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Identifying and mitigating risks in the future supply of raw materials in lithium-ion batteries

Master's thesis in Supply Chain Management, Management and Economics of Innovation

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Gothenburg, Sweden 2020
Report No. E2020:047

MASTER’S THESIS E2020:047

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Gothenburg, Sweden 2020

Abstract

The global demand for raw materials used in lithium-ion batteries is expected to increase dramatically in the coming years, primarily due to large scale electrification of the global vehicle fleet. The demand has been initiated by increased environmental awareness from the society as well as tightened regulations on emissions from governments. A steep demand increase creates uncertainty whether the supply of the raw materials will match the demand in the right time, leading to potential supply risks and disruptions in the supply chain of raw materials to lithium-ion batteries.

This master thesis creates a theoretical framework including supply risk indicators, used to identify supply chain risks in the extraction and refining level of raw materials used in lithium-ion batteries. The framework was in this master thesis applied to identify supply chain risks for the materials cobalt, nickel, lithium and graphite up until the year 2025. To do this, an extensive data collection was made on data points needed, such as operating company name, country of origin, country of operations, the country's corresponding WRI and WGI score, produced product, production capacity and expansion plans up until 2025. The data was used to calculate the supply chain risk indicator for each of the mentioned materials. The framework includes boundaries for each indicator, making it possible to not only identify risk but also assess the magnitude. We conclude that there is a difference in what risks that are prominent for each material, but all materials supply chains will be facing challenges to cope with the increased demand.

In addition, this master thesis provides a number of mitigation strategies, found in a literature review, that can be used to mitigate the identified risks. These strategies have been applied to every risk indicator from the above-mentioned framework, to determine the effect on each risk indicator. We conclude that there are a lot of dimensions to consider when applying a mitigation strategy since the same strategy can decrease one risk but increase another. Thereby a trade-off between the corresponding cost of using the mitigation strategy and the potential benefits needs to be considered for each specific context.

Acknowledgements

There are a number of people involved in this project whom we would like to show our gratitude. Firstly, we would like to thank our supervisor Mats Johansson, Full Professor at the division of Technology Management and Economics, Department Logistics and Supply Chain Management, for continuous support throughout the master thesis providing guidance and knowledge. Secondly, we would like to thank the employees at the Raw Material Department and Electromobility team at Volvo Group for giving us their valuable time and sharing their knowledge within this field. Lastly, we would like to show our special gratitude to our industrial supervisors Paul Emmanuel, Gustav Svärd and Jan-Olof Falkejon from the Raw Material Department at Volvo Group, for helping us setting up this master thesis and showing commitment to the project even though the unanticipated circumstances of COVID-19.

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List of Abbreviations

ASM	Artisanal mining
BAM	Battery anode material
DRC	Democratic Republic of Congo
EU	European Union
EV	Electric vehicle
HDV	Heavy-duty vehicle
HHI	Herfindahl Hirschman index
HPAL	High pressure acid leach
LME	London metal exchange
NCA	Nickel-Cobalt-Aluminum (Battery cathode composition)
NMC	Nickel-Manganese-Cobalt (Battery cathode composition)
NPI	Nickel pig iron
PC	Procurement contract
UAE	United Arab Emirates
WGI	World Governance Indicator
WRI	World Risk Index

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1 Introduction

In Section 1.1 a background and context to the master thesis is presented. This is followed with Section 1.2 that includes the aim of this master thesis and in Section 1.3 the research questions are specified.

1.1 Electric vehicle transition

The transport industry has in recent years started to switch towards electrifying their vehicle fleet by using electric motors powered by lithium-ion batteries instead of combustion engines. To make this transition in such a big industry as the vehicle-industry, a lot of pressure is being created on many layers of the supply chain. Especially exposed are many of the raw materials that are used in the lithium-ion batteries since a major increase in demand leads to increased supply risks (Chapman, Christopher, Jüttner, Peck and Wilding, 2002).

The transition has been initiated by increasing environmental awareness from the society as well as governments. The Paris agreement is signed by 194 states, with a clear objective to minimize the increase in global average temperature to well below 2° Celsius compared to pre-industrial temperature levels. To contribute to this objective, there is a need for the road transport sector to accelerate its transition into zero emissions, as it stands for 25% of the total emissions within the European Union (EU) 2016 (EU council, 2019). A quarter of these emissions can be accounted to the Heavy-Duty Vehicles (HDV), which includes trucks, coaches and buses (EU council, 2019). Today's HDV fleet is relying heavily on oil-based fuels and has the second-highest demand for oil on a global level (International Energy Agency, 2017). To further incentives electrified development, the EU has imposed penalties to HDV-manufacturers that are not able to lower their average emissions on sold vehicles by 15% until 2025 and 30% by 2030 (EU council, 2019).

The electric vehicle (EV) passenger car market has grown substantially during the recent years, from 3.1 million to 5.1 million vehicles globally between 2017 and 2018, i.e. an increase of 64% (International Energy Agency, 2019; Earl & Fell, 2019). The HDV electrification is behind the passenger cars since their higher requirements on the batteries has not yet been met on a high scale, but is projected to follow a similar pattern in the near future. The Clean Energy Ministerial which is a unique partnership of 25 key countries has set a collective ambitious goal for all the members to have a 30% market share for EVs looking at the total of all vehicles, not including two-wheelers, by 2030. This goal would lead to a scenario of an EV stock at 100 million by 2025 and 250 million by 2030, which would mean EV sales of 44 million per year by 2030 (International Energy Agency, 2019).

The electrification transition puts a lot of pressure on the established companies in the automotive industry. Paradigm shifts of this kind open up the opportunity for new entrants to establish a presence and create new competitive bases within technology, business model and markets to compete in (Teece, 2018). The established companies will need to expand into new capabilities while some of their current ones render obsolete (Teece, 2018). However, deciding which technologies to invest in is an important decision, as it often requires a big commitment.

The technology that has been dominating the EV's market so far is different types of lithium-ion batteries. The main difference between battery-types lies within the composition of their cathodes, in terms of what raw materials are used and the ratio between them. The rapid growth in the EV market caused by the transition will completely change the demand for some of these raw materials. The steep increase in demand, pressure the raw material production capacity to scale up quickly which creates uncertainty whether the supply will be able to match the growing demand at the right time. The high lead times on building production facilities and the rigidness of the supply could create availability risks of the raw materials for the EV-manufacturers. In the case of shortage in the supply-side of the market, EV-manufacturers not able to secure supply could be forced to use, if available, substituting materials or solutions. Using substitute materials will most likely result in either lowered quality or increased cost of the battery.

The recent increase in predicted demand has created a lot of speculations in the market around the concerned raw materials. As a result of this, the prices of some of these materials skyrocketed in late 2017. This led to a lot of investments to increase the total production capacity in the market. But since then, the demand increase has been somewhat delayed, mostly because of changed subsidiary requirements in China, which have led to lowered prices. These two opposite forces, current underperformance versus kept strong beliefs in the future, have created volatile prices on these materials (Sifon-arevalo, 2019). Volatile prices in supplies create uncertainties and thereby risks for EV-manufacturers dependent on the raw materials, since their vehicle-prices to their customers are a lot stiffer than the daily updated prices on the raw materials, leading to volatile margins on their products.

Volvo Trucks, the industrial stakeholder of this project, has a history of manufacturing trucks that expands all the way back to 1928 when their first truck rolled off their production line. Since then they have developed a deep skillset within the combustion engine and always strived towards creating a more powerful, efficient, comfortable, safer and cleaner truck (Volvo Group, 2020). In the shift towards an electric driveline and energy storage system, they have realised they need to expand their skills into new fields. As a result of this, Volvo Group entered a strategic alliance with Samsung SDI that aims to develop the battery packs for the coming electric trucks. In a press release Volvo states that "Working together with Samsung SDI, Volvo Group aims to accelerate the speed of development and strengthen the long-term capabilities and assets within electromobility, to the benefit of customers in different truck segments and markets" (Volvo Group, 2019).

One function in the Volvo Group that are directly affected by the EV-transition is the raw material department, who operates as business controllers in Volvo Group Purchasing. The raw material team's main task is to follow the markets of the most important raw materials for Volvos current product offering. The team develop and deploy raw material market expertise and governance to secure and improve raw material related performance. This is done by consolidating and use all internal and external business intelligence available and perform value chain analysis to understand how different related factors and risks can influence the commodity market. The team supports other departments in Volvo Purchasing, that needs information such as price estimations and market forecasts on raw materials in short to medium term. The knowledge is also used to support buyers in negotiation and provide contractual guidance for raw material agreements with suppliers. However, not all raw materials are contracted, only the ones where it makes the most sense, often depending on how much value in raw material there is in the total article price.

In the electric trucks, Volvo uses lithium-ion batteries as their storage system which makes up to a big cost of the truck. The lithium-ion batteries include raw materials that the raw material team does not follow today. Given that the raw materials in the battery add up to a big cost item in the truck, there is a need for the team to increase their understanding and create expertise in the new technology materials to secure best possible performance on these materials.

Generally, supply chains of raw material are connecting many different producers, suppliers and buyers all around the globe. There is most often an initial step where the material is extracted from the earth's crust. The extracted mineral does then need to be refined, often in multiple steps and processes, to get the attributes needed for the end-user market. However, even though the different raw materials share the same overall steps in their supply chain, the processes within each step look very different between and even within materials. The same material could need different processes depending on the end-users need. Some applications need a very purified high-quality metal, while other applications have lower requirements. Thereby, there is a need for specialist knowledge, as the supply chain for these materials are complex and underlies challenges and risks such as traceability, geographical concentration, geopolitical issues and resource nationalism. Already today, we know that some supply of new technology raw material originates from politically unstable countries which in turn creates supply challenges in both the short and long term. (Bartl et al., 2018; Schrijvers et al., 2020).

Combining that Volvos dependencies on raw materials used in lithium-ion batteries will increase together with an anticipated overall volatile and increasing price, it is easy to understand why there is an interest in acquiring information to better understand the potential risks and how they could be mitigated.

1.2 Aim

This master thesis aims to contribute to the understanding of what potential risks there are in the future supply chain of the raw materials that are essential to lithium-ion batteries and how these risks could be mitigated, from an EV-manufacturer perspective.

1.3 Research questions

When considering the electric vehicle transitions, there are a number of competing lithium-ion compositions to cater to the increased demand in more eco-friendly transportation. This choice of technological solutions highly affects which raw materials that are used and hence interesting to study further. Even within the same battery type, there are a number of different compositions, which affects companies dependency on these materials. Right now, the common belief is that high nickel-concentrated lithium-ion batteries with the complementary cathode-materials manganese and cobalt (NMC) or cobalt and aluminium (NCA) are the most suitable for HDV in the coming years, due to its high energy-density and high life-cycle count. Overall there is a belief on the market that for the near future the NCA battery technology will be the most commonly used for HDV due to its good life-cycle count. The active raw materials in the anode of an NCA battery are lithium, nickel, cobalt and aluminium and in the cathode, graphite is used.

Furthermore, when making forecasts it is inevitable to also have uncertainties around the data. Rosenau-Tornow, Buchholz, Riemann and Wagner (2009) therefore propose to try to minimize the forecast horizon to the "foreseeable future". In the case of raw material anticipations, the authors state that it is possible to be reasonably accurate in a time frame similar to the lead time for production projects, i.e. 5-10 years.

To keep the findings from this master thesis probable, and minimize the element of speculation were possible, it is the supply chains of the raw materials included in the NCA-technology that will get further examined in this master thesis with a timeframe of five years, i.e. 2025. However, aluminium is already followed by the raw material team on Volvo today and is hence excluded. Cobalt, nickel, lithium and graphite are also used in other lithium-ion battery technologies, such as the NMC, meaning that the results from this master thesis will be applicable to a variety of users.

Further, the focus of the data collection of this report is the supply chain steps that perform the initial extraction of the material from the earth's crust up until it is refined to the required form for the EV-battery industry since it is from these levels the raw material team gathers most of their external business intelligence. From this, the first research question is:

Research Question 1: Which are the risks in the extraction and refining level in the supply chain of Cobalt, Nickel, Lithium and Graphite that exist up until 2025?

When the risks have been identified in the initial extraction and refining level of the future supply chain of Cobalt, Nickel, Lithium and Graphite, the following question, from an EV-manufacturers perspective, is how the risks could be mitigated. The events affecting the supply from these initial levels are outside of Volvos control since Volvo are not directly engaged in these activities. However, the risks originating from the initial levels of the raw material supply chains will affect Volvo differently depending on how they set up their sourcing strategies. Thus, it is possible for Volvo to mitigate risk by utilising risk mitigation strategies. Thereby, the second research question is:

Research Question 2: What risk mitigation strategies could be used to mitigate the risks identified in RQ1?

2 Theory

This chapter provides a theoretical basis that is needed to form a framework that will guide the data collection. There are four main sections covered. Firstly, in Section 2.1 a definition of risk is presented since it is of importance to understand how the word is interpreted throughout the report. Section 2.2 presents theory about the cobalt, nickel, lithium and graphite. Also, the mine development process is described in general. In Section 2.3 risk indicators related to the supply chain of raw materials identified in the literature are presented, some of which are relevant and further used in this master thesis while some are valuated to be non-applicable for answering research question 1. Lastly, Section 2.4 presents strategies to mitigate the identified risks identified in the literature is introduced, also here are some assessed to be relevant and further used in this master thesis while some are not, to answer research question 2.

2.1 Definition of the term risk

According to Miller (1992), the term risks lack a well-defined, fully accepted definition within supply chain management. This creates an ambiguity in when and how the term is used, but often in relation to unanticipated variation in business performance metrics such as profit, costs, market share or revenue (Miller, 1992). The Royal Society tries to define risks with a more quantitative approach, as the probability of a well-defined hazard to occur (Norrman & Jansson, 2004). This leads to the possibility to calculate the risk by multiplying the probability of the event to occur with the potential business impact. This view on the term risks eliminates some of the "unanticipated" aspects that Millers (1992) version covers. Instead, Norrman and Jansson (2004) refer to these unknown events with the introduction of a complementary term, uncertainties.

Further, other researchers are connecting the terms risk and uncertainties as well, with many of them even using them interchangeably (Simangunsong, Hendry and Stevenson, 2012). However, when there is a distinction being argued, it is often the outcome that separates the terms. Risks are related to only negative outcome, while for uncertainties it is unclear whether the outcome will be positive or negative (Simangunsong et al., 2012). What this lack of unanimous definition states is that, regardless of which definition that is used in this master thesis, to not miss out on relevant research, both terms need to be reviewed in the literature.

From here on, when the term risk has been used the outcome of the event is expected to have a negative impact, while the term uncertainties are used when there is less known of the outcome.

2.2 Raw material production for the EV-industry

This section provides a theoretical background on the raw materials used in the NCA lithium-ion battery as well as the phases of developing a mine. The purpose of the following sections is to give the reader an introduction and needed background information on used terminology in raw material production, which will be continuously found throughout the remaining of the report. Further, the attributes for cobalt, nickel, lithium and graphite are presented.

2.2.1 Cobalt

Due to its key characteristics of ferromagnetism, low thermal and electric conductivity, hardness and high melting point, Cobalt is used in many different industries, ranging from batteries, chemical, healthcare to alloys (Slack, Kimball and Shedd, 2017). Cobalt is used in rechargeable batteries, due to its ability to handle high operating temperatures still withholding its ferromagnetic abilities. It is also useful since it can store and transfer energy in an efficient way and do not overheat easily (Zubi, Dufo-López, Carvalho, and Pasaoglu, 2018). In 2017, the battery industry accounted for 30% of global cobalt consumption (Azevedo et al., 2018).

Cobalt exists both in land and seafloor deposits, where land-based mine production is the only source today. Exploiting underwater reserves have legal, economic and technological barriers as some are up to 6 000 meters deep (Slack et al., 2017).

The types of land-based deposits are mainly Ni-Co laterites deposits, Ni-Cu(-Co-PGE) sulfide deposits or Cu-Co sulfides deposits. Depending on the geological setting the types of deposit differ, for example, is Ni-Co laterite common in humid tropical climates, developed by the weathering of ultramafic bedrock (Slack et al., 2017). All of these sources for cobalt can be used for battery production.

There are two steps in the initial supply chain of cobalt production, mining and refining. The mining of cobalt is done by underground and open-pit mining methods. The mined ores are later processed by using extractive metallurgical techniques, in other words, a process to remove worthless materials that cover the wanted mineral and thus improving the economic value. The resulting solutions are in the next step refined, to separate out the individual metals. The refining process often uses chemical precipitation and solvent extraction, to extract the material wanted, which is made possible by using strong acids.

2.2.2 Nickel

Nickels is used in a wide range of industries and applications such as the stainless steel industry, aerospace, military, coins, batteries and electronics (Henckens & Worrell, 2020). In 2018 the battery sector only accounted for 3-4% of the global nickel consumption (*British Geological Survey*, 2018), which could be compared to the 65% that the biggest segment, stainless steel is using (Henckens & Worrell, 2020).

There is a range of different nickel products produced depending on the original nickel content, industrial application, chemical composition and processing complexity. However, there are two main categories of nickel, either Class I (>99% purity) or Class II (<99% purity). The high purity of Class I nickel makes it suitable for almost all application areas, including the battery industry. According to Schmidt, Buchert and Schebek (2016) the most common nickel-product to use in the battery industry is nickel sulphate, which is manufactured through letting class I nickel have a chemical reaction with sulfuric acid. Class II nickel does not have as many potential application areas, but certain steps of the stainless steel industry use the Class II nickel in the shape of ferronickel and nickel pig iron (NPI). What this means is that not all nickel is suitable for a lithium-ion battery, it needs to be high grade nickel (Class I).

The production of nickel starts with mining the earth's crust from either sulfide- or laterite ore. Today, most mines extract nickel from sulfide deposits, even though 60% of the known nickel is found in laterite ore (Henckens & Worrell, 2020). The laterite ore is further subdivided into saprolites and limonites (Schmidt et al., 2016).

From the ore, the nickel content then needs to be refined. Sulfides are generally processed into the intermediate product *matte* before it is refined through a variety of methods into Class I nickel. From the laterite ore, only limonite gets processed to Class I nickel. This is done through High-Pressure Acid Leaching (HPAL) where the intermediate product *nickel sulfides* is obtained, which then further gets processed to Class I nickel. Saprolites is mostly refined into *ferronickel* and *NPI* (class II), which is solely done in China and feeds into their stainless steel industry (Schmidt et al., 2016).

2.2.3 Lithium

Lithium is a metal commonly used in batteries, ceramics, glass, pharmaceuticals and polymers (Bradley, Stillings, Jaskula, Munk and McCauley, 2017). Today, the battery industry stands for approximately 39% of worldwide lithium consumption (Zubi et al., 2018). Lithium is commonly used in batteries due to three reasons, (1) it is highly reactive because it easily loses its outermost electron, which gets current flowing through the battery, (2) it is light and (3) lithium ions and electrons have the ability to with ease move back into negative electrodes (Zubi et al., 2018). There are several methods to extract lithium, the most common ones are to use brines and extraction from pegmatite ores by mining operations.

The brine is pumped from underground deposits in dry salt lakes in regions with high lithium concentration, into solar evaporation basins. The next step is to allow all the water to evaporate from the basin and what remains is different salts including, for example, lithium and potassium (Stamp, 2012). The production, therefore, favours a dry and sunny climate since it is key to allow the brine to dry out in a reasonable time frame. For example, lithium production in Salar de Atacama, Chile, one of the Earth's driest places in combination with a high average of lithium in the water is a key reason why it is one of the largest brine production locations in the world today (Bradley et al., 2017).

The lithium-containing concentration gathered from the basin goes through a refining process, where it gets purified. The last step is to add sodium carbonate to get the end product lithium carbonate. The brine production of lithium allows to keep energy requirements low, due to the use of solar energy and thus gets a low competitive price on the market.

Another commonly used method is to mine lithium from pegmatite ores. Pegmatites are rocks that contain lithium spodumene (Bradley et al., 2017). The mining operations are mainly open-pit, with conventional drill and blast techniques (Stamp, 2012). The mined ores then go through a process of beneficiation, which means that the ores are being crushed and grinded to get rid of unwanted materials covering the lithium mineral (Stamp, 2012).

The last step is to refine the concentrated ore. This is done by adding sulfuric acid, which is needed to produce lithium carbonate or lithium hydroxide. Both lithium carbonate and hydroxide are forms of lithium used in the lithium-ion batteries.

2.2.4 Graphite

Graphite is a mineral consisting of the element carbon, with its atoms arranged in hexagonal structures. The special structure gives graphite special properties such as thermal stability, high electrical conductivity and self lubricity. Graphite is commonly used in battery anodes, electronics, lubricants and steelmaking. Graphite is currently the best material to be used in lithium-ion battery anodes due to its very good characteristics. It has a highly reversible intercalation and deintercalation, meaning that it has no or minor capacity fading after several thousands of cycles with full amount of lithium-ion present in the battery cell (Placke et al., 2018). There are two sources of graphite, natural and synthetic.

The natural graphite is mined from deposits in metamorphic rocks such as marble and gneiss. The mines can both be open-pit as well as underground mines. The graphite is classified into three commodity types, amorphous graphite, flake graphite and vein graphite. Which type that is mined depends on the location of the mine, often one type is consistent per mine. The only type of natural graphite used in lithium-ion batteries anodes is flake graphite due to its ability to be upgraded to 99.9% purity and form a special shape, spherical graphite (Battery Minerals, 2020).

Synthetic graphite is graphite made artificially by using non-graphitic carbon. The process starts with deriving petroleum needle coke from coal tars or by-products from low sulphur oil refining processes. By heat-treating the needle coke the carbon changes it properties dramatically, called the graphitization process, which forms the carbon into graphite structures as well as removing impurities such as sulphur, nitrogen and ash. The end product can be used for battery anode materials producers (Stansberry, 1999).

The natural graphite is less expensive compared to the synthetic graphite, however the synthetic graphite can reach better performance since it is purer in terms of carbon content and tends to behave more predictably.

The natural flake graphite and synthetic graphite is then used to produce Battery Anode Material (BAM) for the anodes in lithium-ion batteries. In this step, the flake graphite is shaped into a form called spherical graphite by a mechanical shaping process. It is then purified to remove elements such as sulfur by using acids. The last step is the coating, which improves the surface of the material. The spherical shape allows for more efficient particle packaging in the battery anode, which results in an increased energy and recharge capacity of the battery (Robinson, 2017). The synthetic graphite is also shaped to fit in the anode. BAM producers traditionally use equal parts of natural and synthetic graphite in the mix to get a good price vs performance ratio.

2.2.5 Raw material exploration

The development of a new mine can take from 6-20 years, which adds to the complexity of being able to ramp up production quickly to meet to the future demand of raw materials from the EV-industry (The University Of Arizona, 2020). There are mainly three steps to get a mine from going from planning to commercialisation, (1) Exploration, (2) Development and (3) Extraction.

The first step (1) includes the process of exploration i.e. making a mining feasibility study, searching for regions containing mineral deposits. The aim is to evaluate and determine if the mining project could mine the mineral resource economically. This process can take two to eight years to complete and can cost 500,000-15 million USD. The exploration phase is set to determine the possible size and value of the deposit that has been found. Samples are taken to determine how much of certain minerals the deposit contains, and to be able to take samples it might be required to have a contractual agreement with the owner of the land. The quality of the material, as well as amount, form and location, might determine if it is worth extracting or not and it must be estimated with a high level of accuracy. (The University Of Arizona, 2020).

The second step (2) including planning and building the mine. This phase takes four to twelve years and costs from 1 million USD to over 8 billion USD depending on what type of mine that is needed. Permits, environmental and social impact reports, mining equipment, the building of infrastructure such as roads, identification of power and water sources, disposal areas for waste and safety precautions are some of the steps needed. (The University Of Arizona, 2020).

(3) The mine can start to extract minerals from the earth's crust. (The University Of Arizona, 2020).

This shows the complexity, lack of flexibility and the involved financial risks included in opening and running a mine.

2.3 Supply Chain Risk Indicators

Looking into the literature, the definition of supply chain risk is based on an assumption that it is a purely event-oriented concept (Heckmann, Comes, and Nickel, 2015). This perception relates risk to the probability of disruptive events to happen. Taking it in a supply chain risk management context, (Heckmann et al., 2015) describes it as events that are characterized by their probability to happen and their related consequences within the supply chain.

There has been a lot of previous research related to identifying supply chain risks that have an impact on the performance of a company in different areas; firm-specific with internal challenges as well as supply- and demand-side issues (Simangunsong (2011); Miller (1992)). Simangunsong (2011) has for instance in his work reviewed and gathered supply chain risks from a number of different frameworks (eg. Miller (1992); Davis (1993); Christopher and Peck (2004)) resulting in a theoretical foundation of supply chain risks to be used for future research. The research contains three categories of sources of risks: (1) risks that come from the focal company, i.e. internal organisation risks, (2) internal supply chain risks that arise within the realm of control of the company or its supply chain partners, (3) external risks from factors outside the supply chain. In total, the three groups contain 14 different risks gathered from the literature.

As stated in the research question 1 this master thesis focus on the initial supply chain level that lies before Volvos own engagement, it is only the risks arising outside of Volvos control that is of interest. Thus, the external risk group from Millers (1992) framework would be of interest. However, because of his effort in being comprehensive, this particular group lacks a lot of the details and aspect interesting from a procurement team perspective. Even though it presents useful aspects, there still was a need to identify more specific risks to a procurement team buying raw material.

Achzet and Helbig (2013) have in their research made an overview of supply risk indicators evaluation specifically for raw materials, by overviewing 15 research papers and comparing their differences and similarities. A risk indicator is used since it indicates if there could be a risk for disruptions of supply, that origins from what the indicator evaluates. The selection of research papers is based on Erdmann and Graedels (2011) assessment of the most important research on supply risk indicators for raw materials. By reviewing these studies Achzet and Helbig (2013) have identified 20 risk indicators, that all affect the supply chain. Some of these indicators are used with different frequency in the different studies, where 10 of them are used in multiple studies, while the remaining ones are mentioned in a single study. Achzet and Helbig (2013) assume that the indicators used more frequently have a higher relevance for supply risk. In addition, the different indicators are used in different time perspective from short, mid to long term. Thus, all the indicators are not suitable in every context.

According to Erdmann and Graedel (2011), the selection of indicators have a severe impact on the evaluation of supply chain risk and therefore they highlight the importance of giving a reason for the selection of criteria. This is why the remaining part of this section will focus on giving reasoning to which indicators that are to be used in this master thesis, and which is deemed to not be relevant. The indicators suitable for the context of this master thesis is discussed more thoroughly, sometimes with further assistance from research papers outside of Achzet and Helbig (2013) review scope, while the remaining indicators have a more shallow explanation together with reasoning why they are not deemed to be relevant. The suitable indicators will then provide the theoretical basis for the framework used in the data collection and analysis.

The indicators that will be presented are: country concentration, country risk, by-product dependency, company concentration, market balance, commodity price, climate risk and lastly the non-applicable indicators.

2.3.1 Country concentration

The most commonly used indicator for raw material supply risk in Achzet and Helbig's (2013) overview work was the indicator country concentration. This indicator measures the country concentration of either production or reserves of the particular raw material under investigation (Achzet & Helbig, 2013). Within this master thesis scope and research question the production aspect is more interesting than the reserves concentration due to that even if a country has a big reserve base of raw material, it doesn't mean they are actually having any production in the short to medium term.

The method to measure country concentration used by many papers and organizations, such as the European Commission (Duclos, Otto and Konitzer, 2010; Frondel, Angerer and Buchholz, 2007; H. Kara et al., 2011; Morley & Eatherley, 2008; Rosenau-Tornow et al., 2009) is the Herfindahl-Hirschman Index (HHI). HHI can be used either to assess the country or the company concentration in a market. A low HHI would indicate that the market has a higher level of competition. The opposite market, one who has a high index indicates that the market is close to being a monopoly (Naldi & Flamini, 2018). The HHI is calculated by the formula:

$$HHI = \sum_{i=1}^{n} S_i^2$$

Here, *S* refers to the market share of the company or country *i* of the total global market. The result is an HHI that goes up to the maximum of 10 000 , i.e. a monopoly. Further, the United States department of justice and the Federal Trade Commission classifies markets with the following guidelines (Achzet & Helbig, 2013):

- Unconcentrated markets: HHI < 1 500
- Moderately Concentrated Markets: 1 500 < HHI < 2 500
- Highly Concentrated Markets: HHI > 2 500

Further, it is important to emphasize that having a high market concentration is not necessarily a problem by itself. Instead it indicates an essential risk of getting highly affected by resource policies, changed taxes or other market conditions that abruptly creates tension in the supply and demand balance (Achzet & Helbig, 2013).

2.3.2 Country risk

The secondly most used indicator in Achzet and Helbigs (2013) overview work is the country risk. There is a number of indexes to assess a country's political stability, but the World Governance Indicator (WGI) by the World Bank is widely used (Achzet & Helbig, 2013). WGI is an index which measures six aspect per country on a scale between -2.5 to 2.5; “voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, control of corruption” (World Bank, 2020). A low number on the scale represents higher risk while a high number means lower risk.

to assess the different governments that the production of raw material supply-chain is exposed to, Ferro & Bonollo (2019) combined the country concentration with the country risk. The result can be seen in the equation:

$$HHI_{WGI} = \sum_{c} (S_{ic})^2 WGI_c$$

In this equation, WGI is used for the producing country “c” and multiply it by the share of global production that originates from the same country. By then summing all of the producing countries together, the end result is an index on how stable or unstable the governmental environment is to the total supply chain of each of the raw materials. (Ferro & Bonollo, 2019).

Different authors have different approaches to what level of WGI that are to be deemed as critical. Frondel et al. (2007) states that all countries lower than 0.59 is critical, while others advocate a more relative approach per study (Morley & Eatherley, 2008). In this master thesis, the threshold of 0.59 will act as the main guideline, but the comparison between the materials will provide further nuance to the analysis.

2.3.3 By-product dependency

A by-product is a mineral produced as a result of the production of a main-mineral (Slack et al., 2017). The by-products production is directly linked with the main-mineral production, not by the need of the by-product (Slack et al., 2017). It has also been concluded that being a by-product strongly influence the pricing and availability of the raw material, since there is a lack of flexibility to adjust the amount of by-product mined to shifting demand, resulting in periods of oversupply or shortage. Being dependent on by-products is thereby seen as a major supply risk for many new technologies (Langhammer, 2010; Nassar, Graedel and Harper, 2015; Slack et al., 2017).

To measure a minerals dependency on other minerals Nassar et al. (2015) has in their work introduced the term companionality. The companionality calculates if a mineral can be profitably produced on its own, meaning if the revenue contribution from a specific metal can cover the entire cost of sales from the mine. When multiple minerals are mined together, the mineral whose own revenue does not cover the total cost of sales is to be considered a companion. On the contrary, if the revenue from one mineral covers the total cost of sale, then the mineral is considered a main-mineral and thus not dependent on other minerals to be produced. In some cases, two minerals can have similar economic contribution and in these cases, they are considered as coproducts. The companionality is calculated in Nassar et al. (2015), with a formula that considers a certain minerals revenue contribution compared to the cost of operations for mining.

The minerals revenue contribution and operating cost vary by operation and thus the calculation is conducted for every operation and then weight-averaged by sales volume to get a single comparable value for every material (Nassar et al., 2015). The companiality-value will be between 0 and 100, where 0 means that the material is self-sufficient and 100 means that the material is completely dependent on other materials to get produced**.**

In Nassar et al. (2015) study, they have evaluated the companionality for 62 different metals including lithium, cobalt, nickel. These evaluations of companiality were used in this report for the by-product dependency for cobalt, nickel and lithium. This data might change upon till the year of 2025, but Nassar et.al (2015) argues that there is an inertia in the industry that makes the calculations valid for more years than the year the study was made. However, that the percentages could change up until 2025 should be taken into consideration while reading the report.

2.3.4 Company concentration

As stated under country concentration in Section 2.3.1, HHI could be used not only between countries but also between companies within a market. HHI is thereby a good measurement to use when assessing the concentration of the raw material producing companies.

In Achzet & Helbigs (2013) overview work the definition on which companies to label as raw material producing companies is divided. Some papers only include the first step in the supply chain, the companies extracting the ore. Others also included the companies refining the raw material, which importance is validated by recent studies (Blengini et al., 2017).

Having a high concentration has historically shown to have a big impact on short-term supply risk. There are a number of cases where big actors have used their power to suppress smaller actors and gaining a dominant position in the market. However, as with the country concentration, the company concentration is not necessarily a risk by itself. Instead, there is a need to assess the concentration within each context. As an example, Achzet and Helbig (2013) assume that how the metal is traded, either through a metal stock exchange market such as the London Metal Exchange (LME), or bilateral agreements have a high effect on the liquidity of the metal. Thereby, having a low concentration in a market with a well-used metal exchange market might not be as impacted as a market traded through directly negotiated bilateral agreements.

2.3.5 Market balance

Market balance is another commonly used risk indicator, but the way to calculate it differs between the papers. In Achzet and Helbig (2013) many of the reviewed papers main focus have been on the demand side of the market, assessing the potential demand growth as an indicator for risks to the raw material supply chain. Even though many papers share a similar rationale for including the demand side; technological development creates completely new application areas for the raw material leading to rapid and big changes in demand, the approach in assessing the demand growth is quite different between the papers. Some take a more qualitative approach when assessing the impact and probability of fast demand growth (Duclos et al., 2010; H. Kara et al., 2011; U.S.

Department of Energy, 2011), while others are using a quantitative approach by estimating the demand from future technologies as add-on to current market conditions (Angerer, 2009).

However, there is one reviewed paper in Achzet and Helbig (2013) from Rosenau-Tornow et al. (2009) that tries to take a more comprehensive approach and argues that it is also needed to include how the supply side will be able to adapt to the new demand to fully understand the risk. To measure the market balance Rosenau-Tornow et al. (2009) calculates the future production capacity by adding the planned project's capacity to the current mine and refinery capacity and then compares this with the predicted growth in demand based on published market sector and economic data.

Incorporating the supply side is further validated in a more recent study from Valero, Calvo, and Ortego (2018). Historical cases have shown that prediction of high demand in the future leads to increasing prices, incentivising new exploration and production capacity development Valero et al. (2018). Thereby, a reliable model needs to incorporate predictions on the development of the production capacity. Valero et al. 2018 finalises the findings by introducing two measurements depending on which time-perspective one wants to assess. In the long-term, it will be the resources and reserves of the raw material that are in focus, while midterm assesses the production capacities ability to adapt to the increased demand. The result is:

1. **Long term**: Compare available resources and reserves with cumulative demand of the raw material
2. **Medium/short term:** Compare raw material production projections with expected raw material demand.

Calculating the market balance, i.e. oversupply or shortage, is an efficient way to highlight just how much stress that is put on the market. The result could thereby be seen as an indicator on the risk of higher prices or supply shortage for the specified raw material in a given year.

2.3.6 Commodity price

Behrendt and Scharp (2007) argue that steep increases in commodity price are a risk for companies that are dependent on the material. They argued that a price increase of 100% in the last three years should be seen as critical. In addition, (Duclos et al., 2010) argues that price increases should not *solely* be the source of commodity price risks. Instead, rapid changes in any direction, up or down, is challenging for the procurement teams of the buying companies and should be considered a risk.

There are many reasons for volatility in raw material prices. Increasing demand in combination with limited global sources of supply is key drivers for price volatility (Christopher & Holweg, 2017). However, it is difficult to predict the demand, resulting in commodity traders making anticipations to get ahead of potential price increases (Argus Media, 2020). An example of that could be price increases triggered by a governmental announcement of export taxes, leading to buyers stockpiling the material to avoid added taxes.

Further, when the prices are falling, some producers could decrease their production output. For example, the mining company Glencore chose in 2019 to close one of the biggest cobalt mines in the Democratic Republic of Congo (DRC) due to falling prices and increased projects costs, cutting several thousands of tons of the material from the market (Mining Journal, 2019). Such a reduction in supply would eventually drive up the price, thus these events create an unpredictable market where volatile changes are common.

Another aspect that could create volatility on commodity prices is according to Nassar et al. (2015) the companionality of a metal. The volatility is created by the fact that by-products often are unable to respond to rapid changes in demand, leading to that possible shortages or oversupply affects the price.

2.3.7 Climate Risk

Achzet and Helbig (2013), argues that climate changes impose risks for the raw material supply chain based on a study from Morley and Eatherley (2008). In their study of raw material supply security, they included a risk indicator that considered the vulnerability to the effects of climate change in supplying regions. This indicator takes in consideration what parts of the world that are likely to suffer from consequences of climate change, which is called climate hotspots. In Morley and Eatherley (2008) study, they have a very long term perspective of climate impact on the supply chain, since it is regions that will experience a higher *change* compared to the average that is assessed to be at risk. Thus, the effect could take decades before noticed in the supply chain.

However, already today there are regions more prone to natural disasters. Christopher and Peck (2004) describes the natural phenomenon as risks that need to be assessed due to the potential impacts it can have for the focal firm as well as firms upstream or downstream in the supply chain. Miller (1992) in turn mentions natural phenomenon such as variations in rainfall, earthquakes and hurricanes in this category. Other natural disasters such as landslides and tornadoes can also cause serious impact. If a supplier is hit by one of these phenomena it can have rippling effects throughout the supply chain and in the purchasing organization, since disruptions for a producing company can cut their supply (Zsidisin, Panelli, and Upton, 2000).

To measure the climate risk the World Risk Index (WRI) was used together with the countries market shares to get a weighted average per element. The WRI is developed by the United Nations University and describes the risk of a disaster to occur and is calculated for 180 countries (St John et al., 2019). The calculation is considering both the exposure to a natural disaster for a country, but also the country's vulnerability by assessing susceptibility, adaptability and coping (St John et al., 2019). Including both a society's vulnerability and exposure to natural disasters is what makes this index unique (Welle & Birkmann, 2015). Prior attempts to measuring the risk of disasters on a global level have only focused on the probability of natural events to occur (Welle & Birkmann, 2015).

To assess which level of WRI that could become a risk, the classification in the World Risk Report where the WRI is presented will be used. The classification can be seen in Table 1 below. That the classification starts at 0.31 and ends at 56.71 is because these are the score from the lowest and highest risk countries, found in the World Risk Report.

Table 1: *The classification of WRI as they are presented in the World Risk Report*

Classification	World Risk Index
very low	0.31 - 3.29
low	3.30 - 5.49
medium	5.50 - 7.51
high	7.52 - 10.61
very high	10.62 - 56.71

2.3.8 Non-applicable indicators

As stated in the initial text in section 2.3, not all indicators are to be deemed as relevant to all studies. In this section, the supply chain risk indicators presented in Achzet & Helbig (2013) that are not applicable to the aim and scope of this master thesis will be shortly presented with the following reasoning to why they are not needed in this particular master thesis.

The indicator *depletion time* aims to calculate how long today's known reserves will last with the current production rate (Achzet & Helbig, 2013). Thus, the approach is very static in both the demand and supply outlook. As the reality most often is more dynamic, Valero et al. (2018) argues that this indicator should only be used to get some initial indications on the state of the raw material balance. Other indicators such as the *abundance in earth's crust* and *explorative degree* try to capture a dynamic reality by presuming that the mere existence of the material in the earth's crust and investments in exploration will over time expand the known reserves. Even if all these three indicators, *depletion time, abundance in earth's crust, explorative degree,* brings interesting aspects, their effect will only be seen in the long-term perspective. As an example, Rosenau-Tornow et al. (2009) argues that the current level of *exploration degree* decides the added supply-output earliest 10-15 years ahead. With this master thesis aim to minimize uncertainties by having a short to mid-term perspective, and stay true to our industrial problem these indicators thereby is not very relevant.

A fourth indicator, *recyclability,* also measures added supply, but not from new production streams, rather how much of the used materials that get recycled Achzet and Helbig (2013). This means that only materials at the end of their life cycles are of interest. Materials with a very steep increase in demand will, therefore, experience a long lag until recycled materials make up an noticeable part of the supply. As this pattern maps well with the materials investigated in this master thesis, *recyclability* as an indicator is to be seen as superfluous.

Another indicator from Achzet and Helbig (2013) is *import dependence.* This indicator was used in three of the reviewed fifteen papers. However, what was common between these three papers were their nationalistic scope. They all reviewed raw material criticality from the perspective of a nation. Thus, they measured how dependent the particular nation was on different raw materials and how big share of that raw material that were imported compared to produced within the country. This perspective is of a higher order than this master thesis, which originates more from a company perspective. Thereby this indicator is not used in this master thesis.

Stock Keeping of resources is a strategy for companies to cope with short-term fluctuations on the market (Achzet & Helbig, 2013). In the risk identifying phase of this master thesis, we look at a five years horizon, which means that the level of stock-keeping is quite small in relation to the total demand by 2025. This combined with the short-term effect that stock keeping give is the reason for why this indicator is not further used as a supply chain risk indicator. Similar arguments could be used for the indicator *temporary scarcity*. This indicator measures the time lag between production and demand which once again is most interesting in a shorter time-perspective than the five years used in this master thesis.

Substitutability is an indicator used in the study from Achzet and Helbig (2013) to see to which extent a material can be changed to another, ranging from being substitutable, substitutable only with high expenses and not substitutable. The substitutability can allow for the ability to adapt in case of supply shortages or price increases of the primarily used raw material, thus if the material is not possible to substitute the risk is higher. However, since this master thesis only considers materials used in the battery technology for the NCA battery, the substitution of materials won't be an option until 2025 and thereby this indicator is not applicable in this master thesis.

Achzet and Helbig (2013) further, discuss the *development of production costs* as an indicator of risk. This indicator looks into how the costs for the extraction of a raw material develops. However, the data to measure this is very sensitive for the companies and therefore it is complicated to get hold of data. Therefore this indicator is not applicable for this master thesis.

The last indicator brought up by Achzet and Helbig (2013) is *risk of strategic use.* This indicator was used by letting an expert group evaluate the raw materials risk of being used in other ways than being a commodity to buy and sell, but that it could become a political or strategic instrument to be used to increase taxes or set restrictions on export. However, it is hard to obtain this data from market experts. Further, this indicator is also somewhat already captured by the country risk indicator, since that indicator considers governance performance. Thereby the risk of strategic use indicator is not going to be used in this master thesis.

2.3.9 Synthesization of Risk Indicators

In Table 2, a synthesisation of the theoretical findings is presented, showing the risk indicators used in this master thesis in column one. In column two are the boundaries presented, which describe how calculated values should be interpreted for every measured indicator. For example, if a raw material gets a score of 1 600 HHI for the country concentration indicator, the market should be considered a moderately concentrated market. All the indicators have different boundaries and are calculated separately. In the third column, the effects that the different boundaries lead to for each risk indicator is presented.

Table 2. A synthesisation of the theoretical findings from section 2.3, containing the risk indicators and its associated boundaries and corresponding effects

Risk Indicator	**Boundaries for the measured value**	**Effects**
Country concentration	Unconcentrated markets: - HHI < 1 500 Moderately Concentrated Markets: - 1 500 < HHI < 2 500 Highly Concentrated Markets - 2 500 < HHI	High concentration increases the impact of regional risks such as resource policies, while unconcentrated markets have a broader range of producing countries
Country risk	To be considered a risk if the calculated WGI < 0.59	A low WGI score infer higher risk for disruption from political instability
By-product dependency	0-100%, 0 means the material is self-sufficient and 100 means the material is completely dependent on other materials to get produced.	By-product price and availability is strongly influenced by the main-metal
Company concentration	Unconcentrated markets: - HHI < 1 500 Moderately Concentrated Markets: - 1 500 < HHI < 2 500 Highly Concentrated Markets - 2 500 < HHI	High concentration have an impact on supply as dominant actors can suppress smaller players
Market Balance	+/- 100 000 tonnes will have an impact on the market conditions	An indicator of the risks of shortages and price-spikes
Commodity price	Raw material prices that have seen an increase by more than 100% within the last 3 years should be considered as a risk.	Volatile prices makes it harder to predict prices for the procurement teams. The commodity price also affects the margin of the products
Climate risk	Very low risk: WRI of 0.31 - 3.29 Low risk: WRI of 3.30 - 5.49 Medium risk: WRI of 5.50 - 7.51 High risk: WRI of 7.52 - 10.61 Very high risk: WRI of 10.62 - 56.71	The effects of environmental disaster can have ripple effect throughout the whole supply chain as it disrupts production

2.4 Mitigation strategies

It's of importance to gather an understanding of how to handle challenges and mitigate the risks that they pose (Simangunsong et al., 2012). According to Ritchie and Brindley (2007); Braunscheidel and Suresh (2009), not having a strategy on how to mitigate risks can have a severe impact on a company's performance.

There has been a lot of previous research made to identify risk mitigation strategies in the field of risk management in supply chains for different contexts (Chopra & Sodhi, 2004; Christopher & Lee, 2004; Jüttner, Peck and Christopher, 2003; Jüttner, 2005; Manuj & Mentzer, 2008b; Miller, 1992). Within the risk management literature, Miller, (1992) defines a risk mitigation strategy as the measures a company take to mitigate potential consequences from identified risks. Talluri et al. (2013) argues that mitigation strategies fall into two main approaches, they are either building on redundancy or flexibility.

Already in 1992, (Miller, 1992) developed a comprehensive framework that outlines risk management strategies that mitigate potential risks for firms operating internationally. Millers framework has a broad perspective, with brief overviews on potential firm responses to deal with identified risks in the range from financial risk management to strategic management. Since the focus of this master thesis is in the context of the future supply of raw materials in a purchasing department perspective, there was an added need to identify risk mitigation strategies more specific for global sourcing, to pinpoint which strategies that are relevant for this master thesis. Therefore additional literature in that particular area needed to be further reviewed.

Ila Manuj (2013) has in her work studied risk management in the specific subarea global sourcing. She identified in her literature review that many of the contributions to the global sourcing risk management field cover similar concepts, but lacks a unanimous naming of the risk mitigation strategies. Summarised, the risk mitigation strategies relevant to a global sourcing supply chain found in (Chopra & Sodhi, 2004; Jüttner et al., 2003; Manuj & Mentzer, 2008a; Miller, 1992; Skipper & Hanna, 2009; Zsidisin & Ellram, 2003) are; *avoiding risks, control through vertical integration, cooperation with supply chain partners, form and time postponement, speculation, hedging through sourcing from manufacturing at multiple locations, sharing/transferring risk through contracts and increasing flexibility for responsiveness.*

In the following sections, the risk mitigation strategies deemed relevant will be presented and explained in detail, while the non-relevant strategies will have a more shallow explanation and why they are not relevant for this master thesis context.

2.4.1 Avoiding risks

Avoiding risk is a strategy used by management when the risk connected to a product or geographic market and supplier is considered to be unacceptable (Miller, 1992). By avoiding the risk, the probability of it affecting the business is driven to zero, since the company is no longer exposed to the risk at all (Manuj & Mentzer, 2008b). If the firm isn't yet committed to the product, market or suppliers the avoiding strategy constitutes of postponing the entering until better conditions are present. On the contrary, if the firm already has commitments to the product, geographic market or suppliers the avoiding strategy means that the firm needs to divest the specialized assets or end the supplier-relationships connected to the dropped operation. However, avoiding risks often comes with some sort of operating or supply and demand trade-off that needs to be considered before using the strategy (Manuj & Mentzer, 2008b).

2.4.2 Hedging through sourcing from manufacturing at multiple locations

According to (Manuj & Mentzer, 2008b) the rationale to use a hedging strategy is to create multiple options when making decisions. Within a global supply-chain business, having a hedging strategy means that the company creates a portfolio of facilities or suppliers that are globally dispersed. The suppliers and facilities should be so dispersed that a single event that leads to a disruption of some sort (e.g. natural hazard or political instability) does not affect the whole supply chain in the same magnitude or at the same time. By having multiple suppliers it is argued that the buying firm can avoid dependency on individual suppliers and thus decrease the risk of discontinuity of supply (Gadde & Snehota, 2000). However, when using a dual or multi-source strategy, the cost is most certainly higher than using a single source (Manuj & Mentzer, 2008b). Therefore, the potential benefits need to consider the disadvantages, meaning that it is most suitable in instances with high risk. Example of risks possible to hedge against is disruption, price, opportunism, quantity, quality and variability in performance (Berger, Gerstenfeld and Zeng, 2004). Diversifying by having suppliers in different geographical markets, enhances the firm's capability to respond to fluctuations in supply (Miller, 1992).

2.4.3 Sharing or transferring risk through contracts

Another strategy for reducing risks in the supply chain is with the help of specific contracts, and there are a number of different contracts that could be used. When using a fixed-price contract the supplier and buyer are responsible to handle their own risks (Zhang, Zhou and Liu, 2014). However, in the situation of a volatile environment, which often is the case for raw materials, risk-averse suppliers would then charge a risk premium in the price for their product (Zhang et al., 2014). Thereby, in many cases, there are reasons to transfer or share risks between buyer and supplier. Sharing and transferring risk is done by creating flexibility in the contracts by including clauses that state how changes in the specified risk or environment should be handled (Manuj & Mentzer, 2008b). This could, for example, be that the final price is contingent on the price index of a raw material or even as far as the specified raw material gets completely separated from the total cost (e.g. car hire + gasoline) (Zhang et al., 2014).

Finally, Zhang et al. (2014) mention Procurement Control (PC) contracts as a way to shift risks from a tier 1 supplier to the buyer. PC contracts are relevant in a multi-layered supply chain. The buyer (tier 0) deals directly with the tier 2 supplier to get the raw material needed in its tier 1 component. This is mostly done when the buyer (tier 0) possesses superior bargaining power or knowledge about the market than the tier 1 supplier (Zhang et al., 2014).

2.4.4 Cooperation with supply chain partners

Cooperation in the supply chain through joint agreements between actors is a mean to reduce risks (Miller, 1992). The main focus is to improve supply chain visibility and understanding between the intertwined actors by sharing information on exposure to risks, in many cases, a joint business continuity plan is formed (Jüttner et al., 2003).

Measures to reduce the risk include long-term agreements with suppliers, alliances or joint ventures with other companies (Miller, 1992). These methods are ways for a firm to cope with and influence their environment to have more control of unpredictable circumstances (Aaker & Mascarenhas, 1984).

In the occasion when a firm ends up with a shortage of supply for raw material, Aaker and Mascarenhas (1984) argue that a way to control the situation is to make long-term contracts for materials with the supplier. However, as argued by Gadde and Snehota (2000), a company can only be highly involved with a limited number of suppliers, since these relationships require a lot of coordination and interaction. High involvement with a supplier is often linked with single-sourcing strategies, while a lower supplier involvement with multiple sourcing (Gadde & Snehota, 2000).

2.4.5 Control through vertical integration

Vertical integration is a mean for a firm in a supply chain to increase control of decisions, processes, systems and methods. Thereby, a vertical integration strategy reduces supply and demand risks that exist when being dependent on other actors (Manuj & Mentzer, 2008b). However, to vertically integrate requires a lot of commitment from the firm in the targeted market because it changes variable costs to fixed costs (Manuj & Mentzer, 2008b), i.e. lowering flexibility.

Further, Miller (1992) emphasises the need to evaluate the context of which a supply chain is operating in before deciding to vertically integrate. As an example, if a company is faced with an unstable environment (e.g. natural hazards, political instability), vertical integration actually increases both the probability and magnitude of a loss, due to the higher exposure.

2.4.6 Non-applicable risk mitigation strategies

Even though the literature review focused on literature within the global sourcing of risk mitigation strategies, not all strategies are applicable to our specific context and industrial problem. The risk mitigation strategies listed in the introduction to Section 2.4 that are not applicable in this master thesis will be shortly presented here, with a following motivation on why they are not chosen.

The two strategies *Form and time postponement* and *Speculation* are strategies opposed to each other. The postponement strategy is done by delaying the commitment of resources to increase flexibility. This could be done either by form (delaying manufacturing, packaging, assembly) or time-postponement (delaying movement of goods up until customer order) (Zinn & Bowersox, 1988). Speculation, on the other hand, is a strategy where changes in form and movement of goods should be made as early as possible to minimize cost (Manuj & Mentzer, 2008b). Concrete examples of speculation strategies include forward buying of raw material, finished goods or early commitment to the form of a product. Both the *form and time postponement* and *speculation* strategies are mitigating demand risk (Manuj & Mentzer, 2008b). Since all of the identified risks in this master thesis are in the part of the supply chain before Volvos involvement, strategies relevant to this master thesis needs to mitigate supply risks. Thus, neither of the postponement or speculation strategies are of relevance for this master thesis.

The strategy *increasing flexibility for responsiveness* highlights the importance of fast responses to the market in today's global and competitive marketplace (Skipper & Hanna, 2009). In the context of responsiveness, this strategy is useful when the ability to respond more quickly than competitors could result in putting the company in a competitively advantageous position (Skipper & Hanna, 2009). This strategy is useful in a context where a rapid variated shift in demand will have a big impact on company performance, e.g. seasonal fluctuation of demand or for products with short technology and product life cycle. Since this master thesis has a five-year time perspective considering raw material for NCA lithium-ion batteries, this strategy will not be relevant for this master thesis.

3 Methodology

This chapter describes how the master thesis has been structured and performed. The first section, Section 3.1, describes the research design and how the master thesis has been structured together with a shorter introduction on the different phases of the workflow. Section 3.2-7 is further presenting each phase in more detail.

3.1 Research design

To be able to achieve the purpose of this master thesis, it began with an initial pilot-study phase. In the pilot-study phase, the aim was to better understand Volvos problem, to stipulate the two research questions that this master thesis was to answer. The pilot study-phase constituted of planning the work of the project, in which a research design was formed, which according to Bryman and Bell (2011) provides a framework for the collection and analysis of data. Thus, to have a clear view of what phases that were needed, a work flow chart was created, which is presented in Figure 1.

The workflow of this project was mostly executed sequentially because the findings and results from each of the phases gave direction on what work needed to be done in the following phase. Because of this dependency, it would have been hard to execute multiple phases simultaneously.

In short, the first phase was *framing of the problem* which resulted in a clear picture of the problem that was to be solved and thereby gave direction to which literature to review. The result from the *creation of framework* was then a synthesisation of the reviewed literature, which acted as a framework on what type of data that needed to be collected to answer our research questions. After this, the *gathering of market data* began which resulted in a data collection comprehensive enough that it was possible to use that data to identify the risks of the studied supply chains. Identifying the risks was then done by analysing the data in the *identify the risks*-phase. The identified risks then provided a basis on what type of risk mitigation strategies that were relevant to include in the theory-chapter. The relevant theory on risk mitigation strategies was collected during the *Risk mitigation strategies*-phase. Lastly, an analysis of what effects the risk mitigation strategies would have on the identified risks for each of the studied raw material supply chains was performed. This was the final phase that is called *Applying the Risk Mitigation Strategies*.

There is one exception to the sequential nature of this master thesis methodology. Information from the gathering of the market insights sometimes had to be updated even after its planned phase was ended. The reason for this was that it was happening a lot in the battery industry over the thesis time-frame, there was constantly new information, new investments and new deals made. To ensure that this master thesis was as relevant as it could be when finished, the market insights got updated in parallel with the remaining phases.

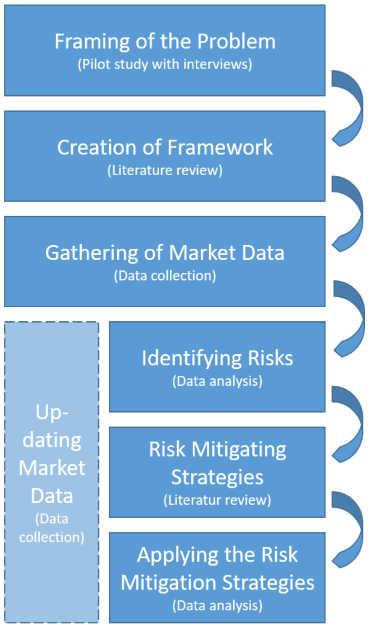

Figure 1: An illustrative figure of the master thesis *workflow*

3.2 Framing of the problem

The industrial stakeholder was as described in Chapter 1 consisting of a raw material team of 12 people gathering business intelligence about materials used in their current product offerings. Since Cobalt, Nickel, Lithium and Graphite was new materials to follow for the team and has not been part of the day to day work, meant that their broad view of the issue for investigation in this master thesis needed to be further specified. For example, information such as what battery technology Volvo is going to use and in what time perspective, the included raw materials, how the procuring process for batteries looks today, details about the Samsung SD partnership and general approach for the EV-transition needed to be collected. There was also a need to understand what intelligence could be gathered in-house and what needed to be collected externally. To answer these questions, an initial pilot-study was performed.

The pilot-study had two aims, (1) frame the problem by establishing the appropriate research questions, (2) create a plan for the remaining work on what needed to be performed to answer the research questions. To work towards this purpose, a number of interviews were conducted. According to Gill, Stewart, Treasure and Chadwick (2008), interviews are appropriate when little is known about the studied topic and when detailed insights are needed from individual participants. When conducting interviews there are multiple ways to structure the interview-format. Frequently used ones are structured, semi-structured or unstructured interviews (Bryman & Bell, 2011). The interviews in this master thesis were held as semi-structured, which means that the interviewer prepares a number of key questions that define the areas to be explored (Bryman & Bell, 2011). The sequence of the questions can vary and does not need to follow an interview schedule. In addition, it allows the interviewer or interviewee to diverge to be able to address an idea or response in more detail, and the interviewee has great freedom in how to reply (Bryman & Bell, 2011; Gill et al., 2008).

This meant that questions were prepared for each interview to ensure that it headed into the identified needed field for each of the interviews. The semi-structured interviews offered us to be flexible and explorative during the interviews to change or add new directions during the interview itself by adding follow-up questions. Given the exploratory nature of this phase of the study it was highly valuable.

In total five semi-structured interviews were conducted with five individuals. Four of them within Volvos organization and one external. The internal candidates were chosen upon recommendation from the raw material team and in some cases from the interview candidates themselves. The external candidate was found while searching online for external expertise about lithium-ion battery compositions, as a source to fill knowledge gaps. The interviews were to a majority held two-on-one with both the authors present and the interviewee. To make sure that information from the interview was collected properly, one author was responsible for asking the question while the other one took notes. After each interview, both authors discussed the notes to make sure everything had been collected to lastly add additional notes. Table 3 consists of the interviewees' position as well as in what spectrum they possess knowledge.

Table 3: *List of interviews including the interviewees positions and what information they had insights on*

Position:	**Insights in information regarding:**
Associate Professor - Chalmers	Predicted and commonly used lithium-ion battery composition in the EV-industry.
Raw Material Specialist - Volvo	Knowledge on how the raw material department work, and (even though limited) possess information on the raw material markets around lithium-ion batteries.
Alternative Drivetrains Engineer - Volvo	Have knowledge on how different anode chemistries affects the characteristics, e.g. life-span and performance, in the lithium-ion batteries evaluated by Volvo.
Project Buyer Electromobility - Volvo	The buying process of batteries from Samsung SDI and current contract status.
Cost-engineer - Volvo	Break-down all the cost-items on the batteries bought from Samsung SDI. Thereby possessing knowledge on how big part of the cost that raw material constitutes.

After this process, the information collected served as the foundation to know what areas that were of interest to further collect data from. From this foundation, two research questions were formed, with an appropriate planed working process to be able to answer them.

3.3 Creation of Framework

According to Bryman and Bell (2011) it is of importance to conduct a literature review to provide a basis for the research. Bryman and Bell (2011) continue to argue that the literature review also informs on how to collect data and thus enables an informed analysis of data. To gain knowledge and information about the topics relevant for this master thesis in a structured way, a five-step method developed by Bryman and Bell (2011) presented in Figure 2 was used.

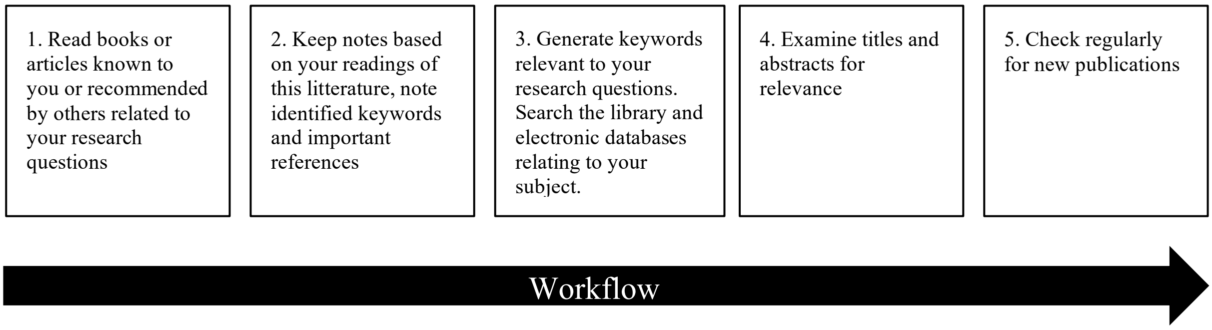

Figure 2: Bryman & Bell five-step method for literature review.

The model indicates the importance of having a structured way of working to get the most out of the literature review as well as keeping track of relevant literature found. It also made it easier to find new relevant literature, by first (1) reading articles recommended by others or know on beforehand. Having identified important keywords and interesting notes (2) the next step (3) was to generate keywords relevant for this master thesis, to find relevant articles. The fourth step (4) was to examine the titles and determine how usable they are for the master thesis and if they should be kept. (5) was to check regularly for new publications which was an important step for this master thesis, since its a field that develops quickly.

The aim of this literature review was to identify previously made research on supply risk indicators, to be able to form a framework that was used to make a risk assessment for the identified raw materials. Thus the literature review had a focus on finding research that has identified supply chain risk indicators that can be applied to this master thesis specific context.

To get hold of academic articles and relevant studies electronic databases such as Chalmers Library and Google Scholar was used. The used search words were, but not limited to, the following: supply chain risks, supply risks, supply risk indicators, raw material criticality, EV batteries, overall sourcing strategies of important raw materials and lastly the value chains of cobalt, nickel, lithium and graphite respectively.

Sources were also found by looking in the bibliographies from initial references, which Bryman and Bell (2011) describes as an effective way to find further relevant sources of information. The method was used by letting academic journals serve as a guide to finding additional sources. Also, the function in google scholar “cited by” was used to find additional sources to strengthen or get different angles on certain areas in the theoretical framework. This was for example used to see how authors had interpreted frameworks of raw material risks from one main source.

3.4 Gathering of market data

The framework created from the literature review in Section 2.3 served as the foundation on what data needed to be collected to answer research question 1. As Section 2.3 describes how to calculate and assess the identified supply chain risk indicators, it highlights the needed data points. To give an illustrative example, to calculate the country risk, data points on the countries market share and their WRI scores was needed. Identifying data points were repeated for every risk indicator.

The result was a list of data points that were to be collected for every company active within the mining and refining level of Nickel, Cobalt, Lithium and Graphite production. The list included information on companies’: name, country of origin, country of operations, the country’s corresponding WRI and WGI score, produced product, production capacity and expansion plans up until 2025. These data points served as the lowest level of data to be presented in the report. However, some supply chain risk indicators required aggregation of multiple data points, such as, how much production capacity a certain country possesses. Which was calculated by taking all active companies in a certain country and added the total production capacity for all companies together. In addition, not only supply-side data were needed, but also demand predictions.

The data gathering started by identifying which companies that operated in the mine and refining level of nickel, cobalt, graphite and lithium. The initial step was to use internal reports from Volvo that included significant raw material companies in the EV-battery industry. These companies were filtered into the ones that were active in producing the studied materials, by investigating the respective company website or their organisational documents. Further, other companies were added by reading market reports published by raw material markets specialist firms such as Wood Mackenzie, FastMarket, MetallBulletin, S&P Global, Roskill and Argus Media.

The collection of data for the following data points: country of origin, country of operations, produced product, production capacity, demand predictions and expansion plans up until 2025 was made through a three-layer method, illustrated in Figure 3 and further explained in the following text below.

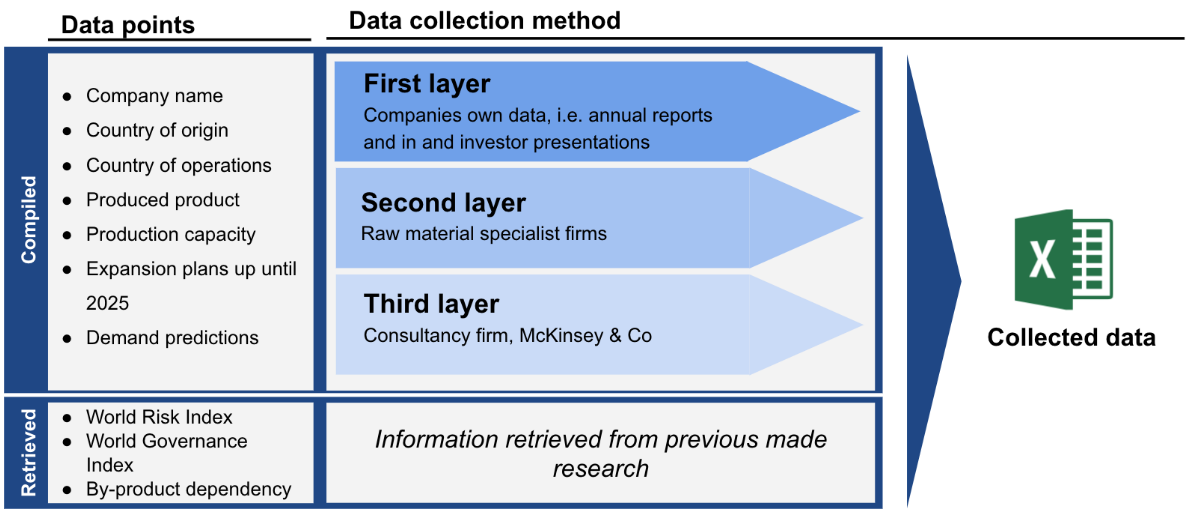

Figure 3. Illustration of the method for data collection.

First layer: In first hand data was collected by using documents produced by the identified companies themselves, such as their annual reports and investor presentations, which according to Bryman and Bell (2011) can be used as a valuable source of organizational information. The organizational documents are also closest to the source of the data, which increases the probability of accurate data.

However, depending on which country the company origins from, there is more or less transparency of internal company information provided to the public. This led to the difficulty of gaining access to organizational documents from some companies. With this master thesis limited resources, in combination with the cases where public-domain documents are not available, there was a need to extract information from other sources as well.

Second layer: The raw material market specialist firms mentioned above does not only provided insights on which companies that are active in the supply chains, but they also possess extensive intelligence in the fields of metals, battery raw materials, mining research and chemicals. By using these sources, information gaps could be filled. The leading information providers in this field are Wood Mackenzie, FastMarkets, Metal Bulletin, S&P Global, Roskill and Argus Media who all provide data with market-reflective insights. The data possible to gather from these sources were, but not limited to, production capacities, supply and demand forecasts, drivers influencing price and active companies in the market.

Third Layer: The third layer of data was collected from the consulting firm McKinsey & Company, who in their work provides information on their take on how the supply and demand situation will evolve in the EV-market. The purpose of this layer was to get demand predictions from not only raw material market specialists, but also firms with broader expertise which enables a more holistic perspective on the markets. The information from this layer was found in consultancy reports accessible from the company's website.

The WGI and WRI are, as mentioned in Section 2.3.2 and Section 2.3.7, indexes created by World Bank respectively United Nations University. These indexes are updated every year and are presented publicly in the creators' websites. The information on each country's indexed score has been collected directly from these sources. Since these sources do not predict indexes for the future, the most recent year available was used which was 2019. Therefore an assumption was made that the numbers will be similar for the year 2025. This could, however, be a source for inaccuracy in the results.

The by-product dependency was collected directly from Nassar et al. (2015) work mentioned in Section 2.3.3. This was since their work made comprehensive calculations on a number of different raw materials by-product dependency, including the ones needed in this master thesis. Their calculations are made with data they found trustworthy for the year of 2015. Since the data could change until the year 2025, the numbers should be considered a potential source of error in the results part of the by-product dependency in this master thesis. However, Nassar et al. (2015) explain that inertia from within the industry makes the results credible for several years.

All of the gathered data for each material were stored in an excel file to keep track of the collected data points. This enabled us to easily calculate the needed data points for all the identified supply chain risk indicators by combining and aggregating the different collected data, but always making sure the original data set were kept unformatted.

As the data in expansion plans of production capacity was built on predictions, an uncertainty arose. The plans to expand might take a longer time to realise and the outcome could be different from expectations. To keep the report credible, the data collection had a limitation to only include expansion plans with a set commercialization date as this indicates secured financing and detailed construction plan.

3.5 Identifying risks

The aim of the identifying risks phase was to answer our research question 1. All supply chain risk indicators needed to be calculated for the supply chains of Cobalt, Nickel, Lithium and Graphite respectively. This meant that there in total was twenty-eight results needed since there were four materials with seven risk indicators each to calculate.

The calculations was made by using each risk indicator theory from the literature review in Section 2.3. The theory served as a guide on how to calculate the risk and by following the theory, a result could be calculated for every indicator. The data needed for the calculations was taken from the excel file, which had been set up by using the data collection method in Section 3.4.

The results from all the calculations were examined in relation to the specific risk indicator boundaries presented in Table 2 in Section 2.3.9. The boundaries were used to be able to tell whether or not the calculated figure is indicating a risk or not. This gave a first notion on which risks that exist in each of the materials supply chains.

In addition, converging the data and having a holistic overview is important to ensure that the researcher is not focusing too much on the individual parts of the case, according to Baxter and Jack (2008). Thereby, all the supply chain risks indicators in the model were analyzed together to get an overview of how the different risks affect each other. As an illustrative example, if one of the supply chains was highly concentrated *and* had a high country risk, these two risks enforced each other. By making this analysis, it was possible to give all the indicators for all materials a value from low to high risk based on how much risk that was indicated from the results of the calculations.

To make a holistic view on how all the indicators affect the different supply chains for all materials, a table was made to synthesise the findings. This table also served as an easily readable summary of the findings and overview of the answer to research question 1. The table can be found in section 5.5.

3.6 Risk Mitigation Strategies

Once the risks was identified in the supply chains of Cobalt, Nickel, Lithium and Graphite, research question 1 had been answered. The next step was to perform a second literature review, this time on risk mitigation strategies. The identified risks gave direction on which risk mitigation strategies that were relevant to collect. The findings from this literature review are presented in the theory chapter (section 2.4).

To get hold of academic articles and relevant studies, the same method as in Section 3.3 was used. Information was mostly found through electronic databases such as Chalmers Library and Google Scholar. Additional sources were also found by looking into the bibliographies from initial references, which is an effective method according to (Bryman & Bell, 2011). To get an even further depth of potential literature, the *cited by* function in Google Scholar was used, which can be effective to see how other reports have used and developed the cited articles.

To get a broad view of risk mitigation strategies, the initial steps in the literature review was to find sources with a holistic perspective to provide a foundation of literature in the area. The search words were the following but not limited to: Supply chain risk management, risk mitigation, and risk management.

The next step was to find more specific and pinpointed articles in the field of mitigation strategies in a raw material procurement perspective. Here the search words were the following, but not limited to: global supply chain risk management strategies, sourcing risk mitigation strategies, raw material sourcing risk strategies.

3.7 Applying the Risk Mitigation Strategies

The aim of the last phase of this study was to answer research question 2, which constituted of two steps.

(1) Examining how the identified risk mitigation strategies affect all of the identified supply chain risk indicators. As stated by Miller (1992), dealing with risks isolated from each other will not give a comprehensive view of which risk exposures that will be relevant for firm strategies, compared to if many types of risks are assessed jointly. Therefore the analysis was made by using the theoretical findings on individual risk mitigation strategies, applying them on the different risk indicators and then evaluate the effect, whether it increase, decrease or not affect the risk indicator at all. The effects each strategy have on the identified risks were then synthesised in Table 38 to illustrate the findings in a more easily accessible way.

(2) The second step was to identify which risk mitigation strategies that are suitable to use in which supply chain of Nickel, Cobalt, Lithium and Graphite. The risk mitigation strategies have pros and cons, meaning that they most often decrease some of the risks, while other is increased. As an example, one strategy could raise the risk for country and company concentration, but mitigate the risk of market balance. Then that strategy would be suitable to use only in supply chains with already low risk of country and company concentration. These kinds of discussions were performed to identify which risk mitigation strategies that are suitable to use based on what risks that exist in the supply chain of Nickel, Cobalt, Lithium and Graphite.

3.8 Research quality

Evaluating the quality of a research is important to assess the trustworthiness of the study (Bryman and Bell, 2011). The research quality can be divided in reliability, validity and generalizability (Bryman and Bell, 2011).

The validity describes whether or not the results of the study actually measure what they are supposed to measure (Bryman and Bell, 2011). In this master thesis, the risk indicators used to identify supply risks for raw materials as well as the risk mitigation strategies is what needs to have good validity. If the wrong indicators are used, it might not measure correctly what risks that best assess what can cause disruptions in supply of raw material to lithium-ion batteries. As well, relevant risk mitigation strategies to address them might not really lower the risks. To cope with this, a thorough literature review was conducted. This literature review showed that there are several authors that have identified supply chain risk indicators (Miller, 1992; Simangunsong, 2011; Davis, 1993); Christopher and Peck, 2004) as well as risk indicators specifically for raw materials where Achzet and Helbig (2013) overviews 15 research papers using risk indicators for supply risk for raw materials. Regarding the risk mitigation strategies, (Chopra & Sodhi, 2004; Christopher & Lee, 2004; Jüttner, Peck and Christopher, 2003; Jüttner, 2005; Manuj & Mentzer, 2008b; Miller, 1992) describes risk mitigation strategies for supply chains in general and (Chopra & Sodhi, 2004; Jüttner et al., 2003; Manuj & Mentzer, 2008a; Miller, 1992; Skipper & Hanna, 2009; Zsidisin & Ellram, 2003) discuss risk mitigation strategies for global sourcing. Thereby we believe that the risk indicators and risk mitigation strategies gathered from the literature study and used in this master thesis are validated and actually measures what is intended to measure.

Reliability describes whether it is possible to repeat the study and get the same results. It tells that it is of importance to use the same method for data collection, when trying to redo the study. Thereby we have in this master thesis created and used a structured data collection method. This method was presented in Section 3.4, Figure 3, and describes how different data for different data points have been collected.

Further, reliability can be increased by using triangulation (Bryman and Bell, 2011). This means that several sources is used in order to back up for statements. The triangulation will improve the confidence in findings by cross-checking measures with other sources measurements on data points (Bryman and Bell, 2011). In this master thesis, triangulation was made for predictions in order to make valid predictions on data points such as demand predictions, production capacities and future expansions by 2025. By using the three layer method, it was possible to find predictions made on a general level (less specific and detailed compared to this master thesis) from other authors to see the if the calculations in this master thesis are way off or in similar ranges. Thereby the collected data have been critically examined by ourselves during the collection, by overviewing the data until it has been cross-checked with other sources, in accordance with the three layer method.

Bryman and Bell (2011) also talk about the generalizability of the study, which means if the results can be used in other occasions than for the particular study. In this case, there is generalizability since the risk indicator framework created and presented in Section 2.3.9 as well as the risk mitigation strategies presented in Section 2.4 can be used for other materials than the ones studied in this master thesis. The generalizability is achieved by including relevant and potential indicators and strategies for raw materials in general and applying them to our specific materials, which makes the frameworks usable for companies wanting to investigate other raw materials. The master thesis is thereby generalizable in the sense of looking into other raw materials. However, if there is an interest to investigate raw materials with a more long-term perspective (beyond 2025), there are risk indicators not included in this master thesis that could be of interest. This could, for example, be recyclability and substitutability, which can play an important part for raw material supply beyond 2025.

The data presented secure generalizability since it clearly describes what kind of data that has been needed and used in order to conduct the research. The reader thereby can understand what is presented and use the data in the correct way, and apply it to other contexts.

4 Presentation of empirical data

In this chapter, all supply chain risk indicators from the literature review in Section 2.3 are calculated, aggregated and presented for Cobalt, Nickel, Lithium and Graphite respectively. All calculations are made in accordance with the theory from Section 2.3, the data was collected and saved in accordance with the method in Section 3.4. The results are presented below, divided firstly per material, then subdivided per the seven supply chain risk indicator, i.e., (1) country concentration, (2) country risk, (3) by-product dependency, (4) company concentration, (5) market balance, (6) commodity price and (7) climate risk.

4.1 Supply chain risk indicators for Cobalt

In this section, all supply chain risk indicators are calculated, aggregated and presented for cobalt. As mentioned in Section 2.2.1, there are two steps in the initial supply chain of cobalt production, mining and refining. As both steps are important for the supply of cobalt to lithium-ion batteries, there is a need to make calculations on both steps, on the following applicable indicators: country concentration, country risk, concentrations of raw material producing companies and climate risk. The result for each step is presented separately to identify if there is a potential risk which only occurs in one of the production steps.

By-product dependency, market balance and commodity price is not affected by the split since they only consider either the extracted ore or the finished product.

4.1.1 Country concentration for Cobalt

The initial step of the cobalt production is the mining and extraction of the cobalt ore. In Table 4 data from the excel file is presented. Historically most of the production has been in the Democratic Republic of Congo (DRC), which are where all the biggest mines are located. It seems like this will stay true up until 2025 as well as most of the expansion plans are for mines in DRC. This dominance from one country creates a highly concentrated market which scores a 6 836 on the HHI.

Table 4. Cobalts mining step's production capacity by 2025 aggregated per country, with the corresponding market share and country concentration (HHI)

Country	Prod. cap. [tonnes]	Market Share	HHI
DRC	164 870	82.44%	6 797.09
Australia	6 944	3.47%	12.06
Madagascar	5 600	2.80%	7.84
Russian Federation	5 000	2.50%	6.25
Philippines	4 100	2.05%	4.20
Papua New	3 275	1.64%	2.68

Guinea			
Canada	3 100	1.55%	2.40
New Caledonia	2 000	1.00%	1.00
Finland	2 000	1.00%	1.00
Cuba	1 688	0.84%	0.71
Morocco	1 400	0.70%	0.49
Total HHI			**6 835.73**

After the extraction of the ore there is a need to refine the cobalt to the right chemistry blend before it is ready for the cell manufacturers. As can be seen in Table 5, no refining is made in DRC, which were the country where most extraction of the ore were made. Instead, China is the dominant country in the refining step. To lessen the dependence on one country there are a number of new refining initiatives outside of China, with Umicore's refinery in Finland being the biggest. The result is an HHI-score of 4 415, which is still well above the 2 500 threshold of a concentrated market found in the literature.

Table 5. Cobalts refining step's production capacity by 2025 aggregated per country, with the corresponding market share and country concentration (HHI)

Country	Production capacity [tonnes]	Market Share	HHI
China	111 600	65.13%	4 242.19
Finland	17 000	9.92%	98.44
Zambia	6 800	3.97%	15.75
Australia	6 344	3.70%	13.71
Madagascar	5 600	3.27%	10.68
Russian Federation	5 000	2.92%	8.52
Norway	4 700	2.74%	7.52
Japan	4 500	2.63%	6.9
Indonesia	4 000	2.33%	5.45
Canada	3 800	2.22%	4.92
Morocco	2 000	1.17%	1.36
Total HHI			**4 415.44**

4.1.2 Country risk for Cobalt

The country risk for the mining step is very high. The combined HHI and WGI for the total market at this level is -1.12, which can be seen in Table 6. The main contributor to this low score is the Democratic Republic of Congo, as they have both a very high market share, but also a very politically unstable country. For DRC, all six aspects measured in the World Bank's WGI are below -1.4, with political stability even being as low as -2.12.

Table 6. The countries mining Cobalts market share by 2025 together with their 2018 country risk (WGI)

Country	Market Share	WGI
DRC	82.44%	-1.66
Australia	3.47%	1.58
Madagascar	2.80%	-0.75
Russian Federation	2.50%	-0.64
Philippines	2.05%	-0.33
Papua New Guinea	1.64%	-0.58
Canada	1.55%	1.59
New Caledonia	1.00%	N/A*
Finland	1.00%	1.76
Cuba	0.84%	-0.46
Morocco	0.70%	-0.30
Weighted WGI		**-1.12**

*New Caledonia is not a territory measured by United Nation University in the World Risk Report

The refining process of Cobalt relies heavily on countries with a negative WGI score, which is presented in Table 7. The market share from these countries is together almost 80% where China is the main contributor. In the measured six aspects in the WGI. China has a negative score on five out of six indicators, where *voice and accountability* are the lowest of -1.45 and *Government effectiveness* is the only one above zero (+0.48).

Table 7. The countries refining Cobalts market share by 2025 together with their 2018 country risk (WGI)

Country	Market Share	WGI
China	65.13%	-0.31
Finland	9.92%	1.76
Zambia	3.97%	-0.36
Australia	3.70%	1.58
Madagascar	3.27%	-0.75
Russian Federation	2.92%	-0.64
Norway	2.74%	1.77
Japan	2.63%	1.34
Indonesia	2.33%	-0.13
Canada	2.22%	1.59
Morocco	1.17%	-0.3
Weighted WGI		**-0.11**

4.1.3 By-product dependency for Cobalt

Cobalt is recovered as a companion to an extent of 85% of global production. In the cases when cobalt is an companion, it is dependent on either nickel or copper. In 50% of global cobalt production it is dependent on nickel and 35% of global cobalt production it is dependent on copper production. According to (van den Brink et al., 2020) cobalt production had a value of USD 3.5 billion, while copper had a value of USD 97 billion and nickel a value of USD 20 billion, thus the value from the cobalt production is quite insignificant compared to the host metals.

4.1.4 Company concentration for Cobalt

Most production in the DRC is owned by foreign companies. As can be seen in Table 8, Glencore is the biggest one, which owns two of the biggest cobalt mines in the DRC. Other big companies operating in DRC are Chemaf (UAE), CMOC (China), ERG Congo (Netherlands), Wanbao (China) and Zhejiang Huayou Cobalt (China). The market concentration is calculated to an HHI score of 1 028, which is to be seen as an unconcentrated market.

Table 8. Cobalt mining step's capacity by 2025 presented per company, with the corresponding market share and company concentration (HHI)

Company	Prod. Cap [tonnes].	Market Share	HHI
Glencore	41 644	23.90%	569.35
Chemaf	22 200	12.70%	161.80
CMOC	14 960	8.60%	73.47
ERG Congo BV	14 000	8.00%	64.35
Wanbao	9 750	5.60%	31.21
Zhejiang Huayou Cobalt	9 000	5.20%	26.59
Gecamines	7 660	4.40%	19.26
Nornickel	7 000	4.00%	16.09
Pengxin	7 000	4.00%	16.09
Sumitomo Metal Mining	5 312	3.10%	9.68
Jinchuan	5 070	2.90%	8.44
Vale	5 100	2.90%	8.54
Nanjing Hanrui	4 600	2.60%	6.95
China Nonferrous Metal Mining Company	4 080	2.30%	5.47
MCC	2 784	1.60%	2.54
Managem Group	2 400	1.40%	1.89
Zijin Mining Kolwezi	2 400	1.40%	1.89
Korea Resources	2 257	1.30%	1.67
Sicomines	2 000	1.10%	1.31
Sherrit	1 516	0.90%	0.75
IGO Limited	1 000	0.60%	0.33
General Nickel Company	844	0.50%	0.23
Mitsui & Sojitz	930	0.50%	0.28
Ni Asia	410	0.20%	0.06
Cobalt 27	282	0.20%	0.03
Government of Papua New Guinea	210	0.10%	0.01
Total HHI			**1 028.29**

As seen in Section 4.1.1, a lot of production in the refining step comes from within China. But when examining the supply chain on a company level, which is seen in Table 9, the supply is spread across multiple companies. Outside of China, the biggest producers are Umicore, Glencore, SMM and Nornickel. Together the market gets an HHI-score of 1 142, which is an unconcentrated market.

Table 9. Cobalt refining step's capacity by 2025 presented per company, with the corresponding market share and company concentration (HHI)

Company	Prod. Cap.	Market Share	HHI
Zheijang Huayou	33 000	19.26%	370.93
Jiangsu Cobalt Nickel	31 000	18.09%	327.33
Yantai CASH	23 600	13.77%	189.71
Jinchuan Group	16 000	9.34%	87.20
Umicore	15 000	8.75%	76.64
Glencore	7 944	4.64%	21.50
Sumitomo Metal Mining	7 171	4.19%	17.52
Nornickel	7 000	4.09%	16.69
ERG Congo BV	6 800	3.97%	15.75
Pure Minerals	3 100	1.81%	3.27
Jinyuan	3 000	1.75%	3.07
Sherrit	2 572	1.50%	2.25
Guangxi vinyl	2 500	1.46%	2.13
Jiayuan	2 500	1.46%	2.13
Korea	2 257	1.32%	1.73
Managem Group	2 000	1.17%	1.36
General Nickel	1 900	1.11%	1.23
Tsinghan	1 000	0.58%	0.34
GEM	1 000	0.58%	0.34
CATL	1 000	0.58%	0.34
Huayou	1 000	0.58%	0.34
Total HHI			**1 141.79**

4.1.5 Market balance for Cobalt

As seen in Figure 4, both the mining and refining step of the Cobalt production will have similar production capacity by 2025, almost 180 000 tpa.

In the mining step, there's uncertainty regarding the artisanal and small-scale mining (ASM). In 2019 it is estimated that ASM accounted for 22 500 tonnes of cobalt production (Sovacool, 2019). There are numerous organisations and media coverage, such as Amnesty, The Guardian and Aftonbladet, that highlights the bad conditions the artisanal miners have to face in their work of extracting ore containing cobalt (Amnesty International, 2016; S. Kara, 2018; Lindberg & Andersson, 2019). Ever since these conditions got highlighted, pressure has increased to stop, or at least minimize cobalt origin from these small-scale operations into the global market.

However, Sovacool (2019) published a research with the aim to give a more multi-layered view of the artisanal mining community in the DRC. In their research, they emphasise that there are now around 100 000 people in DRC dependent on artisanal mining as their income. With lowered ASM, a lot of problems occurs such as unemployment, corruption and choked revenues to the communities and municipalities. The people most affected will be refugees and orphans.

On the other hand, increasing the ASM production capacity results in other problems such as more child labour, more landslide and other accidents, bad effect on local ecosystems and overall an even deeper dependency on mining as a source of income (Sovacool, 2019). Thereby it is hard to anticipate the development of the ASM and how it will contribute to the total production capacity of cobalt up until the year of 2025.

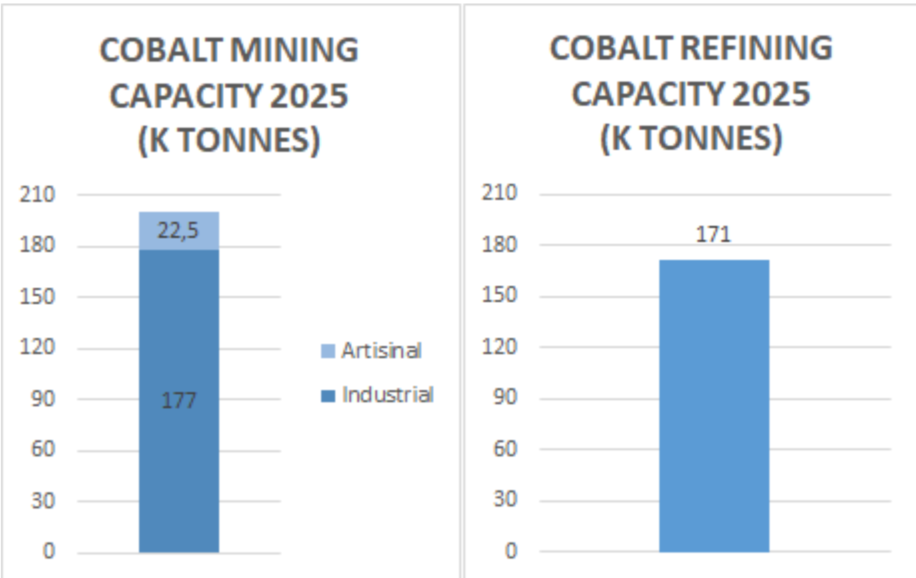

Figure 4. Global production capacity for Cobalt's mine and refining step by 2025, with ASM production separated.

When assessing the market balance, two scenarios were created with one scenario including artisanal mining production capacity and one scenario not including. In the scenario including ASM, the production level of 22 500 tonnes cobalt is assumed to stay steady from 2019 to 2025.

To fully assess the market balance, there is also a need to estimate the demand side for 2025. Due to the complexity of doing such an estimate five years in advance, demand-figures have been collected not only from internal reports on Volvo but also an external report from McKinsey.

The result from adding the supply and demand side together can be seen in Figure 5. The left graph includes the controversial artisanal mining production while the right graph excludes the same. In three out of four scenarios, the cobalt market will face a deficit in 2025. It is only if the internal Volvo predictions hold true combined with a continued supply from ASM that the supply is higher than the demand resulting in a surplus on the market.

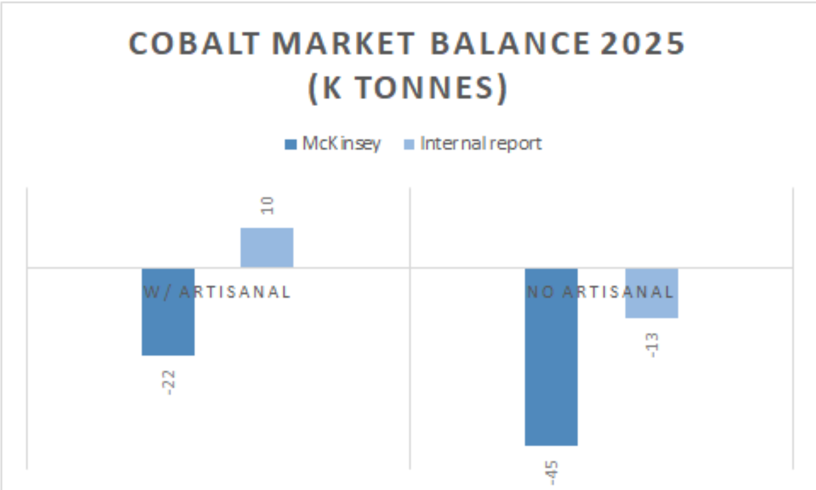

Figure 5. The supply and demand balance by 2025 for cobalt.

4.1.6 Commodity price for Cobalt

The cobalt spot price saw a tremendous increase in the whole year of 2017 up until its peak in march 2018, as can be seen in Figure 6. During this time period, the price went from 22 000$/tonne to almost 95 000$/tonne, which equals an increase of 332%. Since then, the price has quickly dropped to levels close to the start of 2017 and then stabilised for the last year around 30 000$/tonne. Still, these heavy volatility is to be seen as a risk factor according to the literature.

Figure 6. Price evolution of Cobalt futures on the LME in USD per tonne since 2017.

4.1.7 Climate risk for Cobalt

The mining step of the cobalt supply chain has a weighted WRI-score of 8.74 which is within the classification of a *high risk*. In Table 10, all cobalt producing countries in the mining step, their market share and WRI score is presented, as well as the weighted average WRI. The main driver of the score is the DRC, which have a market share of 82.44%. The DRC has *low* exposure to natural disaster events, but when it hits, the country has a *very high* vulnerability which makes them get a *high* WRI of 8.8.

Table 10. Cobalt's mining steps market share per country by 2025 together with their 2018 climate risk (WRI)

Country	Market Share	WRI
Papua New Guinea	1.64%	22.18
Philippines	2.05%	20.69
Madagascar	2.80%	10.49
Congo. Dem. Rep.	82.44%	8.8
Morocco	0.70%	5.83
Cuba	0.84%	5.7
Australia	3.47%	4.49
Russian Federation	2.50%	3.52
Canada	1.55%	3.03
Finland	1.00%	1.94
New Caledonia	1.00%	N/A
Weighted WRI		**8.74**

The refining step of cobalt passes through several countries with a high risk of disaster. However, the high market share from China lowers the WRI to a weighted average of 5.61, which is just over the *medium* classification. In Table 11, all cobalt producing countries in the refining step, their market share and WRI score is presented, as well as the weighted average WRI. The Chinese score is divided through a *medium* exposure but *low* vulnerability.

Table 11. Cobalts refining step market share per country by 2025 together with their 2018 climate risk (WRI)

Country	Market Share	WRI
Indonesia	2.33%	10.58
Madagascar	3.27%	10.49
Japan	2.63%	9.19
Zambia	3.97%	7.83
China	65.13%	5.84
Morocco	1.17%	5.83
Australia	3.70%	4.49
Russian Federation	2.92%	3.52
Canada	2.22%	3.03
Norway	2.74%	2.34
Finland	9.92%	1.94
Weighted WRI		**5.61**

4.2 Supply chain risk indicators for Nickel

In this section, all supply chain risk indicators will be calculated, aggregated and presented for nickel. As mentioned in Section 2.2.2, the nickel ore extracted and the end product bought by lithium-ion battery manufacturers is produced at the same production site. Thus, there is only a need to collect data from one supply chain step. Further, not all nickel produced is suitable to use in the EV-batteries. Thereby, only data points from companies producing nickel suitable for EV-batteries have been collected.

4.2.1 Country concentration for Nickel

As mentioned in Section 2.2.1, since not all Nickel produced is suitable to use in the EV-batteries, thereby mapping of the production is only considering Class 1 nickel and nickel produced through HPAL. As seen in Table 12, Russia and Canada are the two biggest countries nearly accountable for 50% of the Nickel production. However, behind them there is a relatively big spread in the production which makes this stage of the market score an HHI of 1 622, making it a medium concentrated market.

Table 12. Nickel suitable for the EV-battery industry's production capacity by 2025 aggregated per country, with the corresponding market share and country concentration (HHI)

Country	Prod. Cap. [tonnes]	Market Share	HHI
Russian federation	272 000	25%	628.46
Canada	247 000	23%	518.24
Indonesia	147 000	14%	183.56
Australia	140 000	13%	166.49
China	70 000	6%	41.62
Madagascar	60 000	6%	30.58
Philippines	60 000	6%	30.58
Cuba	37 000	3%	11.63
Papua New Guinea	33 000	3%	9.25
Turkey	10 000	1%	0.85
South Africa	9 000	1%	0.69
Total HHI			**1 621.96**

4.2.2 Country risk for Nickel

The two biggest countries to supply the nickel ore suitable for the EV-industry are very different when it comes to country risk. As seen in Table 13, the supply from Russia is at higher risk as their WGI score is only -0.64. while the Canadian supply has a quite high score of 1.59. The supply from Canada and Australia could all be seen as low risk, but it only accounts for a third of the total supply.

Table 13. The countries mining suitable Nickel for the EV-battery industry's market share by 2025 together with their 2018 country risk (WGI)

Country	Market Share	WGI
Russian Federation	25%	-0.64
Canada	23%	1.59
Indonesia	14%	-0.13
Australia	13%	1.58
China	6%	-0.31
Madagascar	6%	-0.75
Philippines	6%	-0.33
Cuba	3%	-0.46
Papua New Guinea	3%	-0.58
South Africa	1%	0.13
Turkey	1%	-0.48
Weighted WGI		**0.06**

4.2.3 By-product dependency for Nickel

The majority, 98%, of global nickel production is self-sufficient. The remaining 2% is produced as a companion of the element platinum. Nickel is however often co-produced with copper but the economical contribution from copper is not big enough to make nickel a companion.

4.2.4 Company concentration for Nickel

In nickel production suitable for the EV-batteries the Russian company Nornickel is by far the biggest actor by 2025 producing almost a fourth of the total market. However, there is a big spread in the market share between the remaining actors resulting in an HHI-score of 1 224, which is presented in Table 14. This HHI score is to be seen as an unconcentrated market.

Table 14. Nickel suitable for the EV-battery industry's capacity by 2025 presented per company, with the corresponding market share and company concentration (HHI)

Company	Prod. Cap. [tonnes]	Market Share	HHI
Nornickel	276 500	25.48%	649.43
Vale	154 000	14.19%	201.46
Glencore	133 000	12.26%	150.26
BHP Billiton	100 000	9.22%	84.95
Jinchuan	70 000	6.45%	41.62
Sumitomo Metal Mining	68 760	6.34%	40.16
Zheijang Huayon	47 300	4.36%	19.00
MCC	28 050	2.59%	6.68
Sherritt	25 700	2.37%	5.61
Kores	24 000	2.21%	4.89
Tsinghan	19 100	1.76%	3.10
China Moly	18 600	1.71%	2.94
General Nickel Company	18 500	1.71%	2.91
Harita	18 500	1.71%	2.91
Ningbo	18 500	1.71%	2.91
Mitsui & Sojitz	14 040	1.29%	1.67
GEM	12 500	1.15%	1.33
CATL	12 500	1.15%	1.33
Ni Asia	6 000	0.55%	0.31
Zorlu	5 000	0.46%	0.21
GSR	5 000	0.46%	0.21
Rainbow Minerals	4 500	0.41%	0.17
Cobalt 27	2 838	0.26%	0.07
Papua New Guinea	2 112	0.19%	0.04
Total HHI			**1 224.16**

4.2.5 Market balance for Nickel

The nickel suitable to use in an EV-battery is as mentioned in Section 2.2.2 mainly nickel extracted as nickel sulfide or HPAL nickel. To set up a new HPAL facility is more complicated than other nickel-processing plants. This has led to that many HPAL operations have had trouble to keep within budget and be completed in the set timeframe. The HPAL production process is too very complex, leading to that many of today's running HPAL operations have not been able to deliver the initial advertised nameplate capacity cutting the supply side shorter than expected.

Despite this, there are numerous projects in Indonesia initiated in the recent years, with Tsinghans, a company mentioned in Section 4.2.4, project as the main focus. The company claims to be able to build new HPAL facilities for half the money, half the production time and lastly, higher production capacity compared to earlier building projects by other actors. HPAL projects usually need an investment in the ranges of $1.5-2B for a production capacity of around 30 000 tonnes nickel per year. Tsinghans have in their announcements showed plans of constructing an HPAL facility for $700 million with 50 000 tonnes nickel per year in production capacity and to be ready to start production before 2025. Some analysts have however expressed their scepticism to Tsinghans claims, due to the ambitious timeline.

The total supply of nickel i.e. the total production capacity is shown in Figure 7 where the global production capacity will be somewhere between 938 000 and 1 085 000 tpa. The graph shows total production from sulfides as well as total production from HPAL processes. The red dotted line shows the potential capacity expansion from Tsinghans new HPAL projects.

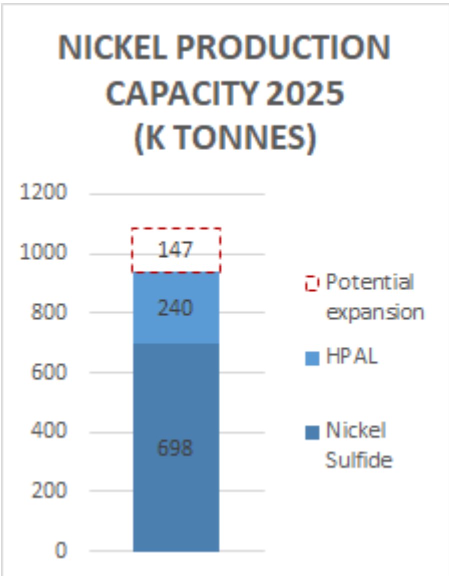

Figure 7. Global production capacity by 2025 of nickel suitable for the EV-batteries.

Because of the supply uncertainty, two market balance scenarios have been created. One scenario is conservative without including the new HPAL facilities production capacity. The other scenario is optimistic where it is assumed that all three ambitious Tsinghan HPAL projects succeed.

The demand is predicted five years in advance which is creating uncertainties. The demand has thereby been collected from both internal estimates on Volvo and an external estimate from McKinsey. Taking the supply from both scenarios and adding the demand side figures from Volvo respectively McKinsey creates four cases in the market balance which can be seen in Figure 8. In both the optimistic and conservative scenario, regardless of which demand figures that are chosen, there will be a big deficit in the global market ranging from -237 000 to -562 000 tpa.

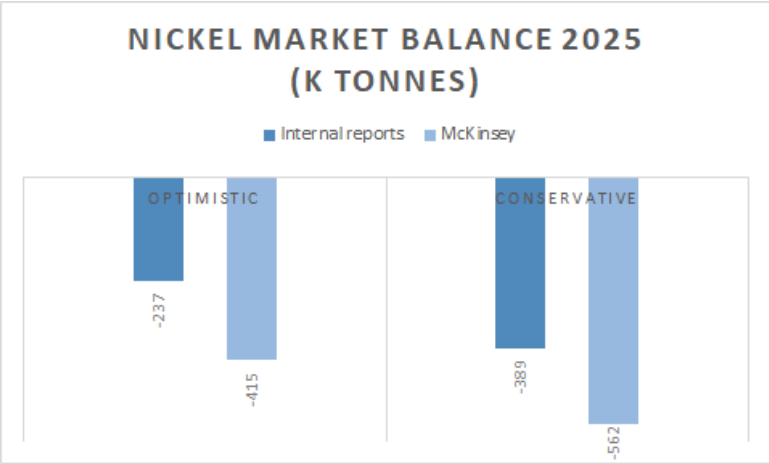

Figure 8. Market balance of the Nickel suitable for the EV-batteries.

4.2.6 Commodity price for Nickel

During the last three years the Nickel spot price has seen big shifts, as can be seen in Figure 9, which is figures from London metal exchange (LME). At its lowest in June 2017 it was traded around 8 500$/tonne compared to its peak in September 2019 with prices above 18 000$/tonnes.

Figure 9. Price evolution of Nickel futures on the LME in USD per tonne since 2017.

4.2.7 Climate risk for Nickel

The weighted WRI for the nickel supply chain suitable to use in the battery industry is 6.65, which is to be assessed as *medium* risk. In Table 15, all nickel producing countries, their market share and WRI score is presented, as well as the weighted average WRI. However, 61% of the supply comes from very stable countries with low overall risk, i.e. Australia, Russia and Canada. It is the supply coming from south-east Asia and Madagascar that have a higher risk. Indonesia and the Philippines have both *very high* exposure to natural disaster, while Madagascar has *high* exposure. The opposite holds for vulnerability were Indonesia and Philippines have *high* and Madagascar *very high.*

Table 15. Nickel suitable for the EV-battery industry market share per country by 2025 together with their 2018 climate risk (WRI)

Country	Market Share	WRI
Papua New Guinea	3%	22.18
Philippines	6%	20.69
Indonesia	14%	10.58
Madagascar	6%	10.49
South Africa	1%	6.4
China	6%	5.84
Cuba	3%	5.7
Turkey	1%	5.06
Australia	13%	4.49
Russian Federation	25%	3.52
Canada	23%	3.03
Weighted WRI		**6.65**

4.3 Supply chain risk indicators for Lithium

In this section, all supply chain risk indicators will be calculated, aggregated and presented for lithium. As mentioned in Section 2.2.3, the lithium production phase is split into two steps, first mine and brine step, which is treated as one since both produce lithium concentrate and second, the refining step. Since these two steps are performed separately and are equally important for the supply of lithium to the EV-batteries, there is a need to make calculations on both steps in the following applicable indicators: country concentration, country risk, concentrations of raw material producing companies and climate risk. The result is separated between the two steps to identify if there are a difference in potential risk for the two production steps.

By-product dependency, market balance and commodity price is not affected by the split since they only consider either the mines and brines or the refined product.

4.3.1 Country concentration for Lithium

The initial step of lithium production is split between mine and brines. Historically the brines in Argentina and Chile have dominated the market. The recent projections of the increased lithium demand due to the battery-industry have however led to a lot of construction of mines extracting lithium in Australia. By 2025 the market for lithium extraction will thereby have an HHI score of 3 815, which are to be seen as a highly concentrated market. Table 16 shows countries producing mined or brined lithium, their production capacity, market share and calculated HHI value.

Table 16. Lithium mine and brine production capacity by 2025 aggregated per country, with the corresponding market share and country concentration (HHI)

Country	**Prod. Cap. [tonnes]**	**Market Share**	**HHI**
Australia	481 250	58%	3 372.05
Argentina	112 500	14%	184.27
Chile	93 000	11%	125.93
China	90 000	11%	117.93
Canada	26 000	3%	9.84
Spain	15 000	2%	3.28
Finland	11 000	1%	1.76
Total HHI			**3 815.07**

In the next step the lithium concentrate needs to be refined into either lithium hydroxide or lithium carbonate to be used in the cathode of the lithium-ion batteries. Today refining of lithium is mainly done in China, as can be seen in Table 17, which includes production capacity, market share and HHI score for all countries refining lithium suitable for EV-batteries. However, there is a trend to build refineries more closely linked to the extraction sites in each individual country, which makes China's market share more diluted. However, the weighted HHI score is still 2 392 which is a high market concentration.

Table 17. Lithium refining step's production capacity by 2025 aggregated per country, with the corresponding market share and country concentration (HHI)

Country	Prod. Cap. [tonnes]	Market Share	HHI
China	229 400	36%	1 265.33
Australia	186 500	29%	836.32
Argentina	82 500	13%	163.65
Chile	44 000	7%	46.55
South Korea	40 000	6%	38.47
Canada	37 500	6%	33.81
USA	15 000	2%	5.41
Japan	10 000	2%	2.40
Total HHI			**2 391.95**

4.3.2 Country risk for Lithium

Lithium mine and brine production facilities are generally located in countries characterised with low country risk, i.e. high WGI score. In Table 18 all countries with lithium extraction, the countries market share and WGI score is presented. Argentina and China are the only one under the critical level of 0.59, making 75% of the supply coming from low-risk countries.

Table 18. The countries producing Lithium through mine or brine's market share by 2025 together with their 2018 country risk (WGI)

Country	Market Share	WGI
Australia	58%	1.58
Argentina	14%	0.01
Chile	11%	1.01
China	11%	-0.31
Canada	3%	1.59
Spain	2%	0.81
Finland	1%	1.76
Weighted WGI		**0.54**

The refining step of the lithium supply chain is a bit different from the resource step, which can be seen in Table 19 that includes all countries that refine lithium, the countries market share and WGI score. The results show that there is mainly a switch from low-risk Australia to higher-risk China between the resource step and refining step, resulting in a HHI-WGI score of 0.11. This value is well below the 0.59 threshold and is to be seen as critical according to the literature.

Table 19 The countries refining Lithium's market share by 2025 together with their 2018 country risk (WGI)

Country	Market Share	WGI
China	36%	-0.31
Australia	29%	1.58
Argentina	13%	0.01
Chile	7%	1.01
Canada	6%	1.59
Korea. Rep.	6%	0.91
Japan	2%	1.34
United States	2%	1.24
Weighted WGI		**0.11**

4.3.3 By-product dependency for Lithium

Looking at lithium, 52% of global production is obtained as a companion of another metal or mineral. Depending on which source the lithium is extracted from, mine or brine, the share of lithium in the obtained material is different.

For mined lithium-rich spodumene lithium is the dominant metal. But the spodumene also often contain minor amounts of other metals such as tin, beryllium or niobium. In brines, lithium is a coproduct of namely potash i.e. they have a similar economic contribution to generated revenue. The brine production can also to some extent obtain magnesium, bromine and boron. However, there are also some brines that only recover the lithium such as the Salar del Hombre Muerto in Argentina. The co-produced elements from the brine extraction are often produced in much larger quantities, which results in the economic viability of the operations.

4.3.4 Company concentration for Lithium

Historically the lithium market have been dominated by the four brine-operating actors SQM, Albemarle, Livent and Orocobre. However, the many and big projects to construct mines that produce lithium have diluted their market share by 2025, which can be seen in Table 20. Table 20 presents all companies operating in the mine and brine step for lithium, their production capacity, market share and HHI value. Albemarle has however diversified their operation to include both brine and mines which makes them keeping their top spot in the market. Overall the HHI-score in the resource step of Lithium production by 2025 will be 886, which is far lower than the threshold for an unconcentrated market (HHI<1 500).

Table 20 Lithium mine and brine step's capacity by 2025 presented per company, with the corresponding market share and company concentration (HHI)

Company	**Prod. Cap. [tonnes]**	**Market share**	**HHI**
Albemarle	135 400	16.34%	276.34
Pilbara minerals	110 000	13.27%	182.39
SQM	82 500	9.95%	102.59
Tianqi	81 600	9.85%	100.37
Rongda lithium	70 000	8.45%	73.86
Ganfeng	48 525	5.86%	35.49
Mineral resources	44 125	5.32%	29.35
Livent	30 000	3.62%	13.57
Orocobre	28 263	3.41%	12.04
Nemaska Lithium	26 000	3.14%	10.19
Altura	25 000	3.02%	9.42
Galaxy	25 000	3.02%	9.42
Wesfarmers	22 500	2.71%	7.63
Alliance Mineral Assets limited	20 000	2.41%	6.03
Qinghai Salt Lake	20 000	2.41%	6.03
Lithium America	19 600	2.37%	5.79
Infinity Lithium	15 000	1.81%	3.39
Keliber Oy	11 000	1.33%	1.82
Total HHI			**885.71**

The refining step of lithium, where the lithium ore is turned into hydroxide or carbonate is a bit more concentrated than the mine and brine operations, with an HHI score of 1 080. In Table 21, all companies producing refined lithium is shown, including their production capacity, market share and HHI score. Overall, many of the companies have vertically integrated to have operation within both producing steps. However, there are some exceptions among the biggest actors in the refining step who has not vertically integrated, such as POSCO (South Korea) and Shandong (China).

Table 21: Lithium refining step's capacity by 2025 presented per company, with the corresponding market share and company concentration (HHI)

Company	**Prod. Cap. [tonnes]**	**Market Share**	**HHI**
Albemarle	141 500	22%	481.42
Tianqi	83 400	13%	167.24
POSCO	65 000	10%	101.59
Ganfeng Lithium	62 400	10%	93.62
Shangdong Ruifu Lithium	58 000	9%	80.89
Livent	45 000	7%	48.69
Nemaska Lithium	37 500	6%	33.81
Wesfarmers	22 500	3%	12.17
SQM	22 500	3%	12.17
General Lithium	22 000	3%	11.64
Mineral Resources	20 000	3%	9.62
Lithium America	19 600	3%	9.24
Orocobre	19 138	3%	8.81
Yahua Lithium	18 000	3%	7.79
Toyota Tsusho	6 875	1%	1.14
Jujuy	1 488	0.2%	0.05
Total HHI			**1 079.89**

4.3.5 Market balance for Lithium

The global lithium production from mines and brines will in 2025 be close to 830 000 tpa, as presented in Figure 10. In the refining step of the value chain, the production capacity is more uncertain. As seen to the right in Figure 10 it is estimated to be somewhere between 645 000 to 843 000 tpa, where the red dotted line shows potential expansions. The uncertainty constitutes mostly on the fact that some of the bigger expansions plans initiated in the price-hype of 2017 have been postponed, due to unfavourable market development. In Section 3.4 of this master thesis, it was explained that only projects with a set commercialisation date would be included. However, in the lithium case, many of the postponed projects would be able to go live within a short timeframe if the market conditions were changed to the better. Thereby, projects which already started construction, but postponed the commercialisation date is represented as potential expansion in an optimistic scenario. In the conservative scenario of 645 000 tpa, the same projects are excluded.

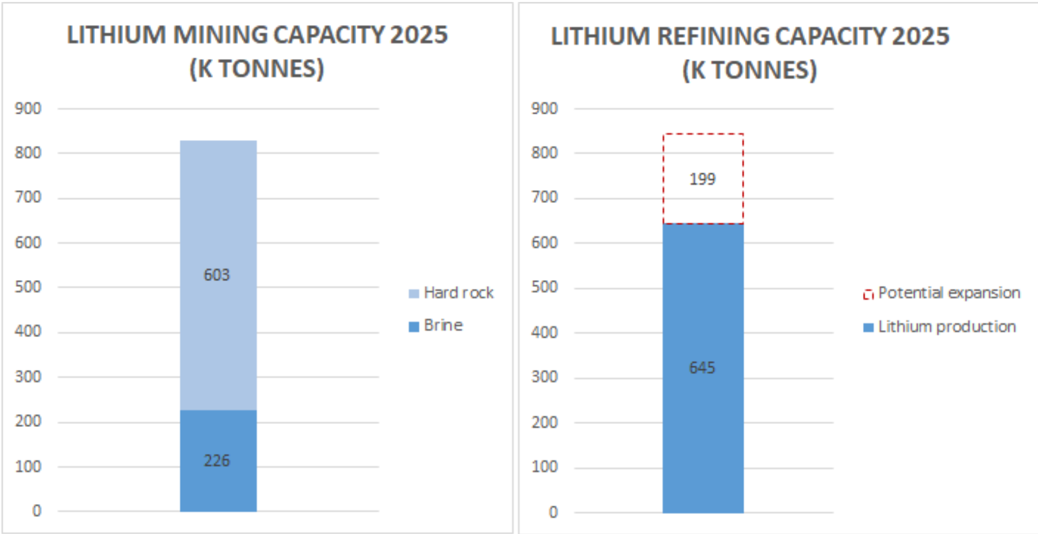

Figure 10. Global production capacity of lithium by 2025 separated between mine and brine step and refining step.

The demand is once again predicted five years in advance. This creates uncertainties and therefore internal estimates from Volvo together with external estimates from McKinsey was used. The result from adding the supply and demand side together can be seen in Figure 11. The figure includes one optimistic scenario and one conservative. The optimistic scenario use supply capacity including the potential expansions of production from the new projects. The conservative scenario does not. It is only in one out of four scenarios the market would be in a deficit. This would happen in the conservative estimates on the production capacity expansions for the refining step together with McKinsey's demand figures. In the three other scenarios, the global production capacity will be above the demand for lithium by 2025.

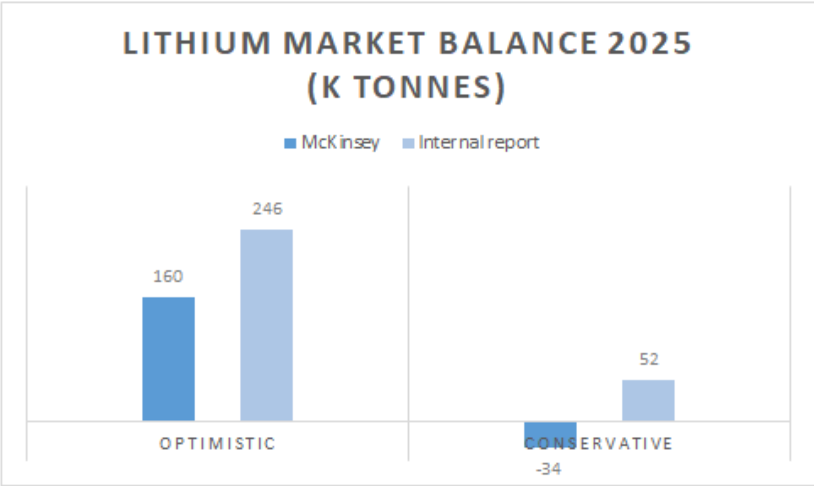

Figure 11. Market balance of the Lithium in 2025 with a optimistic and conservative scenario.

4.3.6 Commodity price for Lithium

Historically metal exchange companies, such as the LME, have not included lithium as one of their trading metals. Therefore it lacks a well-established index. Though recent interest from the battery-industry have made some actors try to establish themselves as a good indicator. Trading Economics started monitoring the lithium carbonate spot price in China (the biggest market for lithium) by May 2017. The result can be seen in Figure 12. From the peak in December 2017 to today, the price has fallen by over 70%.

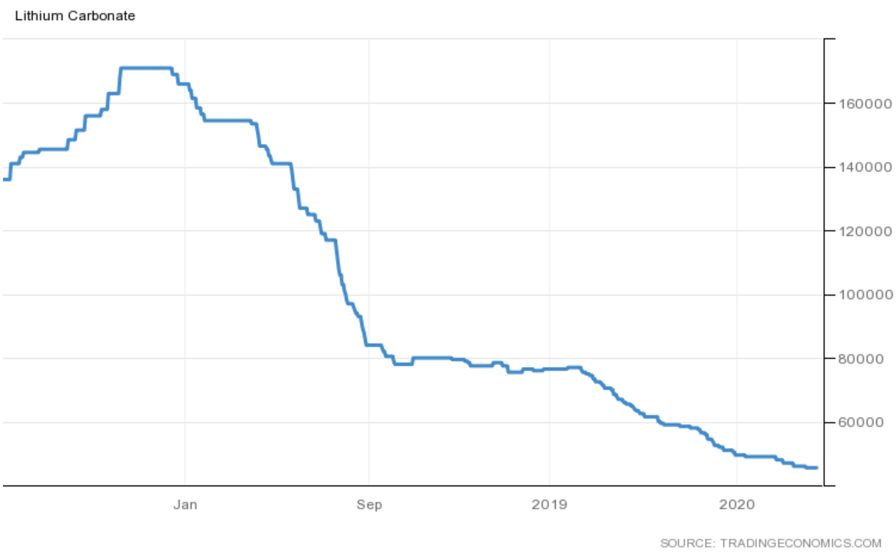

Figure 12. Price evolution of Lithium Carbonate in China monitored by Trading Economics in CNY per tonnes since May 2017.

4.3.7 Climate risk for Lithium

In Table 22, all lithium mine and brine producing countries, their market share and WRI score is presented, as well as the weighted average WRI. The initial mine and brine step of the supply chain of Lithium has a weighted WRI score of 5.3. This is in the upper region of the classification *low*. Chile is the main contributor to the higher risk of the supply chain with a WRI of 12.45. When examined further, Chile has *very high* exposure, but *low* vulnerability. The projected market share of 58% that originates in Australia all has an overall *low* risk, as Australia has a *very low* vulnerability. However, they still have *high* exposure in Australia.

Table 22. Lithium mine and brine step market share per country by 2025 together with their 2018 climate risk (WRI)

Country	Market Share	WRI
Chile	11%	12.45
China	11%	5.84
Australia	58%	4.49
Argentina	14%	3.53
Spain	2%	3.46
Canada	3%	3.03
Finland	1%	1.94
Weighted WRI		**5.30**

The refining step of the lithium supply chain has a very similar weighted WRI score as its the previous-step of 5.27. In Table 23, all countries with lithium refining production, their market share and WRI score is presented, as well as the weighted average WRI. Once again, Chile is the country with the highest risk. In the refining step, China has a higher share and their individual risk is assessed to be *medium*, with *medium* exposure and *low* vulnerability.

Table 23. Lithium refinery step market share per country by 2025 together with their 2018 climate risk (WRI)

Country	Market Share	WRI
Chile	7%	12.45
Japan	2%	9.19
China	36%	5.84
Australia	29%	4.49
United States	2%	3.76
Argentina	13%	3.53
Korea. Rep.	6%	3.08
Canada	6%	3.03
Weighted WRI		**5.27**

4.4 Supply chain risk indicators for Graphite

In this section, all supply chain risk indicators are calculated, aggregated and presented for graphite. As mentioned in Section 2.2.4, the initial steps in the graphite supply chain to EV-batteries are graphite flake production and synthetic graphite that then are the feedstock into the second step, BAM production. For applicable risk indicators, calculations have been made for both steps to be able to identify if there is a difference in potential risks between the two steps. This was applied to the following indicators: country concentration, country risk, concentrations of raw material producing companies and climate risk.

However, the synthetic graphite production operations are not transparent which created difficulties in obtaining reliable production data from these operations. But as mentioned in Section 2.2.4 the second step, BAM production, uses a mix of synthetic and natural graphite in their end-product, which meant that some aspects of the synthetic supply chain are still captured in our results.

4.4.1 Country concentration for Graphite

Table 24 presents countries in the graphite resource step, their production capacity, market share and calculated HHI value. In recent years China have imposed several environment regulations in the regions where most of their flake production happened, resulting in a consolidation of companies and lowered total production capacity from China. Since the demand is projected to grow, a void has been created which needs to be filled. The most notable project aiming to fill this void is the Balama mine in Mozambique, owned by Syrah Resources, which is single-handedly predicted to be able to produce up to 350 000 tonnes per annum (tpa) of graphite flake by 2025. This is the main driver to a more concentrated market of 2 729 HHI.

Table 24. Graphite flake production capacity by 2025 aggregated per country, with the corresponding market share and country concentration (HHI)

Country	Prod. Cap. [tonnes]	Share	HHI
Mozambique	538 000	42%	1 758.37
China	350 000	27%	744.19
Canada	150 000	12%	136.69
Brazil	95 000	7%	54.83
Russian Federation	55 000	4%	18.38
India	35 000	3%	7.44
Ukraine	30 000	2%	5.47
Norway	16 000	1%	1.56
Pakistan	14 000	1%	1.19
Total HHI			**2 728.10**

Before the graphite gets used in the EV-batteries they need to be refined to *Battery Anode Material* (BAM). Table 25 presents countries in the BAM step, their production capacity, market share and calculated HHI value. China has been early in expanding its production capacity as they have had an early demand rise on EV, compared to other countries and markets around the world. However, up until 2025 the Korean POSCO and Japanese Hitachi are also planning to become relevant actors within the BAM-production. However, even with these expansion plans, the market is still highly concentrated when aggregating all the production capacity to a country level, meaning that international actors will be highly dependent on especially China, but also Japan and South Korea for their feedstock of BAM.

Table 25. Graphite BAM production capacity by 2025 aggregated per country, with the corresponding market share and country concentration (HHI)

Country	Prod. Cap. [tonnes]	Market Share	HHI
China	381 900	67%	4 489
Japan	96 900	17%	289
South Korea	85 500	15%	225
United States	5 700	1%	1
Total HHI			**5 004**

4.4.2 Country risk for Graphite

The supply of graphite flake is heavily dependent on countries which are to be seen as high supply risk countries. In Table 26 all countries in the graphite resource step, the countries market share and WGI score is presented, as well as the weighted average score. Mozambique scores well below zero on all six indicators in the WGI, with Rule of Law, Governmental effectiveness and Political stability all being the three lowest indicators. China's big market share is also a big contributor to the overall supply chain score of -0.14.

Table 26. The countries mining Graphite flake's market share by 2025 together with their 2018 country risk (WGI)

Country	Market Share	WGI
Mozambique	42%	-0.78
China	27%	-0.31
Canada	12%	1.59
Brazil	7%	-0.24
Russian Federation	4%	-0.64
India	3%	-0.11
Ukraine	2%	-0.68
Norway	1%	1.77
Pakistan	1%	-0.97
Weighted WGI	**-0.14**	

As seen in a country concentration above, the BAM step of the graphite production is highly concentrated around only three countries. In Table 27 these countries, the countries market share and WGI score is presented, as well as the weighted average score. Being so dependent on China comes with great risk, as their WGI score is only -0.31, well below the 0,59 threshold found in the literature. As China have a very big market share, these scores affect the combined HHI and WGI very much, giving the total BAM-market a score of -0,08.

Table 27. The countries producing Graphite BAM's market share by 2025 together with their 2018 country risk (WGI)

Country	**Market Share**	**WGI**
China	67%	-0.31
Japan	17%	1.34
South Korea	15%	0.91
United States	1%	1.24
Weighted WGI		**-0.08**

4.4.3 By-product dependency for Graphite

As graphite was not included in Nassar et. al. (2015)s work, explained in detailed in Section 2.3.3, a companiality number is not used. Instead, graphites by-product dependency had to be examined with the support from other sources.

Natural graphite is mined from metamorphic rocks as a main-mineral. There are graphite deposits where vanadium can be found as a by-product (Robinson et al., 2017). The result is that graphite is not considered to have a dependency on other products.

4.4.4 Company concentration for Graphite

If Syrah resources Balama mine project reach their planned production capacity of 350 ktpa they will be the top producer by 2025 by a big margin. Table 28 presents all companies operating in graphite resource step, their production capacity, market share and HHI value, as well as the weighted average HHI value. The Heilongjiang and Shandong area in China has a long history of graphite production but with a complex chain of different actors with little to no information on a company-specific production capacity. Therefore these two areas have been summarised into bigger clusters. The market might, therefore, be even less concentrated than the HHI-score of 1 437 symbolises.

Table 28. Graphite flake production step's capacity by 2025 presented per company, with the corresponding market share and company concentration (HHI)

Company	Prod. Cap. [tonnes]	Market Share	HHI
Syrah	350 000	27.28%	744.19
Heilongjiang cluster	280 000	21.82%	476.28
Nouveau Monde Graphite	100 000	7.79%	60.75
Shandong cluster	70 000	5.46%	29.77
Nacional de Grafite	70 000	5.46%	29.77
Triton	60 000	4.68%	21.87
Battery Minerals	58 000	4.52%	20.44
Battery Minerals	50 000	3.90%	15.19
Dalgraphite	40 000	3.12%	9.72
India Cluster	35 000	2.73%	7.44
Zavalyevskiy	30 000	2.34%	5.47
Brazil cluster	25 000	1.95%	3.80
Ontario Graphite	22 000	1.71%	2.94
Canada Cluster	20 500	1.60%	2.55
Tirupati Graphite Group	20 000	1.56%	2.43
Mineral Commodities	16 000	1.25%	1.56
Uralgraphite	15 000	1.17%	1.37
Pakistan Cluster	14 000	1.09%	1.19
Eagle Graphite	7 500	0.58%	0.34
Total HHI			**1 437.05**

As seen under Section 4.4.1 the battery anode material producing step of the graphite is mainly located within China, however, with several actors who process the graphite, giving the market a weighted average HHI score of 1 622. Table 29 presents all companies operating in the graphite BAM step, their production capacity, market share and HHI value, as well as the weighted average HHI value. Posco (South Korea) and Hitachi (Japan) is the only actor in their respective country. Both are expanding quite rapidly until 2025 making them play a bigger role in the world market.

Table 29. Graphite BAM step's capacity by 2025 presented per company, with the corresponding market share and company concentration (HHI)

Company	Prod. Cap. [tonnes]	Market Share	HHI
Ningbo Shanshan Technology	135 000	24%	560.94
LuiMao	105 000	18%	339.34
Hitachi Chemical Co. Ltd.	100 000	18%	307.79
Posco	85 000	15%	222.38
Shenzhen BTR New Energy Materials Inc.	60 000	11%	110.80
Shenzhen Sinuo Industrial Development Co. Ltd	40 000	7%	49.25
Jiangxi Zeichen Technology Co. Ltd	30 000	5%	27.70
Hunan Shinzoom Technology Co	10 000	2%	3.08
Syrah	5 000	1%	0.77
Total HHI			**1 622.04**

4.4.5 Market Balance for Graphite

The global production capacity of natural graphite flakes is estimated to be 1 283 000 tpa by 2025, which is illustrated in Figure 13. As seen to the right in Figure 13 the Battery Anode Material (BAM) global production capacity in 2025 is expected to be close to 570 000 tonnes. Comparing the two numbers would indicate that the BAM production act as the bottleneck. In the case of graphite, identifying the bottleneck is not that simple due to the fact that Lithium-ion batteries are far from the only application area that consumes graphite flakes.

In 2018 Lithium-ion batteries only accounted for 13% of flake graphite consumption. However, most other graphite flake consuming industries are very mature, which is not the case for the lithium-ion battery market. Thereby, by 2025 the BAM-market will account for a much higher market share. This uneven growth between the application areas creates the need to look at the market balance for both graphite flake production and the BAM-refining step separately.

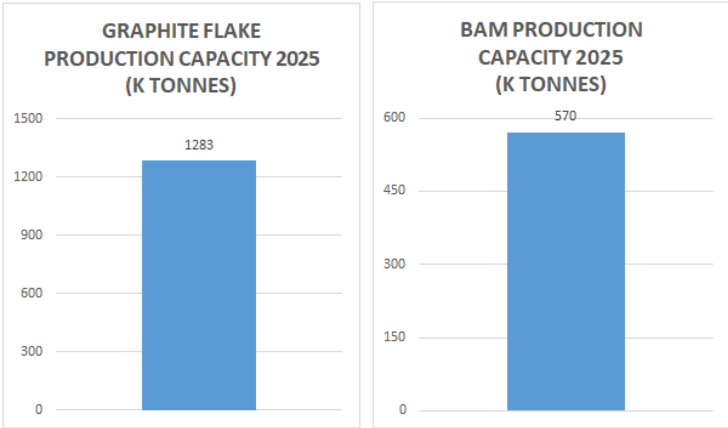

Figure 13. Global graphite production capacity suitable for the EV-battery industry by 2025, separated by flake and BAM.

As the demand-figures is predicted five years in advance uncertainties are created which is handled through using multiple sources and comparing the results. In the case using external sources, the McKinsey report used for Cobalt, Nickel and Lithium is not applicable as they only incorporated predictions for the cathode materials. Instead, a report from Fastmarket is used together with Volvo-internal predictions.

The result from adding the supply and demand side together can be seen in Figure 14. For graphite flakes, the market balance is very even between supply and demand when using the Volvo internal demand predictions. Using Fastmarkets numbers is however showing a deficit of graphite flakes by -289 000 tonnes.

There is a similar case for the global BAM production step, which is seen to the right in Figure 14, which shows the supply and demand market balance based on two different sources of predicted demand in 2025. The Volvo internal demand predictions result in a surplus by 37 000 tonnes, while Fastmarkets numbers result in -216 000 tonnes.

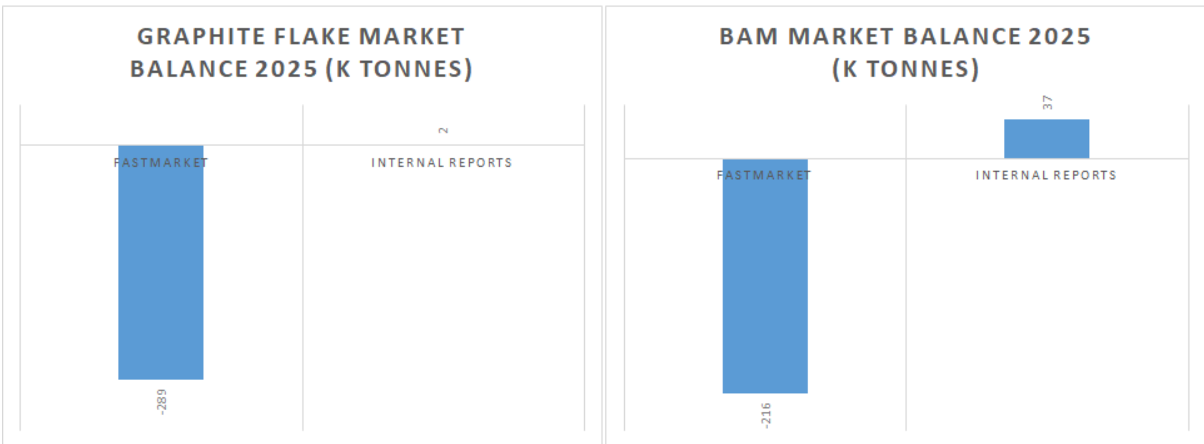

Figure 14. Market balance by 2025 for flake graphite and BAM.

4.4.6 Commodity price for Graphite

Similarly to the lithium price, graphite has not been a mineral that has brought a lot of attention from the metal exchange firms around the world. Instead, it is a mineral who has been sold to steady application industries through bilateral agreements. Thus, there is no standard spot prices or indexes publicly available which could give indications on how the graphite price has developed. Thereby, it is argued that the graphite price does not have enough data points to make a credible evaluation of the risks associated with their commodity price.

4.4.7 Climate risk for Graphite

The graphite flake extraction step has a weighted WRI score of 6.79 which is to be assessed as *medium* risk. In Table 30, all flake graphite producing countries, their market share and WRI score is presented, as well as the weighted average WRI. Notably for this step is that the biggest country of supply, Mozambique, also is the country with the highest risk. Mozambique is a country with *medium* exposure, but *very high* vulnerability.

Table 30. Graphite flake production step market share per country by 2025 together with their 2018 climate risk (WRI)

Country	Market Share	WRI
Mozambique	42%	9.5
Pakistan	1%	7.08
India	3%	6.77
China	27%	5.84
Brazil	7%	4.79
Russian Federation	4%	3.52
Canada	12%	3.03
Ukraine	2%	2.66
Norway	1%	2.34
Weighted WRI		**6.79**

The BAM production step of the supply chain has a weighted WRI score of 5.97. In Table 31, all BAM producing countries, their market share and WRI score is presented, as well as the weighted average WRI. The overall score lies very close to the biggest supplier Chinas score of 5.84. However, Japan with almost a fifth of the supply has a *very high* exposure meaning that it is very likely to face a natural disaster, but it is a country with *very low* vulnerability.

Table 31. Graphite BAM step's market share per country by 2025 together with their 2018 climate risk (WRI)

Country	Market Share	WRI
Japan	17%	9.19
China	67%	5.84
United States	1%	3.76
Korea. Rep.	15%	3.08
Weighted WRI		**5.97**

4.5 Summary of empirical data calculations

In Table 32 all of the results are gathered from Section 4.1-4, to give an overview of the results. The results are presented for each of the risk indicators for all materials in their specific production steps. These are the data points that will be analysed to identify the risk in Chapter 5.

Table 32. Resulting table of all calculated indicators for all materials

Risk Indicators	Cobalt		Nickel	Lithium		Graphite		Unit
	Mine	Refinery	Production	Mine & Brine	Refinery	Flake mines	BAM	
Country concentration	6 836	4 415	1 622	3 815	2 392	2 728	5 004	HHI
Country risk	-1.12	-0.11	0.06	0.54	0.11	-0.14	-0.08	WGI
By-product dependency	85%		2%	52%		0%		Companionality
Company concentration	1 028	1 142	1 224	886	1 080	1 437	1 622	HHI
Market Balance	(-45) to 10		(-562) to (-237)	(-34) to 246		(-289) to 2	(-216) to 37	k tonnes
Commodity price	+332%		+110%	-70%		N/A		Spot price
Climate risk	8.74	5.61	6.65	5.3	5.27	6.79	5.97	WRI

5 Identified risks

This chapter analyses the collected data, presented in the previous chapter, to identify the risks that exist for each supply chain of Cobalt, Nickel, Lithium and Graphite. The findings from this chapter serve as the answer to the research question one.

In the chapter, the analysis of every material is divided into their own sections. In each section, every supply chain risk indicator is assessed. In the last section of this chapter, the assessed risks are summarised into a table with the following discussion comparing the risks between the materials included in the master thesis.

5.1 Cobalt

In the following section, an analysis of each of the supply chain risk indicators for the Cobalt supply chain is presented.

The country concentration for Cobalt is the highest of all analyzed materials with an HHI score of 6836 in the mining step, meaning that the producing countries have a very high concentration and therefore a high risk for supply disruptions. The biggest reason for the high score is the market share from DRC, at a total share of approximately 82.44% of global production by 2025. This can be compared to the following top countries, Australia (3.47% market share), Madagascar (2,80% market share) and Russia (2.5% market share), at drastically lower percentages. The remaining 8.79% of the supply is coming from 7 other countries. The dependency on DRC increases the risk of disruption of the supply and increased prices.

Looking at the country concentration in combination with the country risk where the producing countries of cobalt get a low weighted average WGI score of -1.12, the lowest of all materials, it prevails even further risk. DRC has a WGI score of -1.66 of the six weighted aspects. On the WGI aspect political stability and absence of violence, DRC scores -2.12 which is close to the lowest possible score (-2.5). As a result of the two Congo wars between 1996 and 2003, there are still conflicts ongoing in the country in regions close to mining operations that affect the WGI score and thus increase the risk. In addition, there is a risk that the material could be used as a political or strategic instrument. The government in DRC has a history of increasing royalties for the production of cobalt to get a larger slice of revenues and in addition due to corruption, that money does not always fund the national budget. Being dependent on one country that in turn also has a low score on governance performance arguably increases the risk for disruptions. Together the assessment of country concentration and country risk is to be deemed as very high risk for the mining step of cobalt production.

For the refining step, the country concentration reaches an HHI score of 4 415, the second-highest of all materials. The score is lower compared to the mining step since the majority of the ore mined in DRC is not refined at the spot, but exported to other countries, prominently China who has a 65% market share. After China, the refined supply market share is 9.92% from Finland, 3.97% from Zambia, 3.70% from Australia and the remaining 17.28% from 7 other countries. Disruption on a country level, therefore, could have a severe impact on the supply of refined cobalt. Looking at the country risk, the total WGI score is averaged to -0,11, where China alone has a score of -0,31, indicating weak governance performance. Therefore the refining step is considered to have a high risk for supply.

The company concentration gets an HHI score of 1 142 in the mining step which means that the market is unconcentrated. For the refining step, the HHI score is 1 141, also indicating an unconcentrated market. Many companies are vertically integrated and own both mines and refineries. In total there are 26 companies in the mining step and 22 in the refining step. This provides the market with multiple procurement channels and drives up competition between different actors. It also means that a disruption at a single mine or refinery would only mean a small risk for global supply. Thus, company concentration risk is assessed to be low.

From the results regarding by-product dependency for cobalt, it can be seen that the companionality is at 85%, the highest in comparison to the other materials. The dependency and influence of main-metals production affect the ability to respond to rapid changes in demand. An increase in demand for cobalt could, therefore, stand at risk if the main-metal does not follow a similar trend. The dependency relies on nickel and copper production that are traditional materials with stable demand from many different industries. The high degree of companionality implies that the supply risk is deemed as high. However, since nickel is a material that also is needed in the lithium-ion batteries, increased demand for cobalt for the battery sector also means increased demand for the main-metal nickel. Thereby the materials could follow a similar pattern, with an increased supply of both nickel and cobalt and to some degree lowering the by-product dependency for cobalt.

The commodity price for cobalt has in recent three years once increased by 332%. In combination with the high country concentration and high country risk, it could be argued that the risk for further volatility in the prices until the year 2025 is high. The price peak in 2017 was in the realms of a trade war between the United States and China, where cobalt was stacked in warehouses since investors purchased large quantities to weather through the trade storm. Since then the price has dropped due to slower demand increase than expected and oversupply in the market. With this background, the commodity price risk is deemed as high.

The ethical debate regarding sourcing cobalt from artisanal mines can have an impact on the market balance of supply and demand. Cobalt extracted from artisanal mines is projected to have a share of 12% of world production in DRC in 2025. It could be argued that this helps diversify the mined production since it could to some extent compensate for the shortage of industrial supply. Cobalt is very accessible in the DRC region since the cobalt in some parts of the country is just a few meters down in the ground accessible with only a spade and shovel. This makes the ASM production very flexible since the numerous production sites located in a number of places across DRC are able to respond quickly to variations in price compared to industrial mining that could need a longer time frame to start production and more investments to increase capacity. With artisanal supply, the market is deemed to be quite in balance by 2025, with a market balance range of 10 000 tonnes surplus to a deficit of -22 000 tonnes. If Volvo together with a majority of other buyers wants to source ethical and avoid cobalt sourced from artisanal mining, which is trends already seen today, the supply is slightly more in deficit in the range of -45 000 to -13 000 tonnes. Overall the risk of having a market imbalance is deemed to be medium.

The climate risk gets a WRI score of 8.74 which is the highest of all materials. The reason for this is that DRC stands for 82% of the market and has a high vulnerability on the occasion of a natural disaster event, even though the exposure is low. Since the market share is increasing from now until 2025 this risk will only intensify. In addition, Papua New Guinea, Philippines and Madagascar has a WRI of 22.18, 21.69 and 10.49 respectively and stands for approximately 6.44% of the remaining market share. With this in consideration, climate risk is deemed to have a high risk in the mining step.

In the refinery step, the majority of production is located in regions with lower WRI score and the weighted score is thus 5.61, with the majority market share from China having a WRI score of 5.84. This number indicates that the climate risk for the refining step could be considered medium.

A synthesisation of the outcome from the above analysed risk indicators for cobalt is presented in Table 33 . The table includes the associated risk in terms of low, medium or high for all indicators.

Table 33: A synthesisation of the analysed risk indicators for cobalt

Risk Indicator	**Cobalt**	
	Mine	Refinery
Country concentration	High	High
Country risk	High	High
By-product dependency	High	
Company concentration	Low	Low
Market Balance	Medium	Medium
Commodity price	High	
Climate risk	High	Medium

5.2 Nickel

In the following section, an analysis of each of the identified risk indicators in the nickel supply chain is presented.

Even though nickel is a commonly produced base metal, the fact that many growing application areas, including lithium batteries, have very specific requirements on their needed nickel creates fierce competition on some part of the nickel supply. As further mentioned in Section 4.2.5, the HPAL production technology is a way to increase the supply of nickel meeting the battery criteria. The market balance is thereby affected by whether the ongoing HPAL projects will reach commercialization as planned or not. Either way, the market balance will reach a deficit in 2025 but with a different magnitude between the scenarios. In the optimistic scenario, including the HPAL projects, shows a deficit of between -415 000 to -237 000 tonnes. The conservative scenario, excluding new HPAL projects, shows figures even lower with a deficit ranging from -562 0000 to -389 0000 tonnes. If the HPAL projects succeed, this positive signal might lead to other actors initiating additional new HPAL projects, leading to new sources of supplies beyond 2025 with halved lead times in the long term. But up until the year 2025, the risks associated with the market balance is deemed to be high.

The climate risk for nickel production gets a weighted average WRI score of 6.65 and is thus classified as a medium risk from the theory. However, about 61% of the supply in 2025 comes from countries with low risk, such as Russia (WRI of 3.52), Australia (WRI of 4.49) and Canada (WRI of 3.03). The countries that drives the number up have a very high WRI score and are located in Southeast Asia; Papua New Guinea (WRI of 22.18), Philippines (WRI of 20.69), Indonesia (WRI of 10.58) and in addition to that, Madagascar (WRI of 10.49). Since many of the new HPAL projects are located in Indonesia, that means that an increasing part of the supply will be located in regions prone to natural disasters. Even so, as more than half of the supply comes from countries with low risk, the overall assessment evaluates the climate risk to be considered as medium risk.

The commodity price has for the past three years had an increase of 110%, which is over the limit to be considered a risk according to the theory in Section 2.3.6. The increase is lower compared to the other analysed materials in this master thesis. However, the price has since September 2019 dropped to a similar price point as at the beginning of 2019, a drop from 18 000$/tonnes to 12 000$/tonnes as seen in Section 4.2.6. The price has an important role to play since it will be the support for investments made for new nickel production. If the prices are to low it could be argued that there won't be an incentive for companies to boost the supply of nickel. New HPAL projects will need support from higher prices to cover for the investment. The commodity price is evaluated to have a medium risk.

The country concentration is slightly above medium concentration, getting an HHI score of 1622, with eleven countries producing nickel suitable for batteries. The market share is spread out with Russia having a market share of 25%, Canada 23%, Indonesia 14% and Australia 13% while the remaining 25% is produced in 7 other countries, in the year of 2025. In comparison with the other materials, it is the least concentrated market on a country level of all and thus the risk for disruptions is low. Therefore the country concentration is deemed to have a low risk.

When considering the company concentration the nickel supply chain gets a HHI score of 1224 which is an unconcentrated market. In total there are 24 companies producing nickel suitable for batteries. This lowers the risk since affected supply would be low in a disruption caused if one company would go bankrupt. Further, an unconcentrated market also increases the bargaining power for buyers. In addition, the nickel production industry is mature with many companies having years of experience, which could be argued to lower the probability of disruption overall. The total risk for company concentration is therefore considered low.

The country risk gets a weighted WGI score of 0.06, under the 0.59 threshold and should be considered a risk in terms of governance performance. Taking the number in comparison with the other materials WGI score a score of 0.06 is placed in the mid-range. The countries with the highest WGI score are Canada (1.59) and Australia (1.58) that together stands for 37% implying that more than one-third of the produced nickel comes from countries with very low risk. However, the remaining 63% of the produced nickel comes from countries with a WGI score under the threshold and thus is to be considered a risk. Therefore it could be argued that the country risk is to be considered as a medium.

The by-product dependency at 2% is very low. There is no dependency that should affect the supply situation of nickel to the market and therefore risks such as price volatility caused by the reliance on other production is low, therefore the by-product dependency risk is deemed as low.

A synthesisation of the outcome from the above analysed risk indicators for nickel is presented in Table 34. The table includes the associated risk in terms of low, medium or high for all indicators.

Table 34: A synthesisation of the analysed risk indicators for nickel

Risk Indicator	**Nickel**
	Production
Country concentration	Low
Country risk	Medium
By-product dependency	Low
Company concentration	Low
Market Balance	High
Commodity price	Medium
Climate risk	Medium

5.3 Lithium

In the following section, an analysis of each of the identified risk indicators in the lithium supply chain is presented.

In the mine and brine operations of the lithium supply, the country concentration HHI score of 3 815 is indicating that the market is highly concentrated between the producing countries. Many new mine projects in Australia is projected to be commercialised by 2025, making 58% of the supply originating from Australia. The brine part of the supply has historically been concentrated in Chile and Argentina. This is still the case by 2025, but as their expansion plans are not as aggressive as the mine projects, the market share from brines on the global supply market will be less in 2025 compared to today. Still, the market will be very dependent on these three countries, Australia, Argentina and Chile. Being dependent on a few countries, especially considering one is controlling over half of the world supply always comes with a high risk of disruption or increased prices.

A connected risk to country concentration is the country risk. It could be argued that the effect of being dependent on a few countries will come with even higher risk if the countries you are dependent on are unstable countries. In the world banks calculation of the WGI, Australia has an average score of 1.51 between the six measured indicators. This high score, combined with the high market share is a big contributor to why the weighted WGI of the mine and brine step score a 0.54, which is the highest across all materials studied in this master thesis. So even though a high country concentration always comes with some risks, this risk gets somewhat neutralised by the high WGI of the by far biggest country, Australia. Thereby it is argued that the combined country concentration and country risk is assessed to be of medium risk in the mine and brine step of the lithium production.

The biggest difference in the refining step of the lithium supply chain compared to the brines and mines is that a big part of the low-risk country Australia's (average WGI of 1.51) market share is moved to the higher risk country China (average WGI of -0.31). The split of market share makes the total supply chain more dependent on two countries instead of one, resulting in a lowered concentration to 2 392. This country concentration is just below the threshold of 2 500 that the literature states as a highly concentrated market. The shift towards a higher dependency on China is, however, increasing the country risk in the supply chain to a weighted WGI score of 0.11. This makes the combined assessment of country concentration and risk to be deemed as a medium risk for the refining step of the lithium production.

Today, 52% of the produced lithium are dependent on other materials to be co-produced in order for their operations to be economically viable. Almost all of this by-product dependency are originating in the brine operations, where potassium and lithium are produced together. However, by 2025 the close to 50-50 split that holds today between mine and brine is projected to switch towards 72-28. It is, therefore, reasonable to believe that by 2025 the by-product dependency for lithium will be much lower. Therefore, it is argued that lithium has a low risk connected to by-product dependency.

The market balance in 2025 is assessed through four different scenarios. The result from these four scenarios range from a deficit of -34 000 tonnes to a surplus of 246 000 tonnes. Given that many of the capacity expansion projects were initiated already in 2017, around the price peak, by 2025 the market should be well-adapted to the anticipated demand growth. Even though some of the projects have been postponed, both before and after final construction, and their date for commercialisation is uncertain, these projects will act as a pillow for the market. If there are supply shortage, prices for lithium goes up which leads to better market conditions, leading to projects re-starting. Further, in the optimistic scenario, the market balance surplus is between 160 000 and 246 000 tonnes. This big surplus is indicating that the "pillow" in the market is more than well-enough covering the potential demand. Furthermore, the big surplus indicates that far from all expansion plans needs to be realised for the market to avoid a supply shortage. However, even though the aggregated numbers presented in this report seems to have a low risk of imbalance, the market could still face timing problems. There are lead-times connected to re-starting a project, meaning that if the demand accelerates very quickly or unevenly, the market could for shorter period of times face deficits. Overall though, when aggregating the numbers up until 2025, the risk of a market imbalance will be deemed as low, due to the potential expansions that are waiting for better market conditions.

In the time period of which lithium carbonate price have been monitored by trading economics, there has not been a price increase of 100% or above. However, from the peak in December 2017 to today, the price has fallen by over 70%. This would indicate that the price still is very volatile, and one should be aware of the possibility to see sharp rises once again. Though when doing the full assessment of the commodity price, the "pillow" that was explained above will work as a lid on the price, putting out more supply when prices increase. Therefore, given that there has not been a price increase of at least 100% within the last three years, and there seem to be market mechanisms pushing down the prices up until 2025, the risks associated with commodity price are evaluated to be low.

Even though the country concentration for the lithium supply is high, the same does not yield for the *company concentration*. Both the mine and brine and the refining step are scoring the lowest HHI of all the materials studied in this master thesis. This indicates that within the supplying countries, there are multiple active actors. This minimizes the risk of disruption because of company failure. Another positive effect that comes with low company concentration is that it gives the buyers higher bargaining power, as they have more actors to choose from, i.e. less dependency on their suppliers. The evaluation is thereby that there are low risks associated with the company concentration in the supply chain of lithium producing companies.

The lithium supply chain is exposed to climate risks, the weighted WRI of 5.30 and 5.27 is within the upper part of the low classification presented in the theory chapter. Being in the low classification would indicate that there is only a smaller chance of disruption in the supply chain due to natural hazards. When examining the numbers further, it is interesting to mention that both Australia and Chile, contributing to 69% of the mine and brine supply and 36% of the refined lithium, have *high* and *very high* exposure. Meaning that natural hazards are common to hit the countries. In turn, Chile has *low* and Australia *very low* vulnerability. This means that there is a lower probability that the supply gets affected when any of the two countries are hit by a natural hazard. With the *low* classification of the weighted WRI and that so big market share comes from countries who are able to cope and adapt to natural disasters, the overall risks associated with the climate is deemed to be low.

A synthesisation of the outcome from the above analysed risk indicators for lithium is presented in Table 35. The table includes the associated risk in terms of low, medium or high for all indicators.

Table 35: A synthesisation of the analysed risk indicators for lithium

<table>
<tr><th>Risk Indicator</th><th colspan="2">Lithium</th></tr>
<tr><td></td><td>Mine & Brine</td><td>Refinery</td></tr>
<tr><td>Country concentration</td><td>Medium</td><td>Medium</td></tr>
<tr><td>Country risk</td><td>Medium</td><td>Medium</td></tr>
<tr><td>By-product dependency</td><td colspan="2">Low</td></tr>
<tr><td>Company concentration</td><td>Low</td><td>Low</td></tr>
<tr><td>Market Balance</td><td colspan="2">Low</td></tr>
<tr><td>Commodity price</td><td colspan="2">Low</td></tr>
<tr><td>Climate</td><td>Low</td><td>Low</td></tr>
</table>

5.4 Graphite

In the following section, an analysis of each of the identified risk indicators in the graphite supply chain is presented.

The graphite flake production and BAM-production do look quite different in terms of countries and companies present. Thus, the following analysis on country concentration, country risk and company concentration will be performed separately for the two steps.

Starting with the mining step of graphite flakes, which is the form of natural graphite used in lithium batteries, the response to the predicted increase in global demand is mostly concentrated around the mining projects in Mozambique. By 2025, the predicted market share from Mozambique's is 42% and China's share is 27%. Together they are contributing with 2502 HHI, meaning that they are the reason why the country concentration is above the threshold of a highly concentrated market. Then, when also adding the layer of country risk, it is apparent that the graphite flake supply chain is exposed to a lot of risks. It is only the 13% supply from Canada and

Norway that is not originating from a country which is below the critical WGI-level of 0.59. To further emphasize the country risk, the biggest producing country Mozambique is also one of the worst WGI scoring countries in this master thesis. Only Pakistan and DRC have a lower score. In addition, of the six indicators measured in the WGI, Mozambique's three worst are the Political Stability, Rule of Law and Governmental effectiveness. All these three could be argued as important for assessing the business climate. All in all, the void that is created from the lowered Chinese production together with the increased demand from the battery-industry is trying to be filled by supply coming from the very risky country Mozambique. This is why the evaluation of the country concentration and country risk is assessed to be high for the graphite flake production step.

Even though the mining step is highly concentrated on a country level, when mapping the companies, the HHI is right below the 1 500 threshold, meaning an unconcentrated market. Further, in many areas of the graphite flake production, there was little to no information on the production capacity on a company level. In the absence of alternatives, these areas got clustered as one in the assessment made in chapter four of this master thesis. However, one can assume that at least for some of these regions, there are multiple actors splitting on the production capacity for their regions, meaning that it is probable to believe that the HHI should be even lowered. Given that with the "worst-case-scenario" approach used by calculating the HHI by clustering supply to regions, the HHI is still unconcentrated and thus the company concentration is evaluated to be low risk.

There are only four identified countries producing battery anode materials. In 2025 China will have two-thirds of the market while, except for a small facility in the US, Japan and South Korea are splitting on the rest. This high concentration is resulting in a high HHI-score of 5004. When combining China's negative WGI score of -0.31, it is apparent that being this dependent on China is not optimal. On a more positive note, the remaining 33% of the supply in the market is originating from countries over the HHI-score of 0.59, meaning that one can expect more stable output from at least a third of the world supply. To conclude, the very high HHI combined with the low WGI score from China, the overall risks associated with country concentration and country risk are assessed to be high.

The HHI score for the BAM producing companies are 1 622. This is in the medium concentrated territory. Further, there is only one company in Japan (Hitachi), one in South Korea (POSCO) and one operating in the US (Syrah). Instead, it is the supply from China that is divided between multiple companies, which explains the lower HHI than the country concentration. This means that there are some alternatives for buyers to choose from, which gives them at least a bit of leverage in negotiations. However, if something were to happen within China, either some disruptions in the supply or changes in the policies around the raw material regarding batteries, an international buyer could be forced to buy outside of China. In that scenario, there are only three companies to choose from, giving the supply side very high bargaining power. Thus, the company concentration indicates that there are medium risks in the BAM production step.

By 2025, the market balance is at risk of being in a supply shortage for both the graphite flake and BAM step of the supply chain. However, if Wood Mackenzie's demand numbers are the more accurate, the markets seem to be in equilibrium. Analyzing which institute that has the best demand predictions could be hard, but the conclusions that can be drawn from the market balance assessment is that in the best-case scenario, the market seems to be in equilibrium, and worst case a quite big deficit. Therefore the risk of a supply shortage in both steps is evaluated to be of medium risk.

Mozambique is not only associated with high risks in the countries governance (WGI) but also when it comes to natural hazards. Their WRI is calculated to be 9.50, which constitutes of medium exposure risk, and very high vulnerability. At least up until 2025 most of the probable and significant graphite flake expansion plans are located within Mozambique. Thus, the market is heading towards being more and more dependent on countries with high risks both in terms of their governance and natural hazards. On the contrary, there is still a significant portion of the supply coming from countries with calculated WRIs below 5.5, i.e. low to very low risk. In total, these countries add to 26% of the supply with Canada and Brazil being the biggest contributors. This means that the overall assessment of the risks associated with the climate for the graphite flake mines is medium risk.

Among the BAM producing countries, Japan has the highest WRI score. Their score of 9.19 ends up in the high risk classification. It is their very high exposure to a natural disaster that explains their high score, as it is a country of good adaptability and coping strategies, giving them a very low vulnerability. This means that the probability to see a supply disruption because of a natural hazard still is quite small from Japan. However, given that there is only one company present from Japan, if Hitachi gets affected all of the 17% supply could be affected. This together with the fact that the weighted WRI for the total supply chain is 5.97 (above the medium-threshold of 5.5) the climate risk for the BAM producing step is assessed to be medium.

Further, the by-product dependency has been analysed. In most cases, the flake graphite is mined by itself, and in the instances where it has a co-product, the graphite act as the main-mineral. Thus, there is no by-product dependency for the graphite flake production, and hence no such risks associated with it.

Last is the commodity price risk. As described in Section 4.4.6, there are no established, publicly available price indexes as there are for the other minerals included in this master thesis. Thereby, it is argued that it is impossible to assess the commodity price risks at this point in time. However, this is not the same as to say there is no risk. The market balance assessment on graphite shows that there are predictions on a high demand and supply increase for the coming years. Given the long lead time on expansion plans in raw material production, it could be argued that graphite could face timing issues in the coming years, leading to a volatile price. Volatile prices could lure traders, incentivising market exchange firms to initiate a graphite index. If or when that happens, it would be possible to follow and make a more credible assessment of the risks associated with the graphite price.

A synthesisation of the outcome from the above analysed risk indicators for graphite is presented in Table 36. The table includes the associated risk in terms of low, medium or high for all indicators.

Table 36: A synthesisation of the analysed risk indicators for graphite

Risk Indicators	**Graphite**	
	Flake mines	BAM
Country concentration	High	High
Country risk	High	High
By-product dependency	No	
Company concentration	Low	Medium
Market Balance	Medium	Medium
Commodity price	N/A	
Climate	Medium	Medium

5.5 Summary of identified supply risks

It can be concluded that there is a big difference overviewing all the risks for each material. In Table 37 a synthesisation of the analysis is shown. The table includes the associated risk in terms of low, medium or high for all indicators and materials in their respective production step gathered from the analysis.

As can be seen in Table 37, cobalt has the highest number of indicators marked with a *high* risk of all materials, five out of seven. Only the company concentration is at low risk, while the market balance is at medium risk. The cobalt supply chain is therefore very critical and is at highest risk of all materials to encounter disruptions. The biggest bottleneck is that the mine production is highly concentrated in the cobalt-rich country DRC, that in turn also have poor governance performance. In turn, since cobalt is a by-product to a major extent also increase the risks since it is dependent on the production of its host metals copper and nickel, decreasing the production output flexibility and in turn affecting the commodity price.

The nickel production has only one indicator marked with *high* risk, market balance, while three are *medium* risk and three have *low* risk. Therefore it could be argued that the market balance is the biggest bottleneck for nickel. Since not all nickel mined can be used for batteries due to the high criteria, many sources of nickel supply can't be used, leading to lack of supply to meet increasing demand resulting in the imbalanced market. Successful HPAL projects are needed to make up for some of the deficit. For the remaining indicators, it could be argued that the mature production industry for nickel reduces potential risks. There is also a widely geographically spread out production with many actors in different locations. This means that the market is unconcentrated both in terms of country concentration as well as company concentration.

Lithium shows *medium* risk when combining country concentration and country risk indicators while the remaining indicators are deemed with low risk. Lithium is thereby the material with the lowest risk of all materials analyzed. Diversified production possibilities from both brines and mines contribute to stable production output. In addition, major investments to expand the mining production further increases potential supply in 2025. However, since the historical lithium production has not constituted of a lot of mining efforts, one could argue that this type of production is not as mature as the brine operations. Thereby, if the new mine projects in Australia struggle to produce lithium with a stable supply output, it could be a major bottleneck.

Graphite also shows a *high* risk for the country concentration and country risk indicators. For the company concentration, there is a division between the flake production step and BAM step, with *low* and *medium* risk respectively. Two of the remaining indicators, market balance and climate risk have *medium* risk. Graphite does not have any by-product dependency and the commodity prices risks are not applicable. The biggest bottleneck for graphite is that the flake production is expanding into new countries, especially Mozambique, with high risk related to their WGI-score. Similar patterns are followed in the BAM step, which is concentrated in China, that in addition have an indication of low governance performance and transparency.

Table 37: A consolidation of the tables of analysed risk indicators for all materials from Section 5.1-5.4

Risk Indicators	**Cobalt**		**Nickel**	**Lithium**		**Graphite**	
	Mine	Refinery	Production	Mine & Brine	Refinery	Flake mines	BAM
Country concentration	High	High	Low	Medium	Medium	High	High
Country risk	High	High	Medium	Medium	Medium	High	High
By-product dependency	High		Low	Low		No	
Company concentration	Low	Low	Low	Low	Low	Low	Medium
Market Balance	Medium	Medium	High	Low		Medium	Medium
Commodity price	High		Medium	Low		N/A	
Climate	High	Medium	Medium	Low	Low	Medium	Medium

Note: The table shows every indicator for each material in both the mine and refinery step and the evaluated risk as low, medium or high risk until 2025.

6 Mitigation strategies for identified risks

This chapter goes through all of the identified risk mitigation strategies from the theory in Section 2.4. The strategies are analysed separately in Section 6.1-6.5 and assess how they affect the supply chain risk indicators identified in Section 2.3. In the last section, Section 6.6, the findings are summarised and visualised in Table 38 together with a discussion on which risk mitigation strategies that are suitable to use for each supply chain of Nickel, Cobalt, Lithium and Graphite. Thereby, the findings in this chapter will serve as the answer to research question 2.

6.1 Avoiding risks

In the following text, analysis of how and what effects an avoiding strategy could have on each of the identified supply chain risk indicators will be presented. As mentioned in the theoretical findings under section 2.4.1, by using the avoiding strategy the probability of an event to impact the supply chain is driven to zero. However, not all risks are possible to avoid, or avoiding the risk leads to other negative effects that need to be considered.

Climate and country risks are risks which indicate how probable and to what magnitude unexpected political or natural events impacts the supply coming from that particular area. As a focal company, when looking over your supplier base, it would be possible to avoid these risks by not doing business with suppliers from risky areas (high WGI, WRI). With avoidance, the aggregated assessment of the focal companies supply chain's climate and country risk would be lowered. A fully utilised avoiding strategy would only expose the supply chain to the areas deemed safer. However, this strategy limits the number of potential suppliers. The dependency on safer suppliers would go up, meaning lowered bargaining power and higher concentration risks, both country and company. Further, the areas with a high climate and country risk could also have other benefits to them, e.g. cheaper labour cost. In that instance, the avoiding strategy would come with higher supply prices and thereby a beneficial consideration for each specific context is needed.

The by-product dependency is another risk which in most cases are *possible* to avoid. This is because the by-product dependency is specific to each extraction sites operational cost and its ore composition. This means that a focal company could choose to only source the raw material from mines which are not dependent on multiple minerals to be profitable. By doing so, the focal companies supply would not have a by-product dependency even though the overall market for that mineral does. However, similar to the climate and country risk, the avoiding strategy would limit the number of potential suppliers which lowers bargaining power and increases concentration risks.

The risk indicator market balance and commodity price would be increased when using an avoiding strategy. As concluded above, an avoiding strategy is always limiting the number of possible suppliers to source from. Thus, it would lower the possibility to secure raw material in a market shortage because you have less potential suppliers. For the commodity price risk, a lowered amount of suppliers means higher dependencies on the ones left, i.e. lowered bargaining power that in the end results in higher prices.

6.2 Hedging through sourcing from manufacturing at multiple locations

As mentioned in the theoretical findings under Section 2.4.2, implementing a hedging strategy means creating options. Thus, for all the risks identified in Section 2.3 that are associated with being dependent on a small number of options, a hedging strategy would lower the risk. Thereby, a hedging strategy could mitigate the risks associated with country concentration, country risk, by-product dependency, company concentration and climate risk. The following text will go through how to use the hedging strategy to all of these risks.

Even though a concentrated market necessarily not is a risk by itself, it still indicates that the market will be more affected when a disruption occurs as few companies and countries control a big share of the market. To mitigate concentration risks with a hedging strategy, the focal company would increase its numbers of suppliers and the country the suppliers operate within. By doing so, they lessen the impact from a disruption to one of their suppliers, as they now possess more options. Further, the hedging strategy would also give the focal company a higher bargaining power, as they will not be as dependent on any of their suppliers. They could even let the suppliers play out against each other to get as good terms as possible.

If any of the other risks mentioned above are present as well, the focal company should be strategic when deciding which suppliers to expand with. If planned correctly, there is a good opportunity to reduce multiple risks at once, by ensuring that their suppliers are diversified in all of the aspects that the identified risks are present within.

To reduce country or climate risk the focal company should ensure that their supplier base is geographically dispersed, preferably in countries with low WGI or WRI. However, sometimes there are other benefits that outweigh the political instability or natural hazard risk. In these cases, the focal company could still hedge the country and climate risk by having suppliers from countries with a low probability of being affected by the *same* events, even if they all have a high WGI and WRI.

If it is possible to use a hedging strategy to the risks associated with by-product dependency is relying on which dependencies that exist for each mineral at risk. If not all supply is dependent, or if there are different main-minerals in different mines or brines there is a possibility to hedge against the by-product dependency risks. Mitigating the risk is done by ensuring that the supply is spread between the main-minerals. As an example, the risks associated with Cobalts dependencies on copper and nickel could be mitigated by ensuring that the focal company have supply originating from both types of mines. Thereby, if bad market conditions exist for one of nickel or copper, the supply dependent on the other main-minerals would still be stable.

All of the risks mentioned above has been possible to mitigate through a hedging strategy. However, in the cases of market balance and commodity price risk, the hedging strategy is not very effective. In the event of a more long-term market shortage, having multiple suppliers is not beneficial. The shortage will be aggregated throughout the whole market, which means that it will be the price and relationship that determines which buyer gets supply. As the theoretical findings states, having many suppliers makes it harder to have a close relationship and high commitment levels. The supplier will instead sell their product to the buyers they have been working closely with over a long period of time, as they want to preserve that profitable long-term relationship. Thereby, it could be argued that using a hedging strategy could affect the market balance risks negatively.

The risks associated with the commodity price is not really affected by the hedging strategy. As the commodity price risk is market-wide and highlights the volatility and risk of steep price increases. Having many suppliers will not affect how the focal companies buying price is developing compared to the market. Yes, as stated prior in this section, having many suppliers increases bargaining power, which could lead to a lower final price. However, the price is still following the market, letting the suppliers play out each other could give a temporary "discount". The focal company would still be as dependent on the market price development as without the hedging strategy.

6.3 Cooperation with supply chain partners

The cooperation strategy implies that joint agreements with suppliers are a measure to decrease the risk for the involved parties. This strategy is however argued to increase the country and company concentration risk as well as the country and climate risk since as according to theory in Section 2.4.4, a firm only can be highly involved with a few companies. With a high involvement supplier relationship strategy by cooperating with few partners, the geographical dispersion and company dispersion would be lowered, leading to increased risk.

Regarding the by-product dependency, it could be argued that having long-term agreements with supply chain partners could be suitable depending on what kind of materials that are supplied. Since it depends on whether or not the supplier has a by-product dependency on the material that is sold. This means that there are two scenarios, if the supplier is dependent on other materials than what is going to be bought to be profitable, the risk will increase. On the contrary, if the supplier is not dependent on any other material to be sold to make production possible, the risk will decrease. For example, only sourcing from a supplier that mines cobalt as their main product, such as from the mine in Morocco, would decrease the by-product dependency. However, since cobalt is dependent to an extent of 85%, there would not be many suppliers to choose from. The majority of global supply would still be a by-product, not depending on if a joint agreement is made or not. However, you can choose to cooperate with those who have low dependency but may create other problems, see 6.1 avoidance.

Regarding the market balance risk, it could be argued that it can be decreased. Having a long-term contract with a supplier will make sure that the buyer will get the amount of raw material needed, as long as the supplier can keep the capacity at the same level as demanded. It will be of importance for the supplier to follow the contract and make sure to provide according to the terms. Having a long-term contract gives the buyer more chance to influence the supplier and have more control over unpredictable circumstances. In the mining industry, off-take agreements are a common way to secure future supply, where parts of or all the future output are purchased and sold. The agreement is made between a producer and buyer, often negotiated far in advance before construction of the mine and production has begun. This is to guarantee that the future output has a demand, making it easier to get financial actors to loan money to the project. In turn, the buyer has a chance to lock in a price and secure future supply.

The commodity price is considered to be mildly affected by the cooperation strategy. Cooperation between buyer and supplier can make it possible for the buyer to get a price discount compared to the market price since the deal might lead to long-term investments that can decrease costs. However, the price would still be dependent on the market price. For materials that follow the LME index, only minor price adjustments could be done in correlation to the index, where the supplier could charge a premium. Thus, the risk of steep price increases in the short time frame would still exist and thereby a cooperation strategy is not deemed to impact the commodity price risk.

The last risk indicator to take into consideration is the climate and country risk. As argued at the beginning of this section, higher involvement with fewer suppliers would decrease the geographical dispersity and thus increase the effects from a political and natural hazard event. However, the risks could be mitigated by choosing to cooperate with suppliers located in regions with low WRI and WGI. Though, unexpected events which affect the supply chain is always possible which means that being dependent on a few regions for the supply is associated with a high risk. Even if there is a low probability of these kinds of event, a disruption would be devastating, as the focal company are so dependent on a few regions.

6.4 Control through vertical integration

Using a vertical integration strategy is argued to lower the supply risks for the focal firm who acquires or increases its shares in the raw material supplier firm. Since the supplier can decide which buyer that should receive the produced raw material, vertical integration will allow the focal company to gain control of the decisions and processes Thereby, the focal company have a greater influence on how much is produced and who to ship the product to, which lowers dependencies on other actors. The risks argued possible to mitigate through a vertical integration strategy is, therefore, market balance, commodity price and by-product dependency.

In the market balance risk, it is a shortage of supply that are deemed to negatively affect a manufacturing company dependent on supply. In a scenario of market shortage, it will be the price and relationship with the supplier that decides who will secure their needed input products. For the focal company to vertically integrate and thus owning and operating the mine or refining step all by itself could be seen as the highest level of commitment possible. By fully control their own supply, they would always firstly secure supply to their own manufacturing to then only sell abundant supply to the market.

A vertical integration strategy would lower by-product dependency risk. It could remove the dependency completely if you vertically integrate through acquiring an extraction operation with a cost to produce the mineral that is seen by the focal company as an acceptable input cost. However, if the production costs are high and the operation is dependent on selling other minerals to cover the costs, a dependency would still remain. Though, the dependency would be lower compared to when buying supply from the market. This is because utilising a vertical integration strategy when there is a low market price on the main-mineral would enable the extraction operation to keep running, even though this particular step of the supply chain is not profitable. The focal company doesn't necessarily need to make a profit in every step of the production workflow, instead, they can have a more holistic perspective. The crucial number for a manufacturing company is that their end-product is profitable. In a contrary scenario, a self-operating extraction company would pause production until better market conditions to enter, thereby the vertical integration strategy actually mitigates the risks associated with by-product dependencies in both scenarios explained above.

Similarly, the vertical integration strategy lowers the risks associated with being dependent on the markets commodity price. As a manufacturing company, owning the extraction step of raw materials by yourself makes you less dependent on the market price of the raw material as it instead is the operating cost that is your "price".

As mentioned in the theory under Section 2.4.5, having a vertical integration strategy decreases flexibility because variable costs are shifted to fixed costs. This means that the focal company would be very dependent on the very few operations that they own, with no possibility to spread or hedge the risk. Thereby, all the risks that come with being dependent on a small number of options will be increased when applying this strategy. These risk indicators are; country- and company concentration and country- and climate risk.

The concentration risks are being increased by the mere fact that there are less potential suppliers, i.e. more concentrated supply base. For climate and country risk, it would of course be possible to buy a company in the extraction step that is positioned within an area of low WGI and WRI. However, a low WGI and WRI is not a guarantee that there will never be events that cause disruptions. Further, having supply from low WGI and WRI areas is possible without vertically integrate as well. The difference is instead that the focal company still is dependent on a smaller number of suppliers in these low risk areas when using a vertical integration strategy. Thereby, the overall assessment is that the climate and country risk together with the country or company concentration is higher when using a vertical integration strategy.

6.5 Sharing/transferring risk through contracts

Irrespective to what strategy that is going to be used, a contract between buyer and supplier of the raw material is needed. As seen in the theory in section 2.4.3 there are many different types of contracts. The structure of the contract decides how the risk is distributed between the actors.

Using a fixed-price contract, the buyer of the raw material would benefit if the raw material market price would increase since the contracted price point would remain. This would eliminate the market risk for the buyer if the prices increase, but the supplier would experience a loss. However on the contrary, if the prices go down the buyer would overpay in comparison to the market price and the supplier would get a higher margin. Because of the speculative nature of a fixed-price contract, a risk-averse supplier would want to include a high risk premium in the price. Thus, if the focal company can accept more risk than the supplier, either because of firm size or risk-acceptance, including some flexibility in the contract would be a good idea.

Having a contract with flexibility built into it will transfer the risk or share the risk between buyer and supplier. The volatile raw material prices can thus be coped with by developing a contract that makes the final price dependent on the index price for the raw material. Therefore it is argued that developing a contract suitable for the context of the volatile raw material prices can if done correctly decrease the commodity price risk. The contracts can also be a way for the companies to achieve control on the impact of commodity price.

A procurement control contract would benefit a buyer who has more bargaining power or knowledge than its first-tier supplier of raw material. The buyer could use its bargaining power to make sure that the tier one supplier gets the material needed from the tier two supplier with the best terms possible. The buyer would, therefore, have more influence in the supply situation which then is argued to have a positive impact on the market balance.

Regarding the other identified risks in this master thesis, country risk, country concentration, company concentration, climate risk and by-product dependency, the choice of contract is argued not to have a big impact on these risks. Instead, these risks are affected by which of the strategies in Section 6.1-4 that is combined with the chosen contract. Since the contracts are

6.6 Summary of risk mitigation strategies

In section 6.1-5 the risk mitigation strategies have been analysed isolated from each other. In this section a developed analysis is made, on how the mitigation strategies correlate and affect each other. Lastly, Table 38 is presented which is a synthesisation of the analysis in Section 6.1-5, where all the mitigation strategies and risk indicators are compared.

The different mitigation strategies are concluded to have a diverse effect on the identified risk indicators. It is therefore argued that the choice of mitigation strategy is dependent on which risk indicator that is deemed as most important for the specific context.

The table cells in Table 38 are filled with arrows and colours, and how they should be interpreted is now explained. An arrow pointing up is indicating an increased risk and the cell is therefore coloured in red. An arrow pointing down is indicating decreased risk and the cell is coloured in green. If the arrow points to the side, the risk is argued to be unaffected and are colour in grey. Lastly, if there is one arrow up *and* down in the same cell, the effect depends on the context, which is more detailed in the section for that specific risk mitigation strategy. This cell has the colour white.

As can be seen in Table 38, the different strategies have different effects on the risk indicators. Looking at the hedging strategy compared to the cooperation strategy, they are opposite to each other since, as described in Section 6.2, the hedging strategy increase the numbers of suppliers to the focal company while the cooperation, as described in Section 6.3, decrease the number of suppliers. The opposite arrows between the two strategies in Table 38 clearly show this relation. Further, it shows that the number of suppliers clearly have a big influence on the majority of the different risk indicators.

The avoidance strategy, on the other hand, affects on another layer, since the strategy decreases the number of *potential* suppliers. To reduce the by-product, country risk and climate risk this strategy constitute, as mentioned in Section 6.1, of making the choice to avoid the regions and suppliers prone to these risks. This will however, like the cooperation strategy, reduce the supplier base and thus increase the country concentration and company concentration risk.

Lastly, the vertical integration strategy can be seen as an extension of the cooperation strategy, where collaboration is as high as possible, by acquiring companies and thus have had a 100% control of all processes and operations. Therefore the vertical integration strategy and cooperation strategy gets a similar risk response, meaning that the arrows points in the same direction for all but two indicators. One of these two indicators that not point in the same direction are however, for the cooperation strategy, considered to go in both direction depending on the context.

As argued in Section 6.5, the sharing/transferring risk mitigation strategy is about writing contracts suitable for the context between a buyer and supplier. The result from this is as can be seen in Table 38, argued to only decrease the risk for market balance and commodity price, due to the contractual agreement to receive supply at a certain price point. The remaining five other risk indicators are argued to be non-affected, since the sharing/transferring risk strategy focus only on having a contract with a supplier, while it does not say how many suppliers, in what countries or regions. It thus needs to be combined with one of the other four strategies.

Table 38: A synthesisation of the risk mitigation analysis.

Risk indicator	Avoidance	Hedging	Vertical integration	Cooperation	Sharing/transferring
Country concentration	⇧	⇩	⇧	⇧	⇨
Country risk	⇩	⇩	⇧	⇧	⇨
By-product dependency	⇩	⇩	⇩	⇧⇩	⇨
Company concentration	⇧	⇩	⇧	⇧	⇨
Market Balance	⇧	⇧	⇩	⇩	⇩
Commodity price	⇧	⇨	⇩	⇨	⇩
Climate risk	⇩	⇩	⇧	⇧	⇨

Note: The table shows every mitigation strategy and how it affects the identified risk indicators, illustrated by arrows. An arrow pointing up indicates increased risk, down decreased risk and to the side unaffected

6.7 Suitable risk mitigation strategies for each material

In the following paragraphs, the analysis from Section 5 and Section 6 are combined to find suitable mitigation strategies for each material.

The cobalt supply chain has a high risk on 5 of the 7 risk indicators. Given that all risk mitigation strategies have pros and cons, it is argued that choosing a suitable mitigation strategy for cobalt supply is complex. However, the majority of the risk indicators would have a decreased risk with a hedging strategy. The market balance, indicated with medium risk, would though be facing possible risk increase and to cope with this a cooperation strategy would be needed. Thereby there would be a tradeoff to choose if this possible risk increase of one indicator is worth to decrease the risk for five others.

Looking at the nickel supply chain, the indicator with the highest risk is the market balance. To cope with this, either to vertically integrate or using the cooperation strategy would decrease this risk. However, nickel also has medium risk on country risk, commodity price and climate risk, which would be negatively affected by a cooperation strategy. To counter these risk, there would be a need to combine a vertical integration strategy or cooperation strategy with a hedging strategy which could be a complex process. Therefore it could result in a trade off, where a decision has to be made on what risk indicator that has the highest importance for the company, and a mitigation strategy that fits this context should be chosen.

The biggest risks for lithium is the country concentration and country risk that both are indicated with medium risk, as seen in Table 37, while the rest of the indicators have a low risk. By looking in Table 38 it could be argued that the hedging strategy could be a possible strategy to mitigate these risks since both country risk and country concentration risk is decreasing with this strategy. However, with a hedging strategy, the risks associated with the market balance would increase. In the case of lithium, this risk was assessed to be low. Therefore it is argued that hedging lithium supply would benefit more from decreasing the medium country concentration and country risk than it would negatively affect its low market balance risk.

Looking at the graphite supply chain, country concentration and country risk are indicated in Table 37 with high risk. The company concentration, market balance and climate risk are indicated with medium risk. A hedging strategy would decrease the risk for all these indicators expect for the market balance. To cope with the market balance, vertical integration or cooperation would be suitable, but would on the contrary increase the risk for the other indicators. Therefore it is argued that the company has to make a decision on what indicators that is of most importance to decrease the risk for and chose mitigation strategy accordingly.

7 Discussion

To recap, the purpose of this master thesis was to contribute to the understanding of what risks there are in the supply chains of the raw materials essential to the lithium-ion battery and how these risks could be mitigated from the perspective of an EV-manufacturer. The findings and result from this master thesis have fulfilled its aim by (1) identify seven risk indicators from the literature that all were relevant to our industrial problem, (2) compiling and calculating up-to-date market data together with an analysis that highlights the risk profiles for the raw materials investigated in this master thesis, (3) identify risk mitigation strategies relevant for an EV-manufacturer together with an analysis on how they affect the risk indicators, and lastly (4) a discussion on which risk mitigation strategies that would be suitable to further investigate for companies sourcing each of nickel, cobalt, lithium and graphite.

Starting with contribution number one, none of the identified risk indicators is new on their own. They were all identified from the literature, though this master thesis specific combination of the risk indicators are unique and thus contributes as a comprehensive framework capable of highlighting very different risks and thereby offering a comparison between the four raw materials, even if they possess very different characteristics. Prior research has often been more specific, focusing on only one raw material or raw materials with similar challenges and attributes.

Further, the framework on supply chain risk indicators is usable for many contexts outside of our master thesis. Even though the framework is created based on the specific characteristics of our industrial problem, the characteristics are not unique for Volvo, meaning that it is generalisable for similar contexts. The framework is a great method to structure and guide the market intelligence collection for any company who are dependent on raw materials in their more refined end-products. When a company is keeping themselves updated on the market developments of their sourced materials, it is possible to escalate and act upon risks earlier, and thus minimise their effects and probability of occurring.

The second contribution, the compiled and calculated market data with the corresponding analysis of the materials risk profiles is contributing with an update on the different data points. As stated prior in this thesis, the supply chains of these materials are constantly changing, meaning that there will always be a contribution by providing newer data. This data can then be used by any company or researcher who is interested in any of the materials lithium, nickel, cobalt or graphite. However, the fact that the supply chains are ever-changing means that it is impossible to complete the data collection. There will always be a need to update the data points and make new assessments on the current risks. The risk profiles presented in Table 37 should thereby not be interpreted as the final answer, but instead as guiding points on where it is most efficient to spend time on the continued data collection. It is changes to the risk indicators of high risk that would be most interesting for companies to follow. As an illustrative example, a new big nickel mine which would increase the global production capacity would have a greater effect on companies buying nickel than changes to the concentration between the producing countries. Because the market balance risk is assessed to be high, compared to the country concentrations low risk.

Regarding the third and fourth contribution which is connected to research question two, neither of the risk mitigation strategies are new contributions. They all exist in prior research but is in this master thesis identified to be relevant for our specific industrial problem and thus, companies in a similar situation as Volvo could use any of these strategies in their sourcing of raw material. The risk mitigation strategies are then analysed together with the risk indicators in Chapter 6 to see how each strategy affects the risk, if it mitigates or increases the risk. So this master thesis does not only include specific risk indicators *or* risk mitigation strategies. Instead it provides the full match on how the risk indicators and risk strategies affect each other, which means a comprehensive solution to companies sourcing risks associated with raw material. The master thesis methodology can be a guide on how companies can go from gathering market data all the way to choosing sourcing strategies with the aim to mitigate supply chain risks.

In addition to our analysis, the risk mitigation strategies often come with some sort of additional cost. Thereby the companies need to assess how much the risk mitigation strategy would cost, and judge if they can afford it and if the cost is worth the potential benefit that can be extracted from the strategy. This is an area where there is potential to do further research, to identify empirical data on what type of cost that is associated with each strategy. The cost would also give indications on the feasibility of strategies for different companies. It may be that some strategies have a very large initial investment cost, and thus only feasible for large corporations. These kinds of discussions are excluded in this master thesis but would with further research provide more nuance and help decision-makers at the companies. However, this master thesis fourth contribution, the discussion on which strategies that are relevant for which materials, based on the identified risks and how the risk mitigation strategies affect the indicators, can be used as an initial direction to which strategies to *start* investigating the cost and benefit considerations for.

8 Conclusion

To answer the two research questions, this master thesis analysed the supply chain of cobalt, nickel, lithium and graphite to identify possible risks that could affect the supply situation of lithium-ion batteries for the EV-industry by the year of 2025. The identified risks was analysed to find what mitigation strategies that could be used to address the identified risks.

The theoretical findings from the theory section of this master thesis were concluded in a framework which constituted of identified risk indicators, applicable when predicting supply chain risk of raw materials in the extraction and refinery level in a foreseeable future. The framework includes boundaries for each indicator, making it possible to not only identify a risk, but also assess the magnitude. Further, the theory section also presented risk mitigation strategies applicable to address the identified risk indicators, with the aim to minimize the effect of supply disruption. In this master thesis, the theoretical framework was applied to the raw materials cobalt, nickel, lithium and graphite, but the risk indicator assessment is generalisable to any company sourcing any raw material with the aim to identify supply chain risks in a similar time-frame as this master thesis, i.e. around 5 years.

There are limitations on having a method built on the need for data from companies around the globe as countries differ in their level of transparency and governmental pressure on companies to share information to the public. In some cases this made it challenging to retrieve trustworthy and comparable data, creating the need for the use of different types of sources. Different types of sources could have different incentives to share the data, as an illustrative example, mining companies could extrapolate their production capacity to secure financing or consultancy firms could paint a darker picture of the future than the reality to sell projects. Triangulating data by using our three-layer data collection method is therefore deemed to be very helpful.

The data presentation includes a major amount of data that have been collected to be able to calculate and aggregate all of the identified supply chain risk indicators. When the data was analysed, it could be concluded that the supply chain risks and what measures to be taken to mitigate them varies between the studied materials. The specific findings per material will be concluded below.

For the cobalt supply chain, the risk of disruptions is high. The supply of cobalt is strongly concentrated on the country level, in both the mining and refining step. 85% of cobalt is mined as a by-product of either copper or nickel. There is also poor governance performance in the mining countries as well as the refining countries. The strongly concentrated market on the mining side would also be impacted hard in the event of a natural hazard, due to the vulnerability of the largest producing country DRC. A factor that reduces the supply risk is that the company concentration is low, with many individual companies operating in both the mining and refining step. Artisanal mining is a factor that could affect the market balance. The ASM supply a significant share, 12%, of total global cobalt supply. There is an ongoing debate on whether or not to use cobalt from these sources due to ethical concerns. If ASM is not included, the market balance would be facing an even larger deficit. To mitigate these risks, there would be a need to diversify with a hedging strategy. However, since the market is very concentrated, it is complex to find one strategy that would reduce all risks in its entirety. But in order to with high confidence say what strategy that should be used we conclude that there would be a need to assess the tradeoff between the cost to use a certain strategy versus the effects if no mitigation strategy is applied.

For the nickel supply chain, the biggest risks for disruptions is caused by the market balance. High requirements on the material to be suited for an EV-battery makes supply fall short compared to the increased demand. The HPAL projects will play an important part to be able to increase supply. A majority of supply, 63% origins from countries that have indications of low governance performance. However, a factor reducing the supply risk is the market concentration, with many companies in different countries that increase the geographical spread of possible supply. Another factor reducing the supply risk is the very low by-product dependency at 2%. A mitigation strategy to cope with the market balance would be to either vertically integrate or use the cooperation strategy to find a long term supply agreement with a nickel supplier.

The lithium supply chain is concluded to have the lowest risk of all studied materials. The risk of disruption is low. The only factor that increases the risk is that the lithium supply is concentrated on the country level, in both the mine and refining step. However, there is a majority of factors reducing the supply risk. The increased numbers of new mine projects in Australia give the supply a boost to be able to meet the growing demand. Many of the new projects are initiated by new actors on the market, making the concentration of companies within the threshold of a low concentrated market. The risk to face a deficit with supply is also deemed as low. The by-product dependency is low. The conclusion made on how to mitigate the identified risk would be to use a hedging strategy, to diversify the supply from different geographical locations.

Conclusions made on the graphite supply chain is that the risk for disruption is considerable. The supply is strongly concentrated on the country level, both in the mine and BAM step. Big projects in specific geographical locations with good availability of graphite are the reason for the concentration. There is also weak governance performance in these locations making the country risk high in both the mine and BAM step. Even though the production is concentrated on the country level, the concentration of individual companies is within the threshold of an unconcentrated market. Other factors such as the by-product dependency do not affect graphite since it is economically feasible to mine on its own. Conclusions on how to avoid supply disruption would be that it is hard to mitigate all the identified risks with a single strategy. The hedging strategy would lower all risks except the market balance, which in turn would be increased using this strategy. To cope with the market balance a cooperation strategy would be beneficial, but would then increase other risks. Thereby we conclude that the EV-manufacturer has to make a decision on what risk indicators is of most importance for them, together with the corresponding cost per strategy and chose mitigation strategy accordingly.

By returning to the aim of this master thesis, which was to contribute to the understanding of what risks in terms of supply there are in the supply chain of raw materials for EV-batteries and how to mitigate them, it is now possible to conclude that the aim has been fulfilled by (1) identify seven risk indicators from the literature that all were relevant to our industrial problem, (2) compiling and calculating up-to-date market data together with an analysis that highlights the risk profiles for the raw materials investigated in this master thesis, (3) identify risk mitigation strategies relevant for an EV-manufacturer together with an analysis on how they affect the risk indicators, and lastly (4) a discussion on which risk mitigation strategies that would be suitable to further investigate for companies sourcing each of nickel, cobalt, lithium and graphite.

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