that case, it would be interesting to see a similar comparison as in this thesis.

Car manufacturers have already begun eliminating the issues mentioned in the previous paragraphs. European carmaker Renault Group (2021) has signed an agreement with the Finnish mining and refining company Terrafame, one of the companies in the Nordic scenario, to supply nickel sulfate for its lithium-ion battery production needs. The agreement makes sense for Renault regarding emissions at the manufacturing stage from both logistics and production perspectives. Terrafame's production occurs from ore mining to nickel sulphate refining in the same area. The company's bioleaching process in mineral extraction allows for 90% lower energy consumption compared to the industry average (Renault Group, 2021). The agreement also relieves the traceability issues addressed in chapter 2.3 of the thesis. Implementing traceability systems is naturally more manageable when the supply chain is shorter and involves fewer processors.

RQ1: Why is cobalt needed in the European electric vehicle market?

The demand for cobalt in lithium-ion battery cathode chemistry is increasing with the electrification of the automotive industry. As a result, the problem is not demand but supply. Efforts are being made to reduce the need for critical materials due to their over demand and market concentration. In response, new battery types have been developed, such as the LFP battery, which requires no nickel, cobalt, or manganese. However, the characteristics of LFP batteries are different from those of NMC batteries, so they cannot wholly replace NMC batteries and, because of the increase in demand, the cost advantage that existed at the beginning is no longer present.

In the future, car manufacturers are likely to continue to use different types of batteries for various purposes as the market develops so that reducing the use of one mineral leads to an increase in demand for substitute minerals and thus to an increase in their price. As shown in this chapter, a common problem with electric cars is the emissions that occur before the vehicle is put into service. One reason is the concentrated market of critical minerals in Chinese-controlled supply chains. Another major problem is the perceived sustainability and responsibility issues in these supply chains. Therefore, there is a demand for cobalt produced within Europe.

> *RQ2: What are the requirements for the transparency of the cobalt supply chain and the traceability of the mineral origin in the European electric vehicle market?*

Downstream companies have taken steps to minimise Chinese-controlled supply chains' sustainability and responsibility issues. Still, progress has been slow due to a lack of know-how and resources in the countries of mineral origin and their attitudes towards changes are reluctant. In response to these problems, companies have begun to secure their supply by diversifying sourcing of critical minerals from several markets, just as BMW has done. Finland's mineral reserves are an excellent alternative for European car manufacturers. In addition to logistical competitive the advantage demonstrated in this study, guaranteeing the supply chain transparency and mineral origin are much more straightforward when the mineral originates from the European internal market.

> *RQ3: Does Finnish cobalt production have logistical competitive advantages in the European electric vehicle market compared to cobalt mined in DRC and processed in China?*

This study showed that the logistical advantage of the Nordic scenario is 72%–78% in transit time, 77%–82% in greenhouse gas emissions, and 51%–70% in costs but in 5–10 years, the situation may be different than has been assumed in the study. As a future research suggestion for the case company, a study carried out with the same formula could be useful when the start of mining operations is timely and potential customers are known based on the contents of the mined minerals. If there is more time and resources to carry out the research, involving more parties in the research process could have a more comprehensive benefit, for example, in marketing Finnish battery materials or the whole Nordic battery cluster. When more companies are involved in a study under their name and share information for a common goal, the study would not be based on assumptions. Research could include both a logistics and a production perspective. The actual logistics service providers of the companies would produce data on transports based on history and production facilities on production-related emissions, costs, and lead times.

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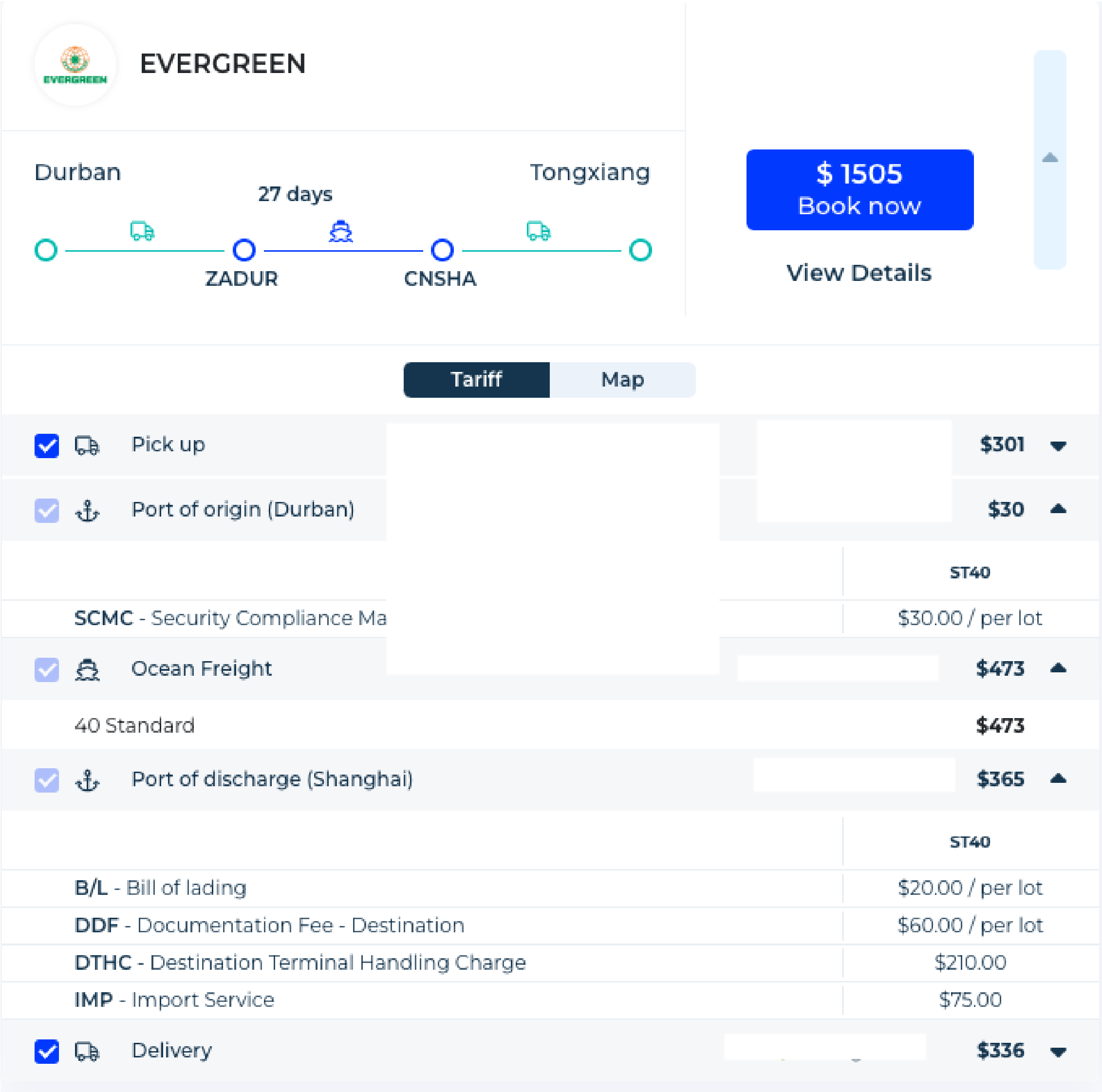
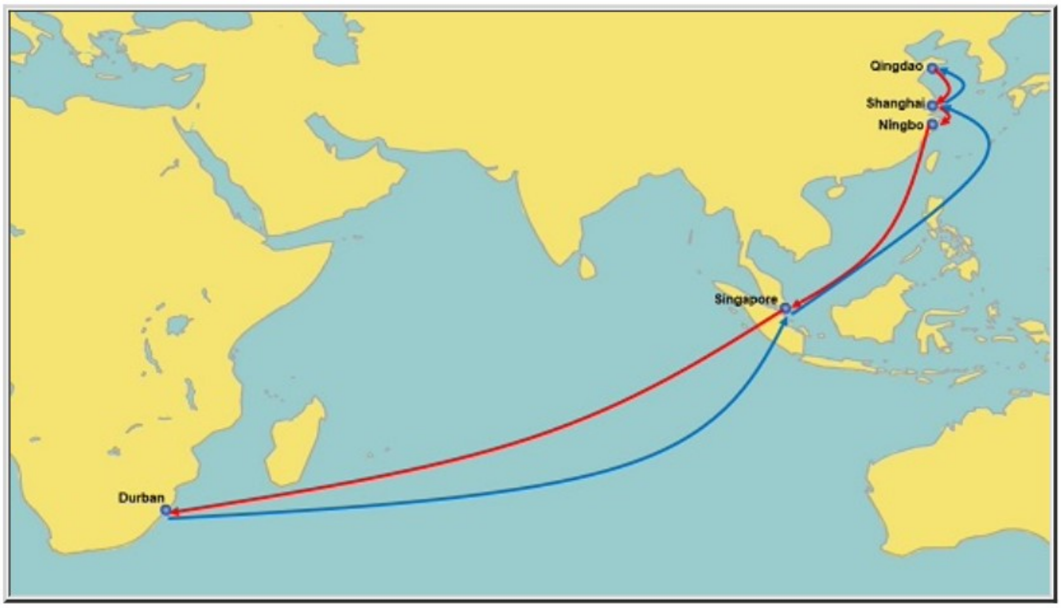
Appendices

Appendix 1. Freight quote, Durban–Shanghai



Appendix 2. Far East – Africa Express (FAX)

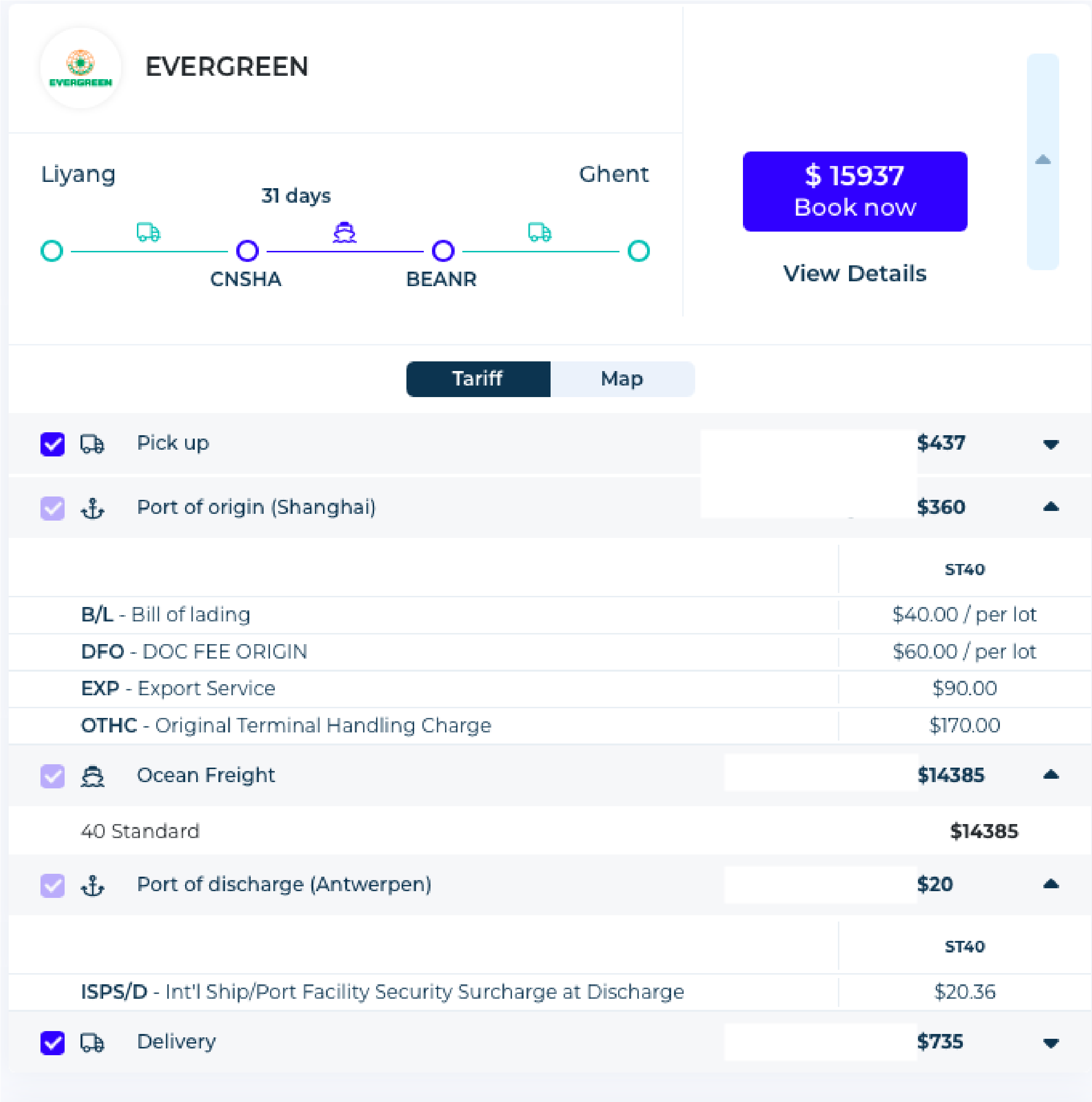
Far East - Africa Express (FAX)



To see Long Term Schedule : HTML Format PDF Format TXT Format

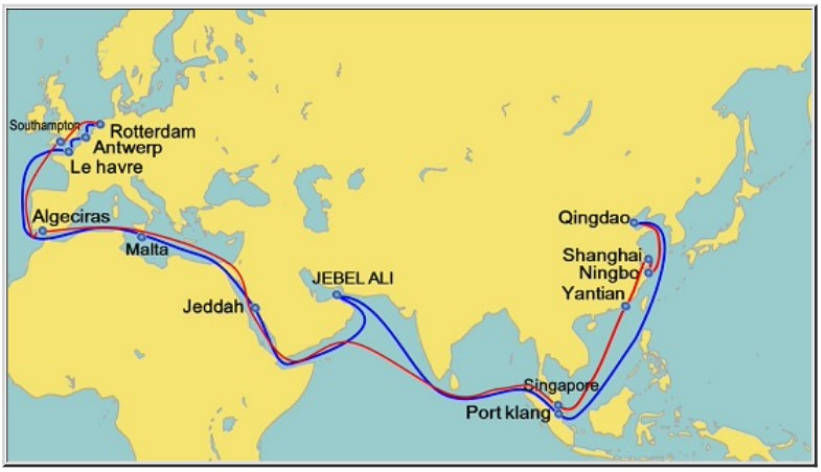
FAX	QINGDAO	SHANGHAI	NINGBO	SINGAPORE	DURBAN	SINGAPORE	SHANGHAI	QINGDAO
ETA	TUE	THU	SAT	SAT	SUN	FRI	SAT	TUE
ETD	TUE	FRI	SUN	SUN	THU	SAT	SAT	TUE
T/S TIME	0	2	4	11	26	45	53	56

Appendix 3. Freight quote, Shanghai–Antwerp



Appendix 4. French Asia Line 3 (FAL3)

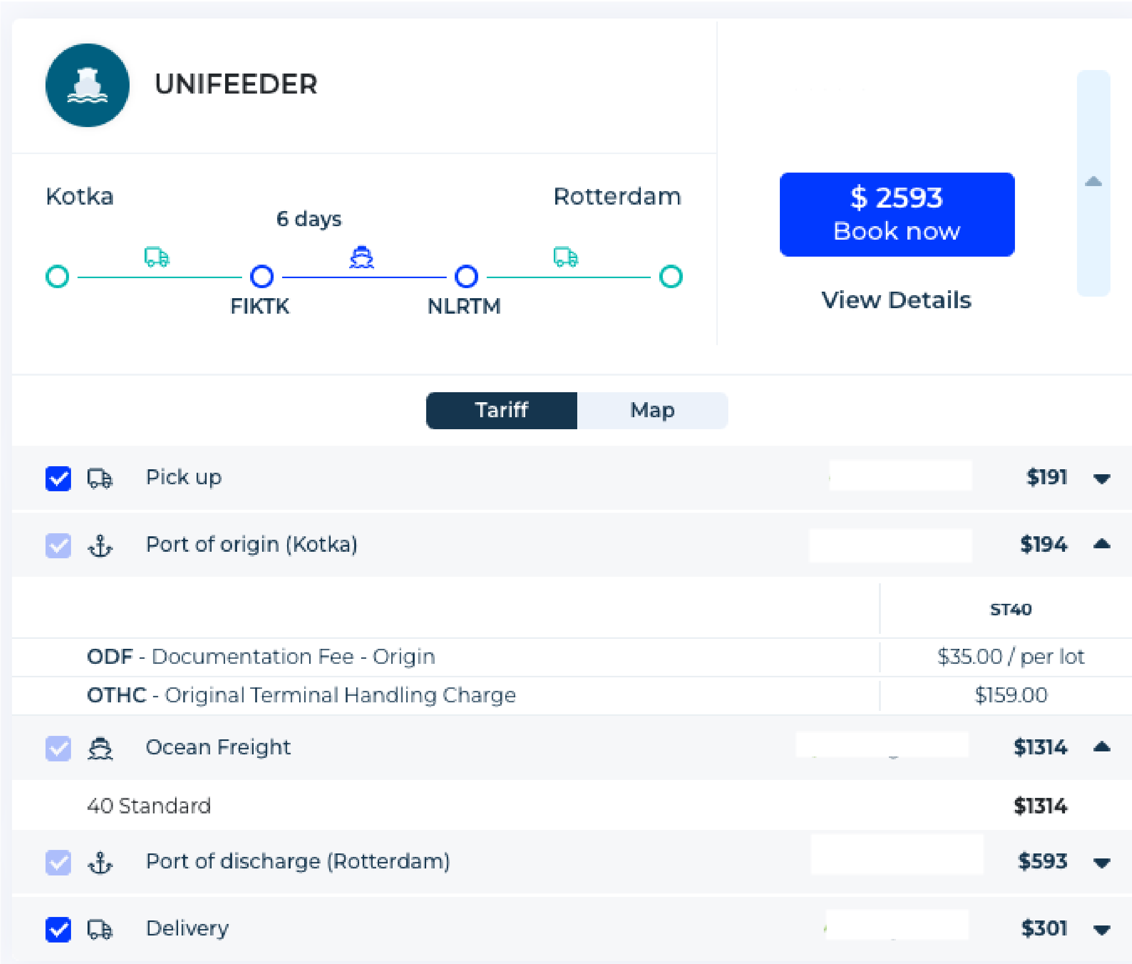
French Asia Line 3(FAL3)



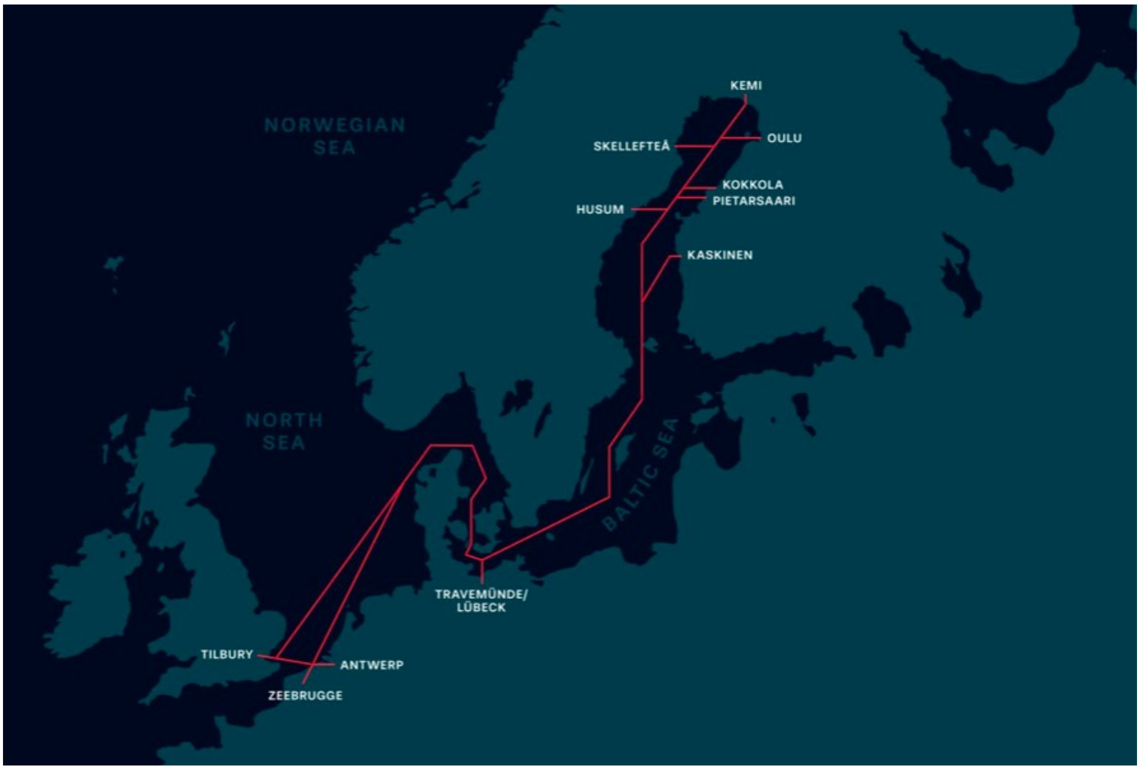
To see Long Term Schedule : HTML Format PDF Format TXT Format

FAL3	QINGDAO	NINGBO	SHANGHAI	YANTIAN	SINGAPORE	SUEZ CANAL	TANGIER	SOUTHAMPTON	ROTTERDAM	ANTWERP	LE HAVRE	TANGIER	SUEZ CANAL
ETA	SAT	WED	FRI	TUE	SAT	WED	WED	SUN	WED	SAT	WED	MON	SAT
ETD	MON	THU	SAT	TUE	SUN	THU	THU	TUE	FRI	SUN	THU	TUE	SUN
T/S TIME	0	1	3	7	12	23	29	33	36	39	44	49	54

Appendix 5. Freight quote, Kotka–Rotterdam



Appendix 6. Wallenius Sol – Route Network



Appendix 7. Monte Carlo Simulation values

Chinese-controlled scenario		Transit time (d)					CO2e (kg/t) 100% Co					Costs ($/t) 100% Co				
ID	Transport leg	Distribution	Min	Avg	Max	St.dev	Distribution	Min	Avg	Max	St.dev	Distribution	Min	Avg	Max	St.dev
1	CDM, DRC –> Port of Durban, South Africa	Normal	-	7,0	-	0,7	Triangle	250,00	381,85	650,00	-	Triangle	300,00	396,83	600,00	-
2	Port of Durban –> Port of Shanghai	Triangle	22,0	30,5	40,5	-	Triangle	650,00	743,92	1000,00	-	Triangle	100,00	185,56	600,00	-
3	Port of Shanghai –> Huayoy Cobalt	Normal	-	3,0	-	0,3	Normal	-	21,96	-	2,20	Triangle	40,00	53,33	80,00	-
4	Huayou Cobalt –> CATL	Normal	-	2,0	-	0,2	Normal	-	11,04	-	0,40	Normal	-	16,81	-	0,60
5	CATL –> Port of Shanghai	Normal	-	3,0	-	0,3	Normal	-	16,75	-	0,30	Normal	-	20,81	-	0,70
6	Port of Shanghai –> Port of Antwerp	Triangle	30,0	40,5	50,0	-	Normal	-	252,63	-	10,00	Triangle	95,00	703,10	950,00	-
7	Port of Antwerp –> Volvo Car Gent	Normal	-	3,0	-	0,3	Normal	-	2,55	-	0,05	Triangle	20,00	35,00	38,00	-
		Forecast:		89,0			Forecast:		1430,70			Forecast:		1411,40		

Nordic scenario		Transit time (d)					CO2e (kg/t) 100% Co					Costs ($/t) 100% Co				
ID	Transport leg	Distribution	Min	Avg	Max	St.Dev	Distribution	Min	Avg	Max	St.Dev	Distribution	Min	Avg	Max	St.Dev
1	Lat66, Kuusamo –> Terrafame, Sotkamo	Normal	-	2,0	-	0,2	Normal	-	97,76	-	9,78	Triangle	150,00	251,11	400,00	-
2	Terrafame –> Battery Chemicals Plant, Vaasa	Normal	-	2,0	-	0,2	Normal	-	54,08	-	5,41	Triangle	90,00	135,67	150,00	-
3	Battery Chemicals Plant –> Port of Vaasa	Normal	-	1,5	-	0,2	Normal	-	0,52	-	0,02	Normal	-	1,12	-	0,05
4	Port of Vaasa –> Port of Umea	Normal	-	1,5	-	0,2	Normal	-	3,02	-	0,10	Normal	-	8,48	-	0,50
5	Port of Umea –> Northvolt, Skelleftea	Normal	-	2,0	-	0,2	Normal	-	5,08	-	0,10	Normal	-	11,05	-	0,50
6	Northvolt –> Port of Skelleftea	Normal	-	1,5	-	0,2	Normal	-	0,42	-	0,02	Normal	-	1,48	-	0,05
7	Port of Skelleftea –> Volvo Car Gent	Triangle	7,0	11,5	12,5	-	Normal	-	130,39	-	7,00	Triangle	100,00	139,53	150,00	-
		Forecast:		22,0			Forecast:		291,32			Forecast:		548,44		

Appendix 8. A normal distribution (Wikipedia, 2022)