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Analyzing the permanent magnet network structure

An assessment for selecting essential desicion making criterias when buying sintered NdFeB magnet

Master's thesis in Supply Chain Management

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Cover: Permanent Magnetic field

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Abstract

Electrification is of increasing importance today. Rare earth elements, particularly those used in magnets for high-tech applications and renewable energy, are essential for Europe's economy and green agenda. Today China produces more than 90% of the world's rare earth magnets. From a European industry perspective, the significant supply risk for these minerals is caused by their high manufacturing concentration, rising potential international conflicts, and expanding domestic demand in China. This situation is mainly driven by an increase in electrical mobility.

The aim of this study is to analyze the permanent magnet value chain and its connected network of actors and relationships. In addition, the aim is to analyse and suggest important supplier selection criterions for permanent magnets, from a buying firm perspective. There is a scarcity of supp chain standards and transparency for governance, social, and environmental implications in the permanent magnet value chain. Therefore, the study also covers an analysis of the resiliency in the permanent magnet value chain.

The theoretical framework of the study builds on network analysis of the resources and the relationships in the permanent magnet network to understand the dependencies and the expected change in the value chain dynamics. The micro, meso and macro levels of the network was a complementary aspect of the study to highlight the structure of the governmental initiatives, actors and their relationships and activities in the value chain. The method of the study focused on the downstream part of the value chain. In total, about 21 distributors, manufacturers and industry experts were interviewed to understand the network of the value chain of permanent magnets and get different perspectives on how various stakeholders approach the market and its development. To get an applicable perspective from a buying firm perspective, a case company called Alpha that is planning to enter the market was included in the study.

The absence of diverse rare earth magnets supply chains and the exponential rise in demand for these high-performance permanent magnets, primarily in the automotive and renewable energy industries is the reason for the expected supply chain disruptions. In comparison to their Asian rivals, EU manufacturers have greater difficulty accessing the resources, and they particularly suffer from speculatively driven price volatility. The rare earth value chain is crucial to sustainably produce magnets in larger volumes and should be considered in terms of supply risks, environment, social and economic factors.

This study identified six areas of importance for the buying firm to consider while entering the permanent magnet market. Firstly, focusing on technological requirements to consider for the selected permanent magnet in the end application and the downstream capabilities. Secondly, sustainability criteria from an economic, environmental and social aspect. Furthermore, the geopolitical factors including intellectual property and localization analysis. As a result, the expected price mechanism and the volume and capacity trends in the market was another essential perspective to analyze. Lastly focusing on the strategic importance of permanent magnets for the buying firm to determine the level of investments needed when entering the permanent magnet value chain.

Keywords: permanent magnet value chain, sustainability, network perspective, supply chain resiliency, supplier selection criterias

Acknowledgements

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First, we would like to thank our supervisor and examiner from Chalmers, Frida Lind, for all the valuable support and input for the research development. She has always been accessible to talk about ideas and to help move forward with the process. Moreover, we would also like to thank the participating interview respondents for the time they have spent and the valuable insights they have provided. Lastly, we would give a special thanks to our supervisor at Alpha who has been a valuable contributor to the thesis. She has been a great source of inspiration and support to start, improve and to complete the thesis.

Ghazaleh Shafaei & Melissa Dilan Gunes, Gothenburg, May 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

Dy	Dysprosium
EM	Electric machine
EV	Electric vechile
HRE	Heavy rare earth
LRE	Light rare earth
Nd	Neodymium
RE	Rare earth
REE	Rare earth elements
REPM	Rare earth permanent magnet
OEM	Original equipment manufacturer
PM	permanent magnet
Tb	Terbium

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Introduction

Rare earth permanent magnets are an essential technology for the electrification of transportation and the shift to clean energy. Europe is expected to continue its dependency on China further into the 2020s for the rare earth magnets that is needed for wind turbines, electric vehicles, consumer electronics and other applications. Therefore, there is a need to investigate the network structure of rare earth permanent magnet value chain. This section will present the background, aim and research questions of this study.

1.1 Background

OEMs are struggling to secure the supply simultaneously as they are planning their electrification journey. The price of the raw material needed for magnets has increased significantly during a short period of time which also gives rise to another challenge for the OEMs. Rare earth (RE) magnets are one of the important aspects to strategize in order to reach the European commission climate target by 2030 and to be aligned with the Paris Agreement (European Commission 2023). There is a push to develop new mines, create substitutes, cut waste, and increase recycling of RE magnets. In line with the goals of the Paris Agreement, European automakers are dedicated to achieving climate neutral mobility by 2050.

China has made significant investments in the development and research of RE technologies since 1927 when they discovered RE resources in Inner Mongolia (Tse, 2011). RE were designated as a strategic and protected mineral by the Chinese government in 1990. The market for permanent magnets (PMs) saw a drastic change (Hurst, 2010). In 1998 Japan, US and Europe produced 90% of the world's magnets, however currently China sells the majority of the RE magnets, or those made with Chinese RE oxides.

In the meantime, plans were being established by the Ministry of Land and Resources for rare earths as a form of strategic commodity (Tse, 2011). However, because of policy ambiguity and poor communication, production levels consistently exceed the quota established by the government. Up until 2008, the output level increased substantially, and China was responsible for more than 90% of the REs produced globally. The government implemented export tariffs to safeguard the domestic supply of vital minerals and the rebates on RE exports were withdrawn due to growing domestic demand. China drastically limited crucial mineral exports in

2010, as a result of a political deadlock, which unexpectedly led to an increase in rare earth element (REE) prices (Humphries, 2010). The unexpected reduction in permitted REE import limits from China as well as the ensuing sharp price increases shook the globe into awakening as China developed into a Goliath in the RE sector (Hurst, 2010). Strategic reliance on China had changed the game and was now being utilized to increase its influence on US, Japan, and EU. Consequently, it served as a wake-up call for the current supply chains for essential minerals and REEs (Critical Materials Strategy, 2011). Some of the important elements, including dysprosium (Dy), neodymium (Nd), terbium (Tr) was shown to be critical for clean-energy applications. It also resulted in some trade disputes for the World Trade Organization.

China has since 2001 been the largest producer of rare earth permanent magnet (REPM) (Dong, 2017). They can offer abundant RE resources with low labor cost, high production capacity and high quality (high magnetic performance) due to well established research programs. Customers can easily find suitable magnet product from China that satisfies all their industry needs. China dominates the production of many magnet-related applications, including wind turbines, electric bicycles, elevators, air conditioners, and different permanent magnet (PM) motors, as a result of the rapid expansion of the RE magnet sector. These application requirements consequently fuel ongoing research of superior and affordable magnetic materials. Since they started their journey, they have reached a higher level of know-how compared with actors that have recently started to look at the magnet industry. While other countries were eliminating mines due to their negative environmental effects, China has been able to dominate the industry through decades of smart investment in miners and processing facilities (Smith et al., 2022). The value of a RE resource depends on how efficiently, affordably, sustainably, and environmentally responsible the metal can be mined (Bisaka et al., 2017). Only a few deposits are mined for RE, irrespective of the fact that many deposits have been found across the world. The three most well-known RE mining facilities are Mountain Pass in the US, Mount Weld in Australia, and Bayan Obo in China.

It is anticipated that the EUs automotive and transportation markets will increase to over €400 billion (Gauß et al., 2021). Market instability and excessive price volatility have always afflicted the PM market (Smith et al., 2022). Given that the market is instable, industrial and technological investments are less appealing since businesses may struggle to turn a profit. Due to the lack of readily interchangeable materials and technologies, users of materials and magnets are also constrained in their ability to respond quickly to high-price environments. Likewise, technological substitutions that occur eventually will sufficiently have high prices due to fluctuations in demand and decreased performance.

REE is of strategic importance for the EU's green and digital transition, particularly their use in permanent magnets in low-carbon technologies such as wind turbines and electric vehicles (Rizos et al., 2022). However, the EU is facing challenges in meeting the expected demand due to limited domestic production capacity, increased geopolitical conflict, and significant dependency on imports. Recycling can help to secure some of this demand, however, due to technological, supply chain, financial, and regulatory barriers, PM recycling has not yet been developed at a large scale in the EU.

1.2 Rare earth elements and magnets from a OEMs' perspective

There are 17 REE and amongst them five have magnetic properties that can be used for PM, neodymium-iron-boron (NdFeB) (Smith et al., 2022). The term "rare earth" is somewhat misleading because these 17 elements are quite abundant. However, they are complex and expensive to extract since they are distributed throughout the crust of the earth. NdFeB and hard ferrite magnets are the market leaders in the magnet industry (Cui et al., 2022). These two magnet components, which have very distinct magnetic properties and price points, account for about 90% of all PM manufactured and utilized today. Hard ferrite magnets make up most of all PM varieties produced by weight, accounting for more than 80% of the world's total output of permanent magnets. PMs have the ability to create magnetic fields and maintain it in the existence of an opposite magnetic field. These PMs improve the efficiency of electrical machinery compared to those without them. All strong magnets consist of RE elements. Due to the rising demand and limited availability of RE elements, such as Dysprosium (Dy) and Neodymium (Nd) they have turned into key resources. The RE criticality problem may be effectively mitigated by streamlining the production process to cut waste and enhance component uniformity. In the EUs strategic aspects of energy and digital transition, the REE such as Nd, Pr, Tb and Dy are classified as a strategic raw material (European Commission, 2023a). These materials are subject to a supply risk in the future.

NdFeB magnets, which includes both sintered and bonded NdFeB magnets, account for the largest portion of the PM market, accounting for 66.5% of sales value (Severson et al., 2022). Sintered Nd magnets make up about 90% of the world's total NdFeB production. Therefore, it can be estimated that 6.5% of the market for PMs is made up of bonded Nd magnets, and 60% of the market is made up of sintered Nd magnets.

NdFeB permanent magnets featuring high performance are essential components for EV motors, and demand for these magnets is expected to increase by an estimated 18% per year until 2030 (Ma and Henderson, 2021). NdFeB has several advantages for both established and new technologies. These technologies include defense technology, clean energy, power tools, sensors consumer electronics, machinery, and many others (Brown et al., 2002). RE magnets, in particular, make it possible to employ technologies that increase the simplicity and efficiency of the electrical machine (EM) (Smith et al., 2022). These technologies make it possible to produce electric vehicle motors that are more powerful, more effective, and lighter.

As a result, several OEMs are attempting to comprehend the PMs, especially NdFeB supply market in order to position themselves and acquire access to these materials for their electrified products and sustainability aim. It is important for OEMs to understand the network dependencies and find a suitable way to build a resilient sourcing strategy that can inhibit risks and be prepared for eventual market volatility. In this research study the starting point is taken from a manufacturing company perspective. This company is working with electric motors to better understand the PM value chain. The company is facing the same challenge as many other OEMs to understand the value chain. This company will be named under the anonymous name Alpha due to confidentiality. Alpha's purchasing department wants to develop their permanent magnet sourcing capabilities.

1.3 Aim

The aim is to describe and analyze the permanent magnet value chain and its connected network of actors and relationships. In addition, the aim is to analyze and suggest important supplier selection criterions for permanent magnets, from a buying firm perspective. This master thesis is the outcome of a collaboration between Chalmers University of Technology and a manufacturing company within the purchasing division.

1.4 Problem discussion

The network of permanent magnets is complex due to several actors and activities included in the value chain. This is generally not understood by a buying firm that is willing to enter the market. The first step for an OEM is to clarify the different sub parts, processes and actors and the different connections in the network. Understanding the market's processes is essential for understanding it from a business standpoint. A determination of the processes will give a common understanding of the different actors' involvement in different parts of the value chain. Hence the first research question regards the process of permanent magnet production.

RQ1. What is the manufacturing process for sintered NdFeB magnets, from mine to finished product?

Based on the understanding of the processes, it is of importance to study the value chain, where the actors are located, at what level of the supply chain they are acting and how they are interrelated. This will give an understanding of the network structure of the permanent magnet but also where the challenges are located. The analysis will be done by using a meso-micro-macro approach. To create sustainable, innovative networks, all three levels—micro, meso, and macro—must be considered and managed (Melander & Lind, 2022). Collaboration with actors at the societal level as well as network actors is necessary for innovation development at the firm level in order to influence and comprehend regulations, consumer trends, and public funding. The second research question will therefore focus on understanding the permanent magnet value chain.

RQ2. How is the network of the permanent magnet value chain structured?

In addition to the criteria, the buying company needs to consider how they view the future purchase of the new product. The company needs to determine what impact the purchased products have on their business. This emphasis the level of effort that the buying firm would like to invest to assess the new sourcing. By using the purchasing portfolio model, Kraljic matrix for the sintered NdFeB magnet the firm can get help to categorize and prioritize their procurement strategy based on the criticality of the product and the complexity of the supply market. The Kraljic Matrix can also help identify potential risks and opportunities in the supply chain of permanent magnets (Garzon et al., 2019). In summary, using the Kraljic Matrix when sourcing permanent magnets can help a buying firm better understand its procurement strategy and prioritize its efforts to ensure a consistent supply of high-quality magnets at optimal costs. The third research question will therefore be constructed in order to classify the sintered NdFeB in a Kraljic Matrix.

RQ3. How would the sintered NdFeB magnet be classified in a strategic purchasing portfolio model?

The network analysis will also result in finding the important factors when sourcing permanent magnets related to macro, micro and meso aspects that eventually can have an effect on an OEM such as Alpha. To support the supplier selection of PM, Alpha needs to consider the suppliers' position in terms of their resources and activities. Furthermore, they need to consider external factors affecting their supplier selection. The fourth research question will therefore focus on the permanent magnet specifications and the requirements that the supplying company needs to fulfill in order to be a potential supplier for an OEM.

RQ4. Which are the important criterias to determine when sourcing sintered NdFeB magnets?

1.5 Limitations

This thesis will be limited to the production of permanent magnets and their overall value chain structure and the specific areas that are of importance for the sourcing of magnets. The report will not include any design specifications or advanced engineering related to the technology behind magnet production as such. Further the report will not investigate the value chain of other applications where magnets also are a key part of, for instance generators and e-axels. The supply market for permanent magnets includes different types of magnets, however this report will focus on NdFeB magnets. This research will not focus on ferrite and RE free magnets.

2 Methodology

This chapter explains how the report will be structured and executed. The subsections include research structure, data collection methods, systematic combining and reflections on the quality of the study.

2.1 Research structure

To meet the aim of this master thesis, an introductory pilot-study phase was conducted. The goal of the pilot study was to better comprehend Alpha's challenge and to define the research objectives that the master thesis would address. The pilot study-phase included organizing the project's work and developing a research design. As Bell et al. (2022) highlight, the research design offers a framework for data collecting and analysis. As a result, a workflow chart, depicted in Figure 2.1, was prepared to provide a clear picture of the stages that were required.

This project's process was mainly conducted sequentially since the outcomes from each step provided guidance on what actions needed to be accomplished in the next phase. The execution of the phases may be done simultaneously due to the complexity of the relations in the supply chain network. It is necessary to continuously review the current stage and turn back to fill the gaps, both in terms of knowledge and data. Therefore, stage 3 and 4 were an iterative process where also stage one was reviewed to secure the relevant theory that could support the analysis of the secondary and primary data. The first stage in the study was to explore literature related to the topic in order to understand what is happening in the market. Further, a mind map was created to start different ideas that can give rise to the objectives of the thesis. The result from the first stage acts as a framework for what sort of data must be gathered to answer the study objective. Secondly, market data collection began, resulting in collection of data that was extensive enough to identify the challenges of the examined value chain of magnets.

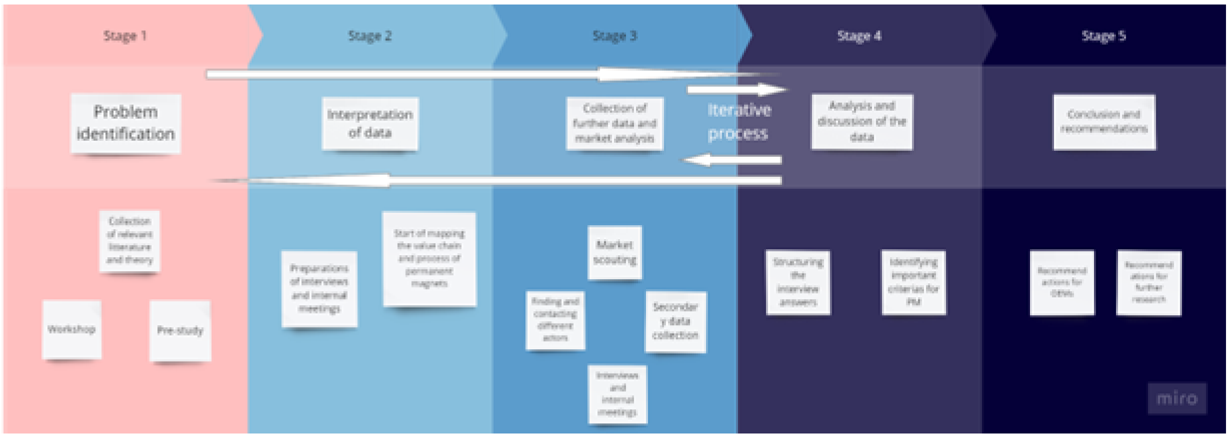

Figure 2.1: *An illustration of the workflow. Inspired by Bell et al. (2022).*

The primary data collection started with a first contact through a workshop with different employees from various business areas within Alpha. Thereafter, secondary data was used to understand the magnet production processes as a base for the market analysis. The market analysis included looking at different actors in the permanent magnet value chain. These actors were then interviewed as the source of primary data. Supplementary data was from secondary data and internal meetings with various functions from Alpha, for instance advanced engineering. This was to get an understanding of Alpha's position in the value chain and help them in their sourcing strategy. Based on the empirical data important criteria's for selecting a supplier were identified. Lastly, a recommendation and conclusion section were constructed to summarize the findings and recommendations on future research.

2.2 Qualitative method

This research is primarily qualitative in nature, with data gathered through workshops, interviews and secondary such as news articles, journals and presentations. Bell et al. (2022) highlights that qualitative research is inductive instead of deductive. This indicates that data collection is the driver for the link between the theory and research rather than the opposite relationship. This inductive approach has been used in order to avoid being constrained by theoretical frameworks during the initial stages of collecting data.

Denscombe (2018) describes that researchers using a qualitative approach want data that is 'close', in order to develop a deeper understanding of their unit of analysis. Such research involves a few events or people in order to make an extensive analysis. Data collection in qualitative research takes place, for example, through interviews, observations and case studies in which the researcher usually participates (Olsson & Sörensen, 2011). Furthermore, Olsson and Sörensen (2011) mention that the researcher and the informant have an open interaction and that the research becomes more flexible where questions can be gradually deepened.

This study aims to understand the value chain of sintered NdFeB magnet and the important supplier selection criteria. The methodology enabled the researchers to gain a deeper understanding of how actors in the network interact with each other and how the network was structured. It was thus appropriate to use a qualitative approach for the study.

2.3 Main study

This section will describe primary data collection of the main study that includes, pre-study, workshops, interviews and secondary data.

2.3.1 Pre-study

In the pre-study the vision and goals of Alpha in the field of permanent magnet were investigated and discussed in order to understand their challenges and opportunities. The research is outlined in the pre-study so that the effort is concentrated on the main issues and areas of the company where the most developments may be made. The initial workshop with the team was an effective way for a present-situation analysis, setting requirements and concept definitions. This was the starting point for the idea proposals and drafting of a first concept for the research. After the objectives and problems were presented during the workshop, it was important to understand the process of raw materials and the current state of the value chain. To do this, recent news, documentaries, reports as well as articles were reviewed. In the same phase, chemical concepts and industry-specific concepts about raw materials and magnets were studied in order to interpret the data. Finally, the process of manufacturing magnets from raw material to useful magnet was visualized. This mapping allowed to identify which scope and which part of the supply chain this thesis would target.

This approach was necessary to get the study off the ground, but it also meant a major focus on problem identification but less on understanding industry specific aspects such as bottlenecks and process limitations for magnets. However, it was necessary to reiterate when knowledge of production processes was lacking in order to understand what suppliers were focusing on.

2.3.2 Workshops

The data collection started by having a two-day long workshop with different stakeholders within the organization to understand the overall responsibilities and the role that this thesis will play in their business strategy. The same format with workshop was further initiated in order to deep dive into the magnet area with the help of different knowledge from various departments, for instance purchasing, advanced engineering, raw material specialists and innovation segment leaders. Weekly follow-up meetings were conducted with the raw material specialist and purchasing segment leader to ensure that the content of the study is in line with Alpha's strategy. In addition, meetings have been held with advanced engineering to get their requirements regarding permanent magnets. These stakeholders have been helpful in developing the interview questions. Additionally, they have also helped to understand Alpha's current situation in the permanent magnet value chain and to understand what type of data Alpha has in hand about the market and non-available data. The data gave an understanding about Alpha's planned development and their view of the permanent magnet value chain.

2.3.3 Interviews

Additionally, primary data was gathered through interviews. In total 21 interviews have been conducted. The initial step was to collect data from actors such as magnet manufacturers (suppliers) and industrial experts in the area by contacting them through LinkedIn, E-mail or their website. This was done in order to exchange information. Subsequently, the interviews were booked as agreed. Ten questions were sent in advance to the representatives. Semi structured interviews were designed together with the raw material specialist and purchasing segment leader from Alpha's purchasing department. In a semi-structured interview, respondents are asked a series of open-ended questions before responding to follow-up questions to delve deeper into their answers and the research topic (Bell et al., 2022). The questions were designed considering the aim of the work, the time limit, current data (from secondary and pre-study) and confidentiality. The questions can be found in Appendix A. Instead of asking the stakeholders basic questions, specific questions were created that took into account their areas of expertise. During the interview, the companies introduced their company and then answered the questions in an open discussion. The interviewed actors consisted of 1 Canadian magnet manufacturer, 3 European magnet manufacturer, 2 recycling companies, 1 Industry patent expert, 1 Rare Earth Industry expert, 2 Japanese magnet manufacturer, 6 distributors, 4 Chinese magnet manufacturer and 1 project buyer from Alpha. Duration of each interview was 45 minutes to one hour. The interviews were transcribed and recorded automatically using a digital tool. Due to the global location of the actors all the interviews were held online. See figure X for a list of the interviewees.

The interviews did not cover all the data needed and therefore it was supplemented by secondary data, as explained in section 2.3.4. The purpose was to gain a deeper understanding of how the permanent magnet value chain works and what the important parameters are for Alpha to build its sourcing strategy.

Information has also been collected from participation in discussions and meetings with Alpha's suppliers. Due to confidentiality concerns, the information obtained from the meetings will only be used as a reference to locate material that is already available publicly. Confidentiality will also apply for the interviews requested by the respondents. The actors want to stay anonymous due to the sensitive data that would be shared.

The organizational scope	The actors' scope in the value chain (up, mid and-downstream)	Role description of the respondent	Interview duration
Chinese magnet manufacturer	Mid/Downstream	Key Account manager	50 min
Chinese magnet manufacturer	Downstream	Key Account manager	60 min
Chinese magnet manufacturer	Downstream	Sales manager	40 min
Chinese magnet manufacturer	Downstream	Key account manager	30 min
Japanese magnet manufacturer	Downstream	Senior Sales manager	50 min
Japanese magnet manufacturer	Downstream	Sales manager	40 min
European magnet manufacturer	Downstream	Nordic Sales manager	30 min
European magnet manufacturers	Downstream	Managing director	60 min
European magnet manufacturers	Downstream	President	50 min
Canadian magnet manufacturing	Mid/Downstream	Key account manager	60 min
Distributor	Downstream	Sales manager	50 min
Distributor	Downstream	Sales manager	40 min
Distributor	Downstream	Key account manager	50 min
Distributor	Downstream	Sales manager	60 min
Distributor	Downstream	Key account manager	50 min
Distributor	Downstream	Key account manager	40 min
Rare earth industry association	Downstream	Rare earth industry expert	50 min
Industry patent association	Downstream	Industry patent expert	50 min
Alpha	Final application firm	Project buyer	35 min
Recycling company	Midstream/Downstream	Sourcing manager &VD	60 min
Recycling company	Midstream/Downstream	Director of research developments	60 min

Figure 2.2: *L*ist of interviewees, scope, role description and duration

2.3.4 Secondary data

Secondary data was used to better understand the value chain of permanent magnets, such as future trends in the market, challenges and barriers. The data was gathered through academical reports, journals, literature and company information. Chalmers Library and Google Scholar were frequently used for academic journals. Furthermore, industry websites were used to understand new trends and relationships in the market.

2.4 Organizing data with coding

In qualitative research, coding is the act of assembling, categorizing, and thematically sorting acquired data to create a structured framework that allows for construct meaning (Williams and Moser, 2019). While theoretical and practical approaches to managing the data that are collected vary between qualitative research orientations, each one uses a mechanism for organizing the data through coding. These techniques enable highlighting underlying themes in the data, suggesting thematic directionality for categorizing the data so that underlying meaning can be coded and presented. In qualitative research, coding is a crucial structural activity that makes data analysis and subsequent stages possible and serves the study's objectives.

To meet the validity and reliability requirements specific to qualitative research, it is essential to make sure that coding techniques are well-defined, exacting, and implemented consistently (Williams and Moser, 2019). This emphasis on following strict data coding guidelines may be traced back in time to seminal qualitative research, which shows that combined data collection, coding, and analysis is the fundamental operation toward the formation of theory.

Coding is crucial in enabling the researcher to effectively advance the research process because it recognizes the interdependence between data organization, categorization, theory building, and construction of meaning (Williams and Moser, 2019). Coding is focused on the idea that it should "reflect the interaction between respondents' and researchers' perceptions of the type and aspects of phenomena under study. Furthermore, an open, axial, and selective method of coding enables for an interactive, continuously comparing, and consolidating data loop whereby the researcher participates. See figure 2.2. When the coding process moves forward, its dynamic and nonlinear function make it possible to identify key themes, codify them, and interpret them in support of a research study's emphasis and add to the literature that surrounds them. This iterative approach necessitates that the researcher thoroughly comprehends the data by repeatedly rereading the information gathered in an attempt for theory to progress.

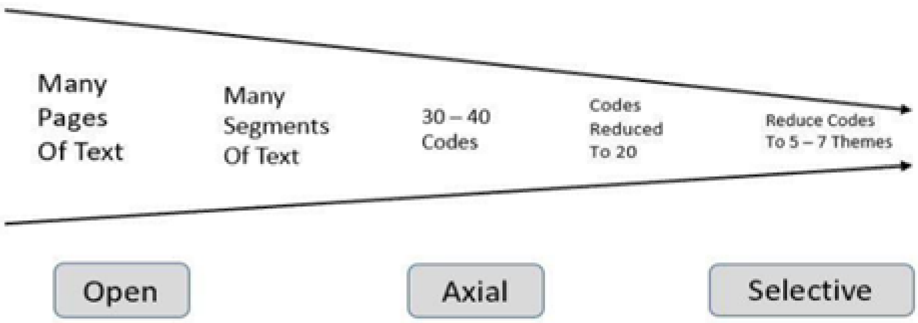

Figure 2.3: *The coding process: Open, Axial and Selective. Retrieved from Williams and Moser (2019).*

The first level is open coding (Williams and Moser, 2019). In open coding different subject fragments and merging topics are identified during data gathering in a structured and methodical manner, it is essential to the effectiveness of the coding. For instance, in order to find thematic connections that would lead to thematic patterns, researchers should reread interview transcriptions, notes, and related data sources that were used in the data collection. Next, the researcher should color code aligned topics. The second level is so called axial coding. Axial coding further clarifies, aligns, and classifies the themes in contrary to open coding, that concentrates on finding emerging themes. The obtained data can be sorted, refined, and organized in order to create clear theme categories in advance of selective coding after open coding is finished and the shift to axial coding is made. The third level is called selective coding. Selective coding allows researchers to choose and include axial code categories in cogent and meaningful terms. Selective coding is a particularly difficult step in the data collection process because it affects not just the theoretical constructs that emerge but also how meaning is presented, which has an effect on how the results are received. Figure 2.3 exemplifies the three levels of codes.

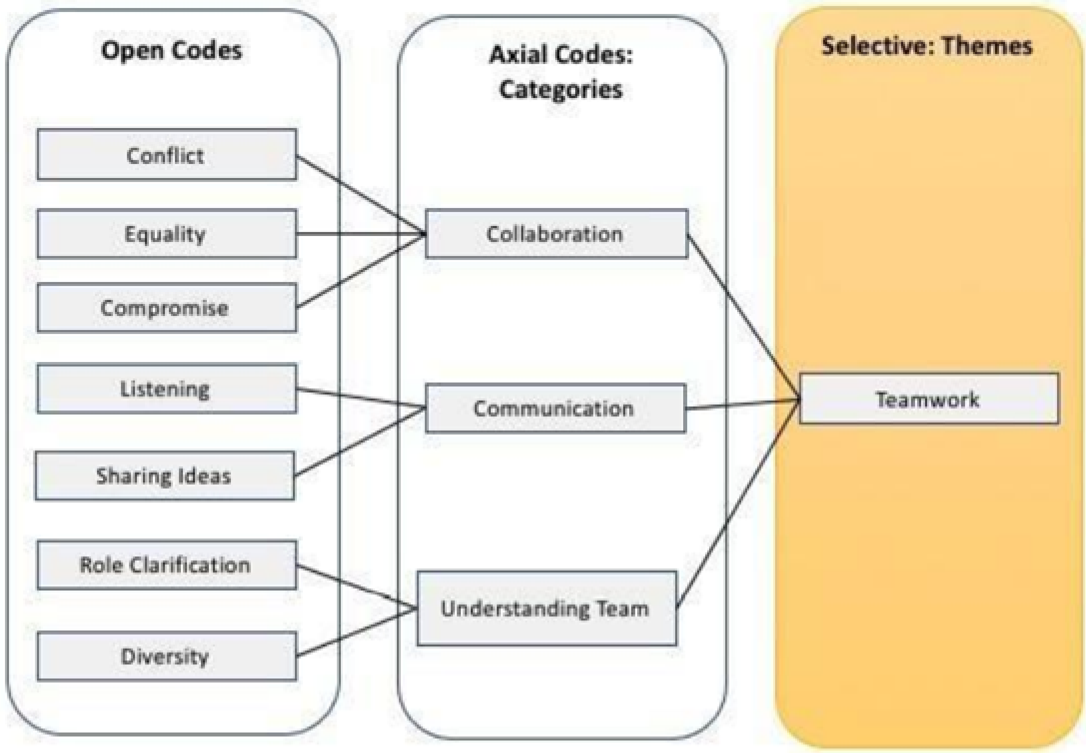

Figure 2.4: *The three levels of coding from open to selective code. Retrieved from Williams and Moser (2019).*

In this research open, axial and selective coding was used. It started by reviewing the transcript data from all interviews followed by re-reading it to color code important topics (open codes) related to the subject of the research. In the second step open codes with different colors were categories in axial codes. Some of the chosen colors were blue for political announcement, red for pricing factors, green for sustainability and yellow for volume and capacity. For instance, localization, trade barriers and certifications are categorized as one axial code called political factors. Another identified axial code was intellectual property. All these axial codes were then reiterated to give rise to the selective theme, in this case geopolitical factors for the permanent magnet area. The detected axial codes corresponded to the subfactors in the permanent magnet criteria and further the selective themes for the main criterias.

2.5 Systematic combining

Case studies offer a special method for the development of theory by leveraging in-depth understandings of empirical data and how they occur (Dubois and Gadde, 2002). Since managing the interconnectedness of all the parts in the research work is the main challenge of case studies, understanding their characteristics and effects necessitates an integrated approach. A researcher can improve his understanding of both theoretical and empirical phenomena by constantly shifting “back and forth” between different types of research activities and between the theory and empirical data. Preconceptions that have been expressed contribute to the foundation of the preliminary analytical framework. It evolves over time in accordance with what is learned through empirical investigation, analysis, and interpretation. This results from the fact that neither theory nor empirical observation can be comprehended without the other. The framework drives the searching of empirical data. Empirical observations may reveal unexpected but related problems that can be further investigated in interviews or with the support of other data gathering techniques. This may necessitate further revision or growth of the model presented in the theory, which would require reorienting the current framework of the theory. This process is referred to systematic combining, see figure 2.4 for an illustration. Any research mission’s primary objective is to contrast theory and reality. In systematic combining the ongoing confrontation is more or less constant. Another conflict between the evolving case and the emerging framework will determine how this process proceeds.

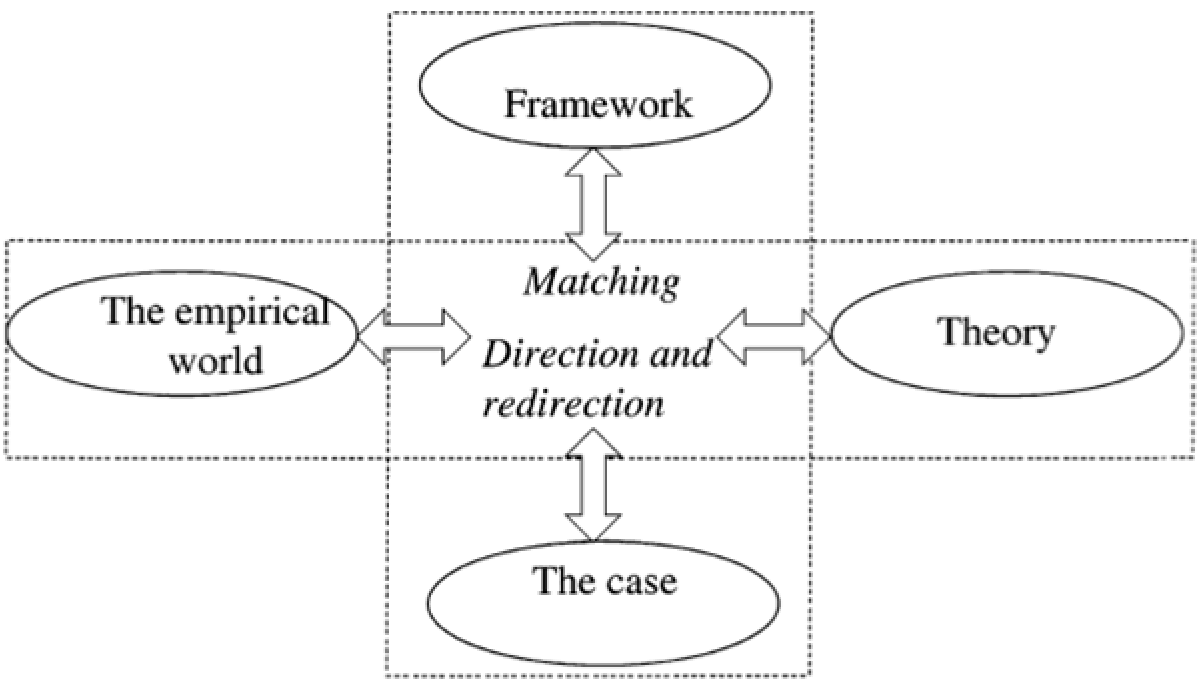

Figure 2.5: *Systematic Combining visualization retrieved by Dubois & Gadde (2002).*

The research process in this study followed a systematic combining method like the one presented in figure 2.4. After the data collection, the empirical data was compared with the existing theory. This was done in order to perform a fair analysis of the permanent magnet value chain. Hence, there was an iterative process between the empirical data, the theory and the analysis to ensure that the research questions were answered in the most accurate form. Some of the theories were both added and removed later in the study when the empirical data evolved, and the applicability was balanced.

One initial framework was created as a predecessor of the current framework in figure 3.3 and as empirical data and theory was collected the main areas and sub-areas were modified and as a result the current one was finalized. The final framework was adapted to the permanent magnet value chain. The required empirical data were analyzed and discussed in order to explain the structure of the permanent magnet value chain and identify the important criteria to consider when sourcing magnets.

2.6 Reflections on quality of the study

Assessing the level of quality in the research is critical for determining the credibility of the study. The quality of the research can be expressed in terms of validity, reliability and generalizability (Bell et al., 2022). The validity states if the study's findings accurately measure what they were intended to assess. Therefore, different criteria were evaluated through primary data and secondary data. Use of incorrect indications could result in inaccurate supplier selection that in turn can lead to disruptions in the supply of the magnets. Reliability defines whether the study can be repeated and yield the same results. It indicates that when intending to repeat the study, it is important to retain the same procedure for data gathering. As a result, a well-developed and organized data collection method was used. The researchers developed a framework with a clear decomposition of the magnet production process to understand the market and collect data along the way that gave rise to a visualization of different actors with different roles in the value chain. This resulted in the selection of relevant stakeholders to interview in order to get different views on the value chain. Therefore, researchers chose to interview different actors with different competencies to combine the different knowledge areas.

Additionally, using triangulation can improve reliability (Bell et al., 2022). This indicates that statements are supported by a variety of sources. By cross-checking data points with various sources, triangulation improves assurance in conclusions. Triangulation is important in order to make accurate estimations on data points including production volumes and potential developments for the future. In this research the primary data was supplemented by the secondary data. To achieve a high standard of data collection, the aim was to have as many interviews as possible but also that these interviews would be within the interests and expertise of different actors. First, the commercial side was interviewed, i.e., suppliers and sellers of permanent magnets. Furthermore, impartial experts who have a lot of relationships and knowledge of the market. In connection with this, secondary data was collected from various sources such as government websites, articles from industry and research papers. This provided a complete perspective from different stakeholders in the value chain. Another way to double-check the data points, the emerging topics were discussed with the contact person at the case company Alpha who has previous experience in the field. Moreover, systematic combining helped with the triangulation in order to iterate between the theory and the collected data. The method created an clear picture of the findings and the important data needed for the sintered NdFeB network structure. The whole value chain for sintered NdFeB network is complex and includes different steps. In order to understand these steps and the important recurring areas it was essential to iterate back the collected data. One way to ensure the quality of the study was to identify recurring themes from the different data collection points. For example, there were the same areas that appeared from theories, interviews with different actors and articles on the subject. Demand growth and geopolitical areas were examples of these recurring and confirmed areas that continuously appeared during the data collection. The quality of the data could then be ensured as several sources confirmed its credibility.

Bell et al. (2022) also discusses the study's generalizability, or if the findings can be used in situations other than the one in question. When presenting the data needed for this study it will be clearly described to secure the generalizability. This is for the readers to use, apply and present the data for other contexts in a correct way. The study is hence generalizable in the meaning that it may be of interest when investigating other similar materials. However, if a longer-term (beyond 2030) investigation of raw materials is desired, risk indicators that are not covered in this study may be of relevance. This might include substitutability such as magnet free electrical machines, which can have a significant impact on magnet supply beyond 2030. This research can be used for all buying firm companies that are aiming for buying or extending their knowledge about the sintered NdFeB magnet. This is due to the chosen perspective of the research where the overall network was analyzed and thus not only from the perspective of Alpha.

3
Theoretical framework

This section will present the theoretical frameworks used to support and understand the results and findings in the study.

3.1 Supply Chain Management

The phrase “supply chain management” (SCM) was introduced in early 1980 by consultants (Dubois et al., 2004). The idea was mostly used to explain the advantages of integrating a company’s internal business processes, such as procurement, production, sales, and distribution. As a result, the original perspective on supply chains were intraorganizational and focused primarily on the internal supply chain of the corporation and how various activities could be combined to facilitate the movement of materials inside the organization. This supply chain perspective is related to the term "value chain" which is referred to by Porter (2011). The supply chain’s scope later expanded beyond this intra-organizational focus to include "upstream production chains" and "downstream distribution channels," which are located outside the boundaries of the focal firm. This supplementary viewpoint provided SCM with an interorganizational rather than an intra-organizational focus.

Although there appears to be a lot of variances with relation to SCM, there are still some parallels amongst the concept’s most recent applications. For instance, Cooper et al. (1997, p. 4) discovered the following parallels across several publications: (1) As SCM develops, intra- and interorganizational integration and coordination increase over time; when interpreted and applied broadly, it covers every link in the supply chain, from the initial source (supplier’s supplier, etc.) to the final users (customer’s customer, etc.). (2) It potentially involves numerous unrelated organizations. Thus, it is crucial to manage relationships within and between organizations. (3) It covers the two-way exchange of goods and information, together with the related commercial and operational operations. (4) It aims to achieve two objectives: creating a competitive chain lead and offering high customer value while making the best use of available resources.

3.2 Supply networks

Lambert and Cooper (2000) outline three factors to consider while evaluating the network structure for a company. First, to determine who the key supply chain members are. Secondly, to identify the network’s structural dimensions, such as the

variety of tiers and the location of the focal firm. Thirdly, to define the various business processes links that the supplier network contains. Companies should start by determining the members being critical for their company and supply chain success and thereafter allocate resources and managerial attention to them. According to Lambert and Cooper (2000) the supporting actors, or those who are only supplying services like logistics, information flows, money transfers, should be discarded at the beginning of this identification process. Contrarily, the key actors are those who contribute value to the supply chain and should therefore be identified as the critical actors.
Furthermore, when analyzing, describing and managing a supply chain it is important to look at the network's three different structural dimensions. The first one is horizontal structure, referring to how many tiers there are throughout the supply chain. The second structure is called vertical and refers to how many suppliers or consumers are represented in each tier. Last and third is the company's horizontal position throughout the supply chain. A business may be located at or close to the primary source of supplies, at or close to the final customer, or somewhere in between these supply chain endpoints.

3.2.1 Supply chain interdependencies

Some authors highlight the importance of analyzing the existing interdependence among and within supply chains (Dubois et al., 2004). In order to clarify this matter, dependence ideas are introduced. It is concluded that supply chains must be analyzed in the context of their environments, thus having an impact on recommendations for how to organize and manage them.

The majority of complex organization models presume the existence of interrelations of organizational parts (Dubois et al., 2004). In the model there are three categories of interdependence (Thompson, 2003): first pooled, second sequential and lastly reciprocal to coordinate the actions of interconnected parts inside a company. A condition in which "each part gives a discrete input to the totality, and each is sustained by the whole" is referred to as “pooled interdependence”. Second, there exists a sequential interdependence if direct dependency between elements can be identified and the sequence of that interdependence can be determined. The "reciprocal" type refers to the third type of dependency, in which one party's outputs serve as the other party's inputs. This enables the understanding of how various organizational units can be connected given the dependency among their functions.

Every organization included in a supply chain will have a distinct perspective on the products (Dubois et al., 2004). The way a firm behaves with respect to their counterparts will likely depend on how the business views the products that come from its similar activities. Due to the way the activities are organized, all the supply chains that lead to its final products make use of resources that are also active in other chains. Hence, even in a simple scenario, there are quite a few interconnected activities, products and resources involved. Moreover, because they are dispersed throughout several companies, the efforts to increase the effectiveness of their individual supply chains will be impacted by their differing ideas on how to organize and govern their products, activities and resources. This may raise the cost of further changes. Firm K in figure 3.1 may be a manufacturer of plastic components and may have invested in a resource, such as mold tailored to the final product.

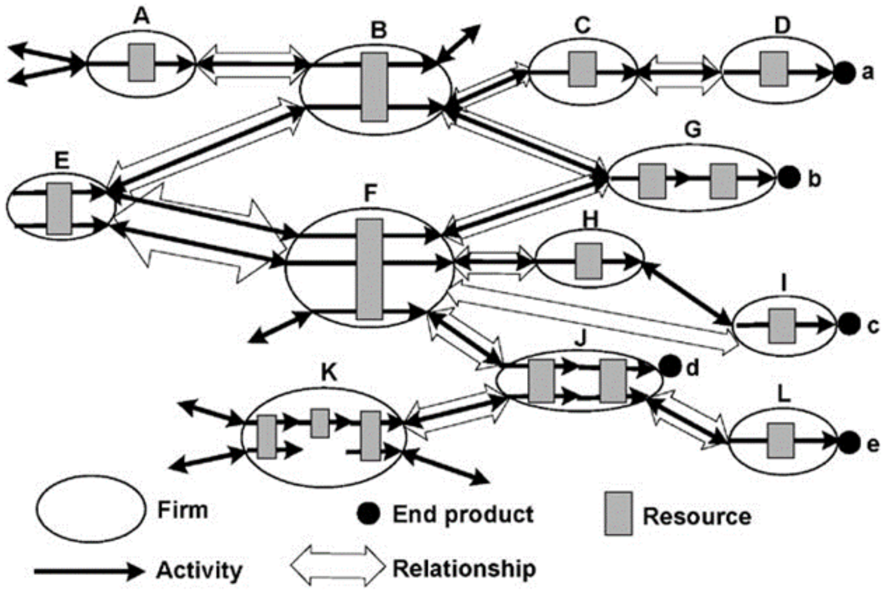

Figure 3.1: *Relationship and activity connections between actors in a network. Retrieved from Dubois et al., 2004.*

Relationship exchanges allow for the identification of goods as a part of that transaction (Dubois et al., 2004). Nevertheless, business partnerships may also be employed for the interchange of several goods, similar to how resources in supply chains are, as demonstrated by the partnership between enterprises F and E in figure 3.1. Additionally, it is not always clear who is selling or buying from whom if we only observe the order flow or the chain of businesses. This is because a manufacturer could, for instance, purchase refining, shipping, storage, etc. from the company "behind" them in the chain.

Irrespective of how it is defined, the activities that make up a supply chain are interdependent with one another since they share several resources with other supply chains (Dubois et al., 2004). To be effective, the various enterprises engaged must match their operations and resources. With relationships, they may also communicate with clients and suppliers to make changes that might enhance some aspect of their performance. These improvements may lead to relationship-specific investments that link organizations together. The firms K, J, and L and their relations will be impacted by this investment.

Due to the interdependence, each modification may have an influence on another part of the supply chain, and therefore on another organization (Dubois et al., 2004). These adjustments may also cause a variety of responses. Firms B and/or F may need to adapt their resources and/or activities if, for example, company G wants to develop the material provided by firm E and utilized as input by companies B and

F to increase the performance of its final product b. When some of the activities incorporated in its supply chains share same resources with the product b's supply chain, this can result in changes that have an effect on the following four end products. Although organizations may change counterparts and do so occasionally, the important questions tend to center on how integration best can work with current counterparts (Wynstra, 1998). When dependency among and within supply chains is acknowledged, as is the case here, this may be seen as being of even greater importance.

First off, according to the SCM literature, companies may choose the "best members" to help them construct the supply chain that would work best for them (Dubois et al., 2004). This suggests that supply chain "members" are viewed as interchangeable and independent. If we acknowledge that every single organization engaged participates in different supply chains and therefore these connections enhance the effectiveness of the supply chain in issue, the "best members" approach presents challenges. The "member's" network context in general, as well as its other supplier and customer relationships determine what makes the "member" a good partner. As linkages are created, modifications to resources and activities may further boost each firm's contribution to the specific supply chain. This results in increased dependency between the participating companies and on the various supply chains which they are involved in.

Second, even though the optimization of various parameters is frequently recommended in the different SCM literature, the methodology here implies that this is not a practical strategy for two reasons (Dubois et al., 2004). Since supply chains are interdependent, it follows that there are no viable boundaries to optimize within. Furthermore, when supply chains are organized and managed, neither activities, resources, nor products can be regarded as "givens" since circumstances for activity coordination and resource utilization are continually changing.

Thirdly, the SCM literature frequently emphasizes rivalry between and control inside supply chains (Dubois et al., 2004). These ideas get hazy when diverse types of interconnectedness both inside and between chains are considered. Since the effective use of different resources is dependent on other uses for those resources, control is difficult to exert. As a result, supply chains that lead to products and competition may be interrelated in terms of shared resource usage.

The functions served by the companies participating in these complicated supply networks are also rarely clear-cut (Dubois et al., 2004). On the basis of the explanation above, a few further management implications can be developed. First, the emphasis may be shifted from seeing interdependence as an issue to be fixed, such as by diminishing or even removing it, to how organizations can handle it in various ways. The attention may be drawn to the distinctive qualities created within a certain supply chain by seeing interdependence as an unavoidable result of changes made by organizations to improve their joint efficiency. Hence, one of these distinctive characteristics is interdependence with other chains. Second, as supply networks are highly dynamic and the viewpoints of the companies engaged in them vary even in terms of how they define empirically meaningful supply chains, multiple alternatives analytically useful boundaries must be imposed for every performance evaluation (Torvatn, 1998). By comparing performance across boundaries, it becomes clear what is not and is covered by benchmarks. This provides a platform for raising awareness of the dependency that exists across borders. Thirdly, as was already said, organizations that encounter cross-firm interdependence of activities and resources do not benefit from retaining a priority on control and competition. As proposed by van Hoek (1998), in these networks managing might instead be viewed as a matter of engaging with others in order to impact and be affected, to further adapt activities and resources. This calls for knowledge of various parts of the firm's operating supply network (Lambert and Cooper, 2000). In accordance with Ford et al. (2003), it is recommended to concentrate on supply network management rather than attempting to control them.

3.2.2 Levels in the network structure

According to Melander and Lind (2022) resources and activities are developed by the firm (micro-level), the network (meso-level) and the societal (macro-level). To create sustainable innovative networks, all three levels—micro, meso, and macro—must be considered and managed. In order to influence and comprehend regulations, consumer trends, and public funding, innovation development at the micro level depends on collaboration with actors at both the network and societal levels. The network's ability to integrate innovation is influenced by societal factors like subsidies, media coverage and regulations. The innovation is impacted by interactions both within and between the levels.

Individual businesses and organizations make up the micro level (Melander and Lind, 2022). Resources owned by firm businesses are essential for value creation at the micro level. Products, facilities, systems, and people are just a few of the resources that businesses own or have access to. However, resources have varying values depending on how they are being combined with resources from other businesses. From a micro level perspective, understanding user dynamics throughout the innovation process requires an in-depth understanding of potential future customers. Customers frequently contribute to the creation of new resources, for instance by offering suggestions while products are being developed. Further to being involved as collaborators in the creation of new products, suppliers are also potential providers of new resources. Cooperation with suppliers is still regarded as crucial for long-term development, even though it might be complicated, for instance due to the existence of rivalry and cooperation factors.

The meso level are networks and business relationships and inter-organizational interactions (Melander and Lind, 2022). Business networks are described by the links between buyer-supplier relationships, and how actions in one relationship affect other ties in the network. Since it is collective, relationships and interactions are crucial. In corporate networks, interaction is essential. Actors, such as various types of organizations or individuals need to maintain business relationships constantly by communicating with stakeholders across the business environment. Interaction can be initiated by a variety of factors, such as problem-solving, adaptability, discussion, or preparation for upcoming market demands. The resources that can be obtained through business connections serve as a crucial foundation for business growth. It must be emphasized, nevertheless, that connections between specific individuals within a network can sometimes operate as roadblocks to change. However, the recent focus on the advantages of supply chain collaboration has encouraged a broader understanding of supplier collaboration. Expanding supplier collaboration results in contact with new types of actors and the inclusion of additional actors in a business network. By participating in a network, businesses can define standards for their industry, conduct pilot projects, and commercialize products in addition to sharing and integrating knowledge.

While the meso level is referred to as the middle level "serving as a bridge" among the other two, innovations have the potential to have a greater impact on society at the macro level by supplying innovative solutions that increase environmental and social value (Melander and Lind, 2022). At the macro level, businesses must navigate societal shifts in customer demand and behavior as well as governmental actions and decisions. Businesses are being pushed to invest in innovative sustainable solutions by government regulations and public awareness of the environment among consumers and public actors. Companies may lack the resources or knowledge necessary to create and implement these innovative sustainable solutions. Regulations may therefore encourage businesses to seek out networks with whom to interact.

Based on these levels, a framework was constructed to distinguish between the actor (micro level), business network (meso level), and governmental and societal (macro level) levels while acknowledging their interconnection, see figure 3.2. In figure 3.2, interconnections across these levels are represented by arrows, demonstrating that innovations are produced and integrated through interactions between various entities in the network rather than in isolation.

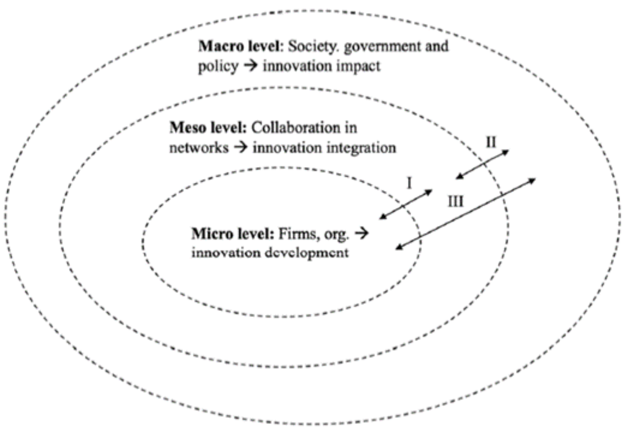

Figure 3.2: *Illustrartion of micro, macro and meso level in the supply chain. Retrieved from Melander and Lind (2022).*

3.2.3 Analytical framework of permanent magnet network structure

An essential step in every sourcing process is supply market analysis (Lobermeyer and Kotzab, 2010). It enables the choice of the appropriate sourcing strategy easier and offers a way to properly analyze market traits. The effectiveness of the purchasing procedures is largely reliant on the level of knowledge of the characteristics of the supply market and a company's position within them.

Based on the availability of data to be used in this master thesis there was no framework suitable for the PM supply market. An inspired framework for market analysis has therefore been constructed by analyzing the micro, meso and macro model explained by Melander and Lind (2022). Lastly, some inputs were considered crucial for a strategic market analysis specifically constructed for the PM supply market. The outcome was a framework for the supply market of PMs. Figure 3.3 shows the structure of it. The framework is divided up to four sections. Starting with a production process by the PM, followed by the market overview, relationships in the market and externalities.

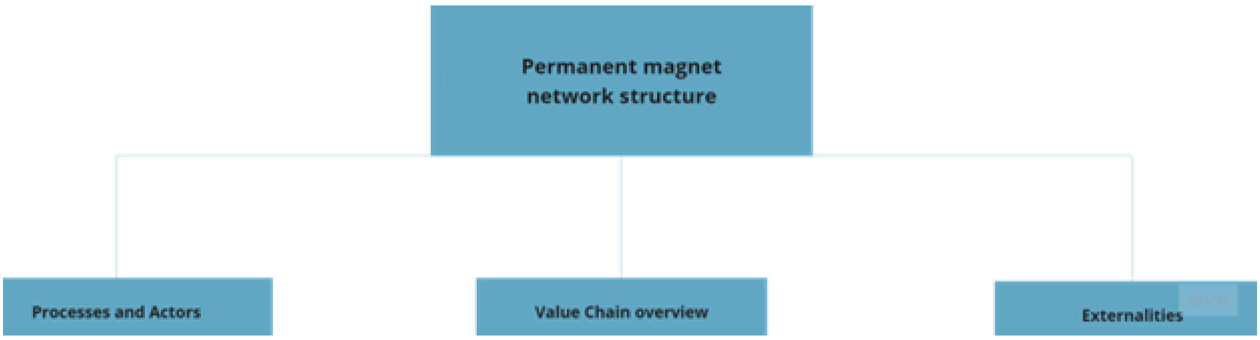

Figure 3.3: *Framework for value chain of permanent magnet*

The first section will describe the manufacturing process needed for a permanent magnet. The characteristics and the productions steps will be explained and analyzed in order to make an accurate market analysis of the actors. Next step will be the market overview where an analysis of the main actors and the market trends are covered. The market's size, expected growth, and the market shares of the various suppliers will be followed and conclude by pointing out market trends. The third part will investigate the relationships between the actors in the PM supply market. This is to get an overview of how different actors are influenced by each other's strengths, knowledge and political factors. External factors such as political, technological, and environmental variables affect the supply chain market for PMs and the suppliers' relations.

3.3 Sourcing strategy and processes

The method by which businesses find, assess, and work with suppliers is known as supplier selection (Taherdoost and Brard, 2019). The process of choosing a supplier uses a significant amount of a company's financial resources and is essential to the success of any business. The main priorities of the supplier selection process are to reduce the purchasing risk, maximize total value to the buyer, and promote close, long-lasting relationships between the supplier and the buyer. This section will describe different factors underlying the supplier selection combined with methods such as Kraljic matrix.

3.3.1 Kraljic Matrix

In the 1980s, Kraljic introduced the initial purchasing portfolio model, which includes a matrix classifying the goods bought by a corporation into four categories based on two key factors: the profit impact and the degree of supply risk (Garzon et al., 2019).

The products to be purchased are arranged along two axes in the traditional Kraljic Model: strategy and risk (Garzon et al., 2019). These axes have the following implications: The profit impact of a specific supply item can be expressed in terms of the volume purchased, as a proportion of overall purchase expenses, or as an impact on the product quality or company growth. The profit impact is the impact of purchasing on financial results. The financial impact of buying on the bottom-line increases as the volume or the amount of money invested increases. The assessment of supply risk considers factors including availability, supplier diversity, competitive demand, storage risks, make-or-buy opportunities and substitute potential. The business classifies all its purchased goods into the groups depicted in Figure 3.4 using these criteria: leverage (low-supply risk, high-profit impact), strategic (high-supply risk, high-profit impact), bottleneck (high-supply risk, low-profit impact) and non-critical (low-supply risk, low-profit impact).

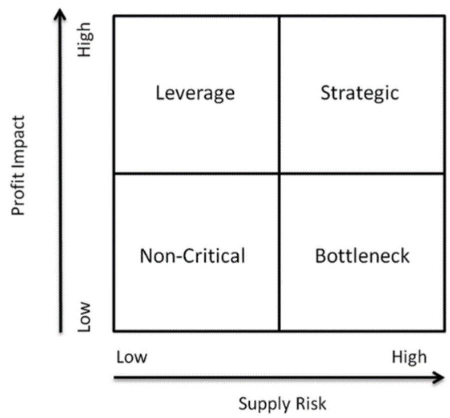

Figure 3.4: *Kraljic Matrix retrieved from Garzon et al. (2019)*

These four categories each call for a unique purchasing strategy, whose complexity is inversely correlated with the strategic implications (Garzon et al., 2019). A broad range of analytical approaches, including as price forecasting, market analysis, computer simulation, risk analysis, and optimization models, and several other types of microeconomic analysis, may be required by the company to support supply decisions of strategic items. When making decisions about bottleneck products, specific market analyses and decision models may be needed, whereas difficulties involving leverage materials may call for vendor and value analyses, price forecasting models, and decision models. Simple market analysis, decision strategies, and inventory optimization methods would typically be sufficient when it comes to non-critical items.

Non-critical items have minimal technical or commercial issues (Van Weele, 2018). There are numerous alternative suppliers, and they typically have low prices per item. This describes the majority of inventory goods. Strategic items are high-tech and high-volume items that are frequently given to customers according to their specifications. There is a single supply source, which would be extremely costly to change in the near future. A large portion of the cost of the final product for the company comes from strategic products. Examples include the gears and engines used by automobile manufacturers, the turbines used by the chemical sector, and the bottling machinery used by breweries. Leverage products are available at standard quality levels from a variety of sources. They are purchased in huge quantities and make up a sizable portion of the cost of the final product. A small price modification can have a large impact on the final product's cost price. This constitutes the reason behind the buyer's intensive sourcing and tendering efforts among a select group of prequalified providers.

3.3.2 Supplier selection

The most important aspect in the purchasing strategy is choosing a supplier, and several actions come prior to this decision (Van Weele, 2018). The first step in the process is to summarize the prequalification requirements that suppliers who will be contacted for a quote must meet based on the purchase specifications. The initial bidders list is then put together and shows which suppliers are most likely to undertake the job. Suppliers with outstanding vendor ratings, which reflect excellent prior performance, are frequently listed as the initial bidders. Each of these long-listed vendors will then receive a request for information (RFI). These suppliers are approached to request references from previous experience, details about their prior work history, and other details that will show that they have the requirements to fulfill the order.

One of the most significant decision-making difficulties in the field of SCM is supplier selection (Taherdoost and Brard, 2019). The selection procedure is crucial for strengthening the company's competitiveness and necessitates the evaluation of many alternative providers based on multiple criteria. The choice of a suitable supplier would increase customer satisfaction, shorten product lead times, increase earnings, and enhance competitiveness. Because of this, it has turned into a crucial area of concern for all purchasing organizations. However, there is no established standard for choosing suppliers. A wrong decision, however, could result in losses for the supply chain, which would have a direct impact on the company's success. In fact, selecting the ideal supplier is never straightforward for purchasing managers, especially now, when supplier selection criterion requirements are evolving. There are three key steps, see figure 3.5. The first step is the identification of the criteria; these are usually cost, delivery performance, cost, capabilities and quality, although cost is no longer the main factor. Indeed, the purchasing situation determines the selection of appropriate criteria. The second step is the questionnaire survey, which is divided into results analysis and criterion weight determination. It is organized with all key criteria and supporting factors, as well as a query for further supplier selection research. The third stage is then the implementation of the multi-criteria decision-making approach, which involves deciding the method to follow in order to identify the best supplier.

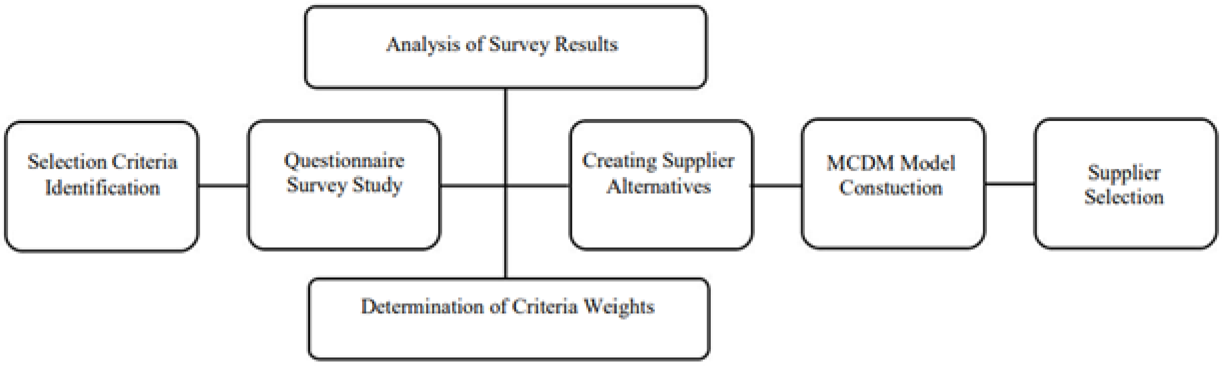

Figure 3.5: *Supplier selection process. Retrieved from Taherdoost and Brard (2019).*

The purpose of a successful supplier selection is to identify the ideal supplier who can offer the buyer the necessary goods at the right time, price and quantity (Taherdoost and Brard, 2019). When producing products with the same standards and quality, it is challenging to keep the same strategy while dealing with varied financial situations and customer reputations.

Choosing suppliers primarily based on price has been the traditional method of supplier selection for many years (Taherdoost and Brard, 2019). However, businesses have shifted to a more thorough multi-criteria strategy as they have realized that focusing solely on pricing as a singular criterion for supplier selection is not well-organized. Recently released criteria include safety awareness, domestic political stability, environmental and social responsibility, and cultural compatibility with the purchasing organization. The drive for new and improved methods of supplier evaluation and selection is motivated by the knowledge that a well-chosen group of suppliers can strategically impact a company's capacity to provide continual improvement in customer satisfaction. Due to the diversity of the organization's overall requirements, using numerous suppliers increases flexibility and encourages competition among alternative suppliers. Despite the strategic significance of supplier selection, many businesses still only consider price performance as one factor when selecting a supplier. For the supplier selection procedure to be effective, many other variables must be considered, therefore evaluating this criterion alone is not the best choice. Currently, it is critical to organize the issue and properly evaluate relevant criteria before making a choice. Several approaches have been created to address multi-criteria issues.

Both quantitative and qualitative aspects are included in the supplier criteria (Taherdoost and Brard, 2019). The purchasing context affects the choice of appropriate criteria. In figure 3.6, multiple supplier selection criteria have been gathered and listed. A definition for each criterion is given. Each organization should select the criterion that aligns with its expectations for the supplier. To identify the best supplier, a ranking will be constructed using these criteria.

Criteria	*Authors*	*Definition*
Quality	[13, 17-29]	The ability of the supplier to meet quality specifications consistently which include quality features (material, dimensions, design, durability), variety, production quality (production lines, manufacturing techniques machinery), quality system, and continuous improvement.
Delivery	[13, 17, 18, 21, 26, 29, 30]	The ability of the supplier to meet specified delivery schedules which include lead-time, on-time performance, fill rate, returns management, location, transportation, and incoterms.
Performance history	[13, 31]	The performance history of the supplier in the financial, economic, social, organizational, and societal area.
Warranties and claim policies	[13, 20]	The superiority of the specified written guarantee that promise to repair or replace product if necessary within a specified period and also the claim policy as a formal request for coverage or compensation for a covered loss or policy event.
Production capacity	[13, 17, 20, 32]	The volume of products or services that can be produced by a supplier using current resources.
Price	[13, 17, 18, 20, 30, 31]	The price criteria includes unit price, pricing terms, exchange rates, taxes, and discount.
Technology and capability	[13, 20, 23, 24, 29, 33, 34]	The technological capability of a supplier and ability to acquire new technologies and technical resources for research and development practices and processes.
Cost	[21-23, 25-27, 29]	The cost is a monetary valuation of effort, material, resources, time and utilities consumed, risks incurred, and opportunity forgone in production and delivery of a good or service.
Mutual trust and easy communication	[29, 33, 34]	The level of trust on the quality of the work provided by supplier. And refers to the obligations owed between the buyer and the supplier. The easy communication is a simple exchanging of information between the firm and the supplier.
Communication system	[13, 17]	The communication system of the supplier including information on progress data of orders.
Reputation and position in industry	[13, 17, 31]	A ranking and reputation of a brand, product, or company, in terms of its sales volume relative to the sales volume of its competitors in the same industry.
Supplier's profile	[22-24, 29]	The superiority and reputability of the supplier's status, past performance, finance, certificates, and references.
Management and organisation	[13, 17, 31]	The reputability of the supplier's management team and the efficiency of their decision making to resolve issues in order to be both effective and beneficial.
Repair service	[13, 18, 20]	The ability of the supplier to restore something damaged, faulty, or worn to a good condition.
Attitude	[13, 17]	The attitude of the supplier while you are in contact with them such as politeness and confidence.
Risk factor	[22, 35]	The risk factor is a measurable characteristic or element, a change in which can affect the value of an asset, such as exchange rate, interest rate, and market price.
Commercial plans and structure	[28, 33, 36]	The supplier's format statement of a business goals, reasons they are attainable, and plans and infrastructure for reaching them.
Labour relations record	[13, 17]	The supplier's relationship between management and its workforce.
Geographical location	[13, 17]	The geographical location of the supplier.
Reliability	[13, 18, 26]	The supplier's quality of being trustworthy and dependable based on the references (buyers feedback), financial stability (capital, annual turnover), past and current business partners, company organization and personnel, diversity of ownership, and cultural awareness.
Service	[22, 25, 26, 29]	The ability of supplier to provide intangible products including the customization (size, shape, color, design, OEM, label service), minimum order quantity, communication (respond time, information, language), industry knowledge, flexibility, and response to change.
Process improvement	[17]	The ability of the supplier to identify, analyse, and improve upon existing business processes within its company for optimization and to meet new quotas or standards of quality.
Product development	[13, 18]	The ability of supplier to modify an existing product or its presentation, or formulation of an entirely new product that satisfies a newly defined customer want or market niche.
Environmental and social responsibility	[37]	The supplier's responsibility to use natural resources carefully, minimize damage, and ensure these resources will be available for future generations.
Professionalism	[13, 21]	The supplier's competence or skill expected of a professional.

Figure 3.6: *Supplier selection criteria retrieved from Taherdoost and Brard (2019).*

There are several criteria to choose from, but the most popular and common ones are price/cost, technology, manufacturing capacity, research and development, delivery, quality, relationship, flexibility and risk (Ho et al., 2010). When deciding if a supplier fits within a company's supply and technology strategy, it utilizes supplier criteria (Kahraman et al., 2003). These factors are largely unrelated to the products or services that the company demands. For instance, the criteria technical or technology is useful when a company needs capable technological support from their suppliers in order to consistently deliver high-quality goods or services, support productive research and development projects, and guarantee future advancements. This is crucial when a company's supply or technology strategy requires the creation of innovative products or technologies or the use of proprietary technology. Technological factors could encourage a company to enter the international market. It occasionally happens that a useful technology has been created abroad and is not offered by domestic suppliers.

Moreover, the criterion of globalization or localization is also important. A company's sourcing strategy may identify specific benefits or drawbacks of selecting suppliers in a certain area or nation (Kahraman et al., 2003). The company should have detected potential concerns in its risk assessment, such as changes in political policy or the currency, as well as the ensuing domestic or global regulatory and market developments.

3.3.3 External factors in supplier selection

External factors, which include economic, sociopolitical, and technological elements, are those that may have an impact on a product's availability both now and in the future in a particular market (Van Weele, 2018). These variables are beyond the supplier's scope of influence. Examples include shifts in the price of goods, labor costs, product innovation and legislation, etc. External factors can impact a product's price in two different ways: directly by changing the cost structure, or indirectly by shifts in the market structure and supply/demand dynamics, see figure 3.7.

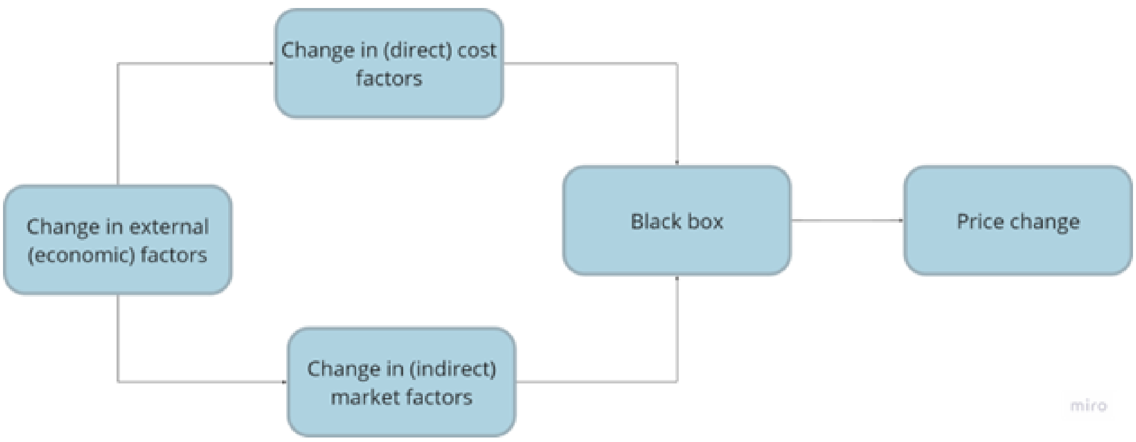

Figure 3.7: *Change in one of the external factors results in modification of the price that is paid. Retrieved from Van Weele (2018).*

Network dynamics creates a particularly challenging strategic field (Menell, 2019). Actors can often pick different strategies when they compete in the network; first to gain control over an entirely new proprietary standard to get a market domination; secondly to adopt a current standard through license or imitation (which is permitted by law). Lastly to collaborate with other businesses in the sector to create an open or practically open standard, whether contractually, through formal associations of businesses, governmental standardization authorities or informally. Different strategies are used to make their goods or services an industry standard, for instance by product licensing in order to accelerate network growth and to foster competition in network expansion.

Researchers show that patents affect global trade, foreign direct investment, licensing, and eventually growth (Maskus, 2002). There are motives to be concerned about firms with greater intellectual property protection exercising market power, the evidence highly indicates that intellectual property rights (IPRs) imply a crucial foundation to promote local innovation, technology transfer, and the growth of the economy in the long term. This finding emphasizes the significance of adopting systems that are tailored to each country's development needs while complying with minimum international norms. Quantitative estimates of the potential gains in technology acquisition and growth for many countries show that the new global system will be positive for developing countries' growth prospects. A patent provides its holder the right to prevent others from developing, distributing, importing, or utilizing the product or method specified in the patent (Maskus, 2000). The courts have always acknowledged the importance of copyright and patent rights to prevent others from exploiting protected technologies and from reproducing works of authorship (Menell, 2019).

Patent owners can exclude activities performed by others to prevent infringement or damaging the property (Maskus, 2002). IPRs define and protect the parameters of legal forms of competition among businesses attempting to capitalize on the value of innovative assets. The rights cannot be extended beyond those boundaries. It is more beneficial to think of IPRs as rules governing the conditions of dynamic and static competition rather than ways for establishing legal monopolies. While IPRs do result in market power, the effects on competition differ significantly depending on the countries, products, and technologies. The level of protection varies depending on the scope of the granted rights, the competitor's ability to develop non-infringing technologies and products and the availability of supply source substitutes.

Moreover, for a buying firm it is important to consider currency risks while purchasing from foreign suppliers (Van Weele, 2018). International contractors that work in the offshore sector will find this to be quite challenging. The currency exchange rates might change significantly between the quotation time and the time when the order is received. There are various options to handle this. One strategy is to agree to the terms of the contract for the goods in the exact same currency as the company expects to be paid by its client. Another option is to apply clauses in contracts describing how the organization shall be compensated through its customer in situations where the exchange rate of a currency fluctuates. Another alternative is to hedge your currency risk, however this is typically only an option for contracts that will last less than a year.

3.3.4 Sustainability factors in supplier selection

Today's purchasing managers need to promote corporate social responsibility (CSR) in order to ensure that the company's supply chains work in accordance with established standards and norms for human rights, as well as regional labor and environmental regulations (Van Weele, 2018). The purpose of corporate social responsibility is about contributing to an improved working and environment conditions (Van Weele, 2018). The goal is to create business solutions that meet the needs of the current global population without compromising the needs of the next generation. Businesses must establish a balance between servicing the demands of "people, planet, and profit," which means balancing the interests of their shareholders, customers, employees, and the environment.

The "people" aspect covers all initiatives aimed at creating favorable working circumstances for employees and an environment where each employee can improve their knowledge and competencies. This explains why businesses and suppliers are currently very interested in safety, health, and the environment.

Any initiatives aimed at maximizing the use of raw materials, energy, and other natural assets are included in the "planet" component. The "planet" aspect includes waste disposal, recycling of scrap, reverse logistics and surplus materials. Additionally, it involves reducing carbon emissions. The "profit" part provides recommendations for a company's long-term, sustainable financial growth. The idea behind increasing profitability is that the business also pays attention to relevant key stakeholders including customers, suppliers, shareholders and employees.

ESG is another way of determining the effort companies invest in sustainability (PwC, 2023). ESG stands for Environmental, Social and Governance. The term includes all sustainability issues that affect companies, organizations and society. Environmental includes issues related to climate change, net zero, green electricity and emission policies. Social includes areas such as gender equality, diversity, human rights and work environment. Governance covers corporate governance topics such as sustainability reporting, due diligence, business models, strategies, transformations, regulatory compliance and whistleblowing systems. To achieve these goals, it is required to have management paradigm transformation and higher awareness of professional training (IASE, 2023). ESG factors are prioritized in the development of these strategies, emphasizing the value of rigorous, globally recognized professional certifications. Companies can demonstrate their expertise in environmental sustainability with a certificate in ESG. The certifications are a worldwide indication of supreme sustainable investment, business criteria and policies that the company is aligned through transparency. Another sustainability related certificate is so called green certificate. This green certificate is official proof that a company has generated a level of green electricity (European Environment Agency, 2023). Green certificates are an indication of the environmental benefits of using renewable energy. In order to serve as the leading international certification authority for all ESG professionals and aspirants, the International Association for Sustainable Economy was founded (IASE, 2023). The international association for sustainable economy helps firms with advisory level specialists and experts.

3.3.5 ISO standards for the industry

Globally there are experts that agree on ISO standards (ISO, 2023). These standards can be considered as a formula that specifies the best method to do something. Standards include a wide range of tasks, including producing products, managing processes, delivering services or materials. Standards are the condensed knowledge of those with subject-matter expertise and a familiarity with the requirements of the businesses they represent, including manufacturers, vendors, purchasers, customers, trade groups, users, and regulators. For example, quality management standards can be used to increase productivity and decrease product failures. Environmental management standards can be used to support waste reduction, environmental impact reduction, and sustainability. Safety and health standards that prevent workplace accidents and energy management standards can help reduce energy use.

In accordance with ISO 9001:2015, a company must have a quality management system if it (ISO, 2023):

a) needs to show that it can consistently deliver goods and services that satisfy customers and comply to applicable regulatory and legal requirements, and

b) strives to increase customer experience through the efficient use of the system, including system improvement procedures and the assurance of adherence to customer and relevant legislative and regulatory requirements.

Each business, regardless of its size, type, or the goods and services it offers, can comply with all of the generic requirements of ISO 9001:2015.

Any environmental management system must comply with the standards outlined in ISO 14001 (ISO, 2023). This standard has been accepted globally. By more effective resource utilization and waste reduction, it aids businesses in improving their environmental performance while gaining stakeholders' trust and a competitive edge. All sizes and types of organizations, including private, non-profit, and governmental ones, can use ISO 14001. It mandates that a business considers all environmental issues pertinent to its operations, including waste management, resource use, air pollution, sewage and water problems, soil contamination, and climate adaptation and mitigation. The requirement for ongoing development of an organization's systems and strategy for addressing environmental issues is a part of ISO 14001. The standard has recently undergone revisions that include significant advancements such as giving environmental management a higher priority in the organization's strategic planning procedures, gaining more input from the leadership, and demonstrating a higher level of commitment to proactive measures that improve environmental performance.

ISO/AWI 17887 is one of the standards under development which is devoted to the permanent magnet field (ISO, 2023). This standard will represent the ability for a company to trace RE throughout the supply chain, from REE to permanent magnets. The proposed standard would set up a management system for tracing materials that contain RE as they travel along the supply chain from producers of permanent magnets that contain RE to suppliers of RE oxides. Moreover, in order to improve the quality of life for people living in mining areas and the interaction between the mining industry and local inhabitants, a new ISO committee for mining reclamation management (ISO/TC 82/SC 7) is currently being developed. Additionally, ISO 14040:2006 is a another standard related to LCA, which means that companies should perform an LCA should be ISO compliant.

3.4 Supply chain resilience

Supply chain resilience refers to a supply chain's capacity to manage unavoidable risk-taking and recovery from disruptions, either to their prior condition or to a new, more desirable state (Gatenholm and Halldórsson, 2022). The idea of risks associated with disruption of the supply chain has changed from focusing solely on demand-side risks to now considering supply-side and control risks, as well as ever-increasing risks brought on by the globalization of supply chain and the greater emphasis on single sourcing. The five different types of supply chain risk outlined by Ho et al. (2015)—macro, manufacturing, demand, supply and infrastructural risks—reflect the concept's relatively broad applicability.

Furthermore, discontinuities are considered to be external in nature, meaning that the point of the disruptive event introduces an unmanageable interval (Gatenholm and Halldórsson, 2022). It has been observed that discontinuities can either be controlled consciously, whether forced or voluntary or left unmanaged by external factors. Designing supply chains to be adaptable and able to respond to changes in demand is a usual response to these disruptions. This can be done by introducing new items, altering volume, controlling transactions in manufacturing and delivery, or customizing product and service characteristics to fit the needs of customers. Information-sharing and leveraging between actors are two other well-established approaches for supply chain resilience. In the wake of the COVID-19 pandemic, increased resilience has been recommended. An additional type of resilience introduced by Azadegan and Dooley (2021) is micro-level resilience which emerges when suppliers and buyers work together directly to prevent and recover from supply risk. Meso-level resilience is the second one moving beyond buyer-supplier coordination and into multi-organizational collaboration. Macro-level resilience happens when businesses, including rivals, work with organizations like the government or industry associations to handle or control a longer-term supply risk.

Gatenholm and Halldórsson (2022) describe resilience in product-based supply chains by using an idea of the Panarchy theory. Release, conservation, reorganization and exploitation are the four successive phases of the Panarchy theory-based adaptive cycle. When resources (assets, employees, capabilities, suppliers, materials, and technology) are employed to take advantage of possibilities that result in conservation as capital is accumulated, this is referred to as exploitation. By gathering resources, the system broadens both its interconnections, which refers to how much it can influence its own course, and its potential, which affects the variety of alternatives for the future. Over time, as connection grows, the system's control becomes more rigid, making it more susceptible to interruptions. As a result, this is the best possible configuration for the existing supply chain and the way the product-based supply chain (PBS) should be formed in the absence of any changes to the external market. Product-based service may be generally referred to as offerings that are delivered throughout the product's lifetime, such as repair, maintenance, and refurbishing. In that case, the supply chain might be constrained into ignoring altered customer demands or a shifting business environment. In this model, COVID-19-related service disruptions were categorized as supply chain "discontinuities" which is described as situations being unexpected, unanticipated, frequently drastic shifts in a system.

Resources are released as a result of the conservation phase's vulnerability to external discontinuities (Gatenholm and Halldórsson, 2022). The release phase starts when the present supply network can no longer meet the evolving demands; this could be because of altered consumer behavior or a changing business environment. This stage can also happen if an external cause, such the COVID-19 epidemic, disturbs the supply chain. The third theoretical element, transilience, is in response to the demand for more research into COVID-19 replies. The capacity to concurrently modify some processes, often drastically, while restoring others is the definition of transilience, an analytical framework that combines the features of resilience and transformability. Transilience aims to combine transformability in assimilating into the new normal with resistance against common disruptive occurrences.

The transition from release to rearrangement is typically rapid, and it is during this time that new combinations may appear and inspire innovations in subsequent stages of the adaptive cycle (Gatenholm and Halldórsson, 2022). However, this is not always the case, there may also be instances where potential is not realized, and the SC no longer fulfills future demands. This stage may result in valuable innovations and long-lasting modifications to the design of the supply chain. This reasoning states that the SC revert to the exploitation and conservation phase following the restructuring to maximize the existing structure, see figure 3.9.

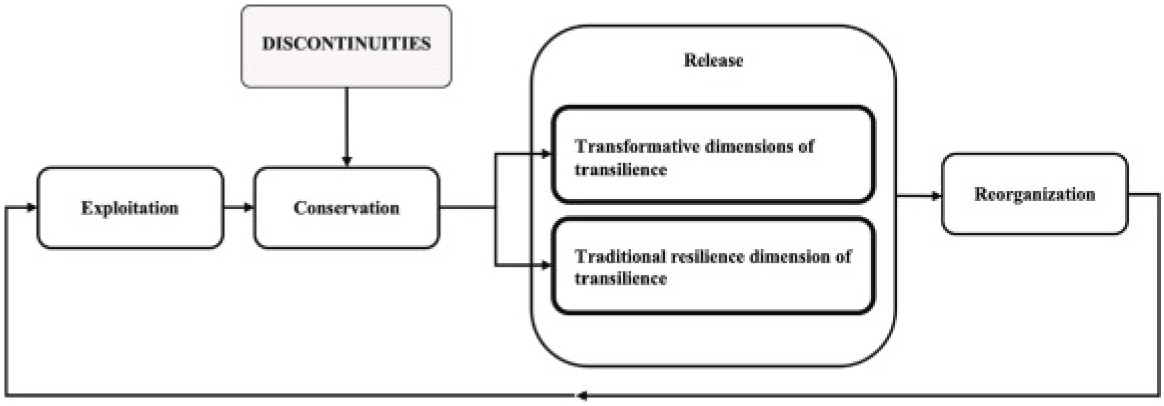

Figure 3.8: *Framework used to analyze resiliency. Retrieved from Gatenholm and Halldórsson (2022).*

Manufacturing SC resilience strategies mostly focus on the product and material flow, using flexible suppliers and information sharing between actors, prepare backup sources and inventory buffers, finally to share the risks with other actors and having multiple sources (Gatenholm and Halldórsson, 2022). A conceptual framework has been established for transilience to encompass the unique dimension that companies in PBS supply chains face. This framework considers not only the characteristics of disruptions that can be either managed or unmanaged but also identifies three distinct modes of response. These responses range from restorative actions to those that require a radical shift. By merging the concepts of panarchy theory and transilience, the framework has been developed to both maintain the current state and pursue a new normal. The framework reveals that disruptions can arise through deliberate actions, either imposed or voluntary, as well as external factors beyond an organization's control.

The release phase has undergone further expansion by incorporating two dimensions of transilience: transformative and traditional resilience (Gatenholm and Halldórsson, 2022). These dimensions encompass a wide range of actions, ranging from making radical changes to a company's service offerings and delivery methods to restoring the current state. The traditional dimension of resilience is divided into the first stage of resilience, which involves scaling up or down the current PBS delivery system. Mode 1 refers to reestablishing and focusing on existing supply chain structure, which does not need a significant rearrangement and can instead quickly change to conservation and exploitation. The transformative aspect of resilience is divided into two other modes: extending the normal by improving or adding the product-based service offering (mode 2) or embracing a new normal state by drastically modifying the PBS offering (mode 3). The organization exploits new consumer behavior and/or the changing business landscape to liberate resources and reorganize. Gatenholm and Halldórsson (2022) argue that the degree of severity of discontinuities noticed by product-based-service supply chain organizations necessitates transilience rather than just resilience, some processes require fast restoring while others also require simultaneous radical changes.

3.5 Supplier involvement and technology

In many industries, suppliers contribute more to innovations than manufacturers themself (Van Weele, 2018). For large manufacturers, the question of how to unleash the innovative ability of suppliers is of utmost significance. These firms must collaborate more closely with their suppliers on new products and business models for innovation. In fact, earlier supplier engagement in product development led to shorter development lead times, improved product quality, and a quicker time to market. Yet, other research revealed that early supplier involvement increases development costs, product costs, market introduction delays, and intellectual property issues.

According to Van Weele (2018), it is not simple to include suppliers early in the development of new products. The parties engaged don't always fulfill the requirements for effective technology collaboration and exchange. The R&D team from both companies may be quite resistant to technological collaboration. An effective partnership across R&D, production, purchasing and product development, is required for the organization. The theory is that internal cross-functional collaboration between the relevant disciplines is a prerequisite for successful supplier collaboration for businesses. There isn't always this kind of cross-functional cooperation among businesses. Additional requirements include the need for experienced project management. To provide quick and effective technical information, the system's integrity should be protected. Both parties frequently undervalue inter-system operability, which can cause serious issues with daily communications and operations.

The R&D potential required to support the customer's new product development activities may be underappreciated by the supplier's side (Van Weele, 2018). An effective producer is not usually a skilled product developer, and vice versa. The transfer of knowledge and experience between the customer and the supplier necessitates a significant investment in time and energy.

The difference in short-and long-term benefits must be highlighted when considering the advantages of early supplier involvement (Van Weele, 2018). Benefits in the short term could include improved quality, less product costs, quicker development times, and lower development costs. These advantages can be attained by utilizing specialized goods and technological know-how supplied by the supplier. Joint research initiatives on emerging technologies, alignment of technological strategies and road maps, and the potential to collaborate with technology suppliers, on a risk-sharing and gaining basis that may have a long-term benefit. Whole new product designs may emerge when businesses can do so.

4

Empirical data

The results of the market study on permanent magnets are presented in this chapter. It first explains the production steps of sintered NdFeB magnet from mining to final product, the structure and the different market actors, the relationships and extrinsic factors shaping the value chain.

4.1 NdFeB in electrical machine

Permanent magnets are used in EVs due to their properties (Severson et al., 2022). The magnets are placed in the rotor inside of the EM. These include remanence and coercivity. A replacement can cause the magnet to become demagnetized if it lacks the proper coercivity. Moreover, special factors like torque, operating temperature, power consumption, current draw, and heat output of the EM when under load must be considered for the electrical equipment. Applications that require sintered NdFeB series magnets include traction motors for EVs. Smaller diameters are possible due to these high-performance (sintered) magnets, which are typically seen as being more crucial than the motor magnet's cost. Due to the space restrictions, a higher power density is needed for EVs, which necessitates stronger magnets.

PMs efficiency advantages are used by almost all automobile motors today (Ormerod, 2022). PMs are often made of ferrite, bonded NdFeB, or completely dense (sintered) NdFeB. These magnets are chosen to provide a good tradeoff in terms of cost, performance, and size/weight for each application within vehicles. Since a few years ago, there has been a tendency toward switching many automotive motors from the ferrite type to sintered NdFeB. Ferrite magnets make it challenging to construct a motor with power density and high torque since they have just a third of the residual flux density and a fifth of the coercivity of NdFeB magnets (Cui et al., 2022). The conversion comes at a high expense since the entire motor must be modified to make use of NdFeB's better qualities, and the new product must undergo a thorough evaluation to avoid failures in use and recalls (Ormerod, 2022). The magnets carry out a variety of tasks. In a hybrid or fully electric vehicle, larger magnets employed in the motors can be used to provide power steering, start the car or even drive the car itself. NdFeB magnets are becoming increasingly used in vehicle motors due to the goal to increase fuel efficiency by minimizing device size, weight, and energy consumption.

All the driving power in full electric cars comes through the power of one or several electric motors. While there would likely be less magnets in a fully electric car, there will certainly be many dozens of other used in things like the window raise motors, seat adjustment, loudspeakers, and windshield wipers. The drive motor, however, has the greatest amount of magnet element in an EV. The size and driving needs of the vehicle determine the magnet material's layout, size, and overall weight. A rough approximation of the whole average magnet weight in passenger car traction drive motors is 1.1 kg. This is around 0.0125 kg of magnet for every kW of motor power. Around 3 kg of magnets could be needed for a vehicle with 250-kW motor power. The International Energy Agency (IEA) predicts that by 2030, the world would sell between 25 to 47 million (Stated Policy Scenario & Sustainable Development Scenario) vehicles annually (Kryder & Kim, 2009). Around 27.5 kilo tons of magnets (NdFeB) would be needed to power 25 million light-duty EVs. This would be in parallel to the demand for trucks, buses, and commercial vehicles. Additionally, Cui et al. (2022) highlights that annual production of EVs and HEVs would exceed 60 million units by 2030. In 2030, more than 120,000 tons will be needed for this one application if each car uses 2 kg of NdFeB-magnets which is a rough estimation.

4.2 The process prerequisites

In this chapter the conditions for sintered NdFeB magnet, the value chain, the production and the characteristics of a sintered NdFeB magnet will be described.

4.2.1 The value chain of sintered NdFeB magnet

For a complete sintered NdFeB magnet, the process starts with the REEs (Smith et al., 2022). The light rare earth (LRE) metals neodymium (Nd) and praseodymium (Pr), the heavy RE (HRE) dysprosium (Dy), and occasionally terbium (Tb), iron (Fe), and boron (B) are used to make the permanent magnets, NdFeB magnets. For a better overview see figure 4.1 and 4.1.

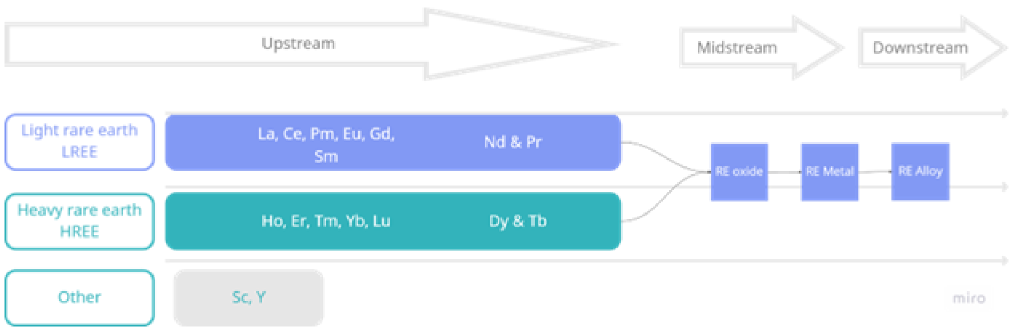

Figure 4.1: *17 rare earth elements divided into light and heavy elements.*

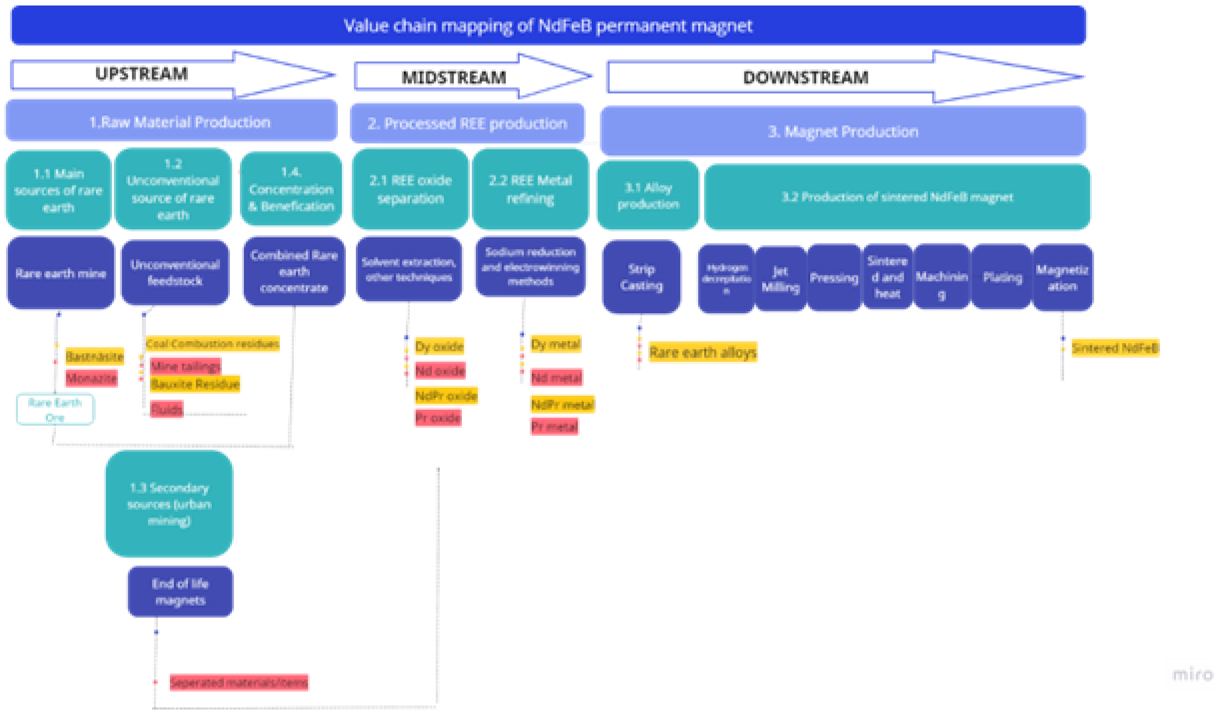

Figure 4.2: *Permanent magnet production flow, from mining to final product.*

In the first step, rare earths are made by mining primary ores (Smith et al., 2022). HRE and LRE can be found in the same deposits, however, LRE have higher concentration than HREs. Monazite and Bastnäsite are two RE-containing mineral ores that are currently extracted. Bastnäsite ore deposit contains significant quantities of Ce, La, Nd, and Pr, as well as modest amounts of Sm, but little HRE material. Monazites are typically abundant in Ce and La, with minor quantities of Nd, Pr, and HREs. REs can also be obtained from unconventional sources. For instance, from alternative upstream processes or byproducts from mining. The following unconventional sources for RE recovery are; the clays and shales below and above the coal seams, coal ash from coal-fired energy plants, geothermal liquid used for production of energy, mine tailings, acid mining drainage, and red mud (bauxite residue) created during the alumina production. See figure 4.1 for a division of the LRE and HREs.

REE-bearing rock must first be dug up from the ground before chemical techniques of REE extraction and separation can be initiated (Long, 2013). Many RE ores are mined using traditional open-pit techniques, which involve blasting rock to break it, loading it into trucks with big shovels, and transporting it to a concentration center. In the next step, the RE minerals will be treated with a chemical which makes them water-repellent, enabling them to rise to the surface linked to air bubbles in stirred tanks, in which they are skimmed into a concentrate. This process is named froth flotation. The REE concentration is processed locally or transported to another place for extraction and separation while the extraneous minerals are discarded as waste. These production steps are part of the up-stream value chain, see figure 4.2.

The various REEs are recovered through a series of processes once the concentration of REE is leached with the acid (Long, 2013). REEs are generally separated using a method called solvent extraction, which involves forcing an organic chemical specifically designed to remove a certain REE countercurrent to the leach solution that contains that REE. The targeted REE enters the organic phase, that is the separation of the leach solution, when using acidic stripping method, the REO will be recovered. Low separation efficiency necessitates numerous solvent extraction steps. Despite the availability of a combined REE oxide product called mischmetal that is commercially accessible, the majority of REEs are recovered again as separate REOs and sold as it is or used to produce other REE compounds, alloys and metals.

Lastly before magnet production can start REO or chlorides must be processed into metals (Smith et al., 2022). The most common metals used for producing sintered NdFeB magnets are didymium (NdPr), a combination of Pr and Nd, pure Nd, and ferrodysprosium (DyFe), while Tb metal being less used. Sodium reduction and electrowinning are the two methods for metal refinement that are most frequently utilized. The electrowinning process uses an electrowinning cell, that has a specific number of cathodes and anodes, to transform REO into alloys or metals. These production steps are part of the mid-stream value chain, see figure 4.2.

4.2.2 Sintered NdFeB magnet production

Magnets are made by alloys or powders which include iron, boron, and REE (Nd and Pr) (Smith et al., 2022). The alloys utilized to make NdFeB magnets are divided into two: alloys for bonded magnets, in which plastic resins are required to bond together the magnetic particles, and the ones needed for sintered magnets. Sintered magnets are frequently used in harsh conditions, higher-temperature environments, whereas bonded magnets are frequently preferred in applications that ask for complicated forms. Small additions (0.5 to 11%) of Dy or Tb for sintered NdFeB magnets should enhance their high-temperature resistance against demagnetization but it then raises the price of the magnet as dysprosium has remained one of the costliest REEs for the past 10 years. Additionally, cobalt, aluminum, and other similar metals may be added to the magnets. Iron and boron make up the remaining 30% of the total RE fraction. Figure 4.3 shows the magnet manufacturing section part of the supply chain.

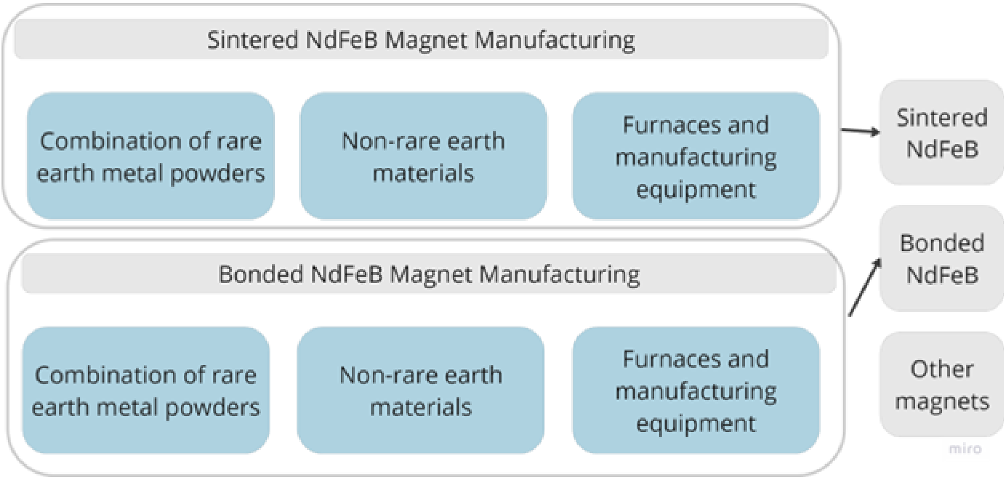

Figure 4.3: *Magnet manufacturing process steps. Retrieved from Smith et al. (2022)*

Magnets that have been sintered frequently use powder metallurgy (Smith et al., 2022). By induction melting the metals, followed with strip casting, which involves pouring molten metal on a cooled metal cylinder's outer surface as the cylinder is turned, magnet alloys with microscopic grains sizes can be formed/produced. This might be supplemented by hydrogen decrepitation to further shrink the grain size, resulting in a strip that are subsequently jet milled utilizing autogenous milling of the alloy to a fine powder that can be utilized to make magnets (Brown et al., 2002). Due to their pyrophoric nature, or propensity to ignite when exposed to oxygen, these powders are challenging to export. The alloys might be formed in a separate melting phase from the casting step, but doing so would raise the cost because a second melting step would be required before casting (Smith et al., 2022). The creation of the powder during the jet-milling process is crucial because the magnet's microstructure, which determines its critical performance parameters, is controlled by the shape of its grains. The powder is thereafter aligned, compressed, and heated to between 1,000°C and 1,100°C during sintering (Brown et al., 2002).

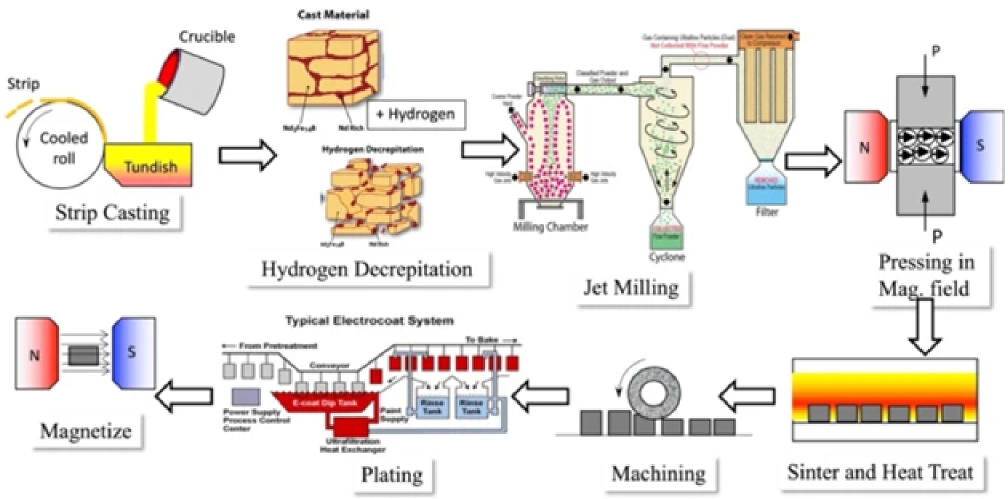

Figure 4.4: *Magnet production steps. Retrieved from Cui et al. (2022)*

After being formed, sintered magnets get machined to the correct shape, and then covered with a nickel metallic coating (5–10 microns thick) to prevent corrosion (Smith et al., 2022). To align the magnet's grain magnetization after plating, the magnets are magnetized into a strong magnetic field. Depending on the ultimate size and form of the magnet, the machining process encounters the most material losses. See figure 4.4 for an illustration of the magnet production steps.

Better manufacturing techniques including grain boundary diffusion (GBD) and dual alloy method, which mixes ferro-dysprosium (DyFe) and NdPr metal, have been widely used by manufacturers to reduce the amount of heavy rare earths (HRE) in NdFeB (Smith et al., 2022). These procedures allow Dy contents for a certain grade to be lowered below the levels shown in figure 4.5. According to magnet manufacturers GBD is the most used technique to lower the HRE waste when producing magnets. The technique helps to cope with the price volatility when it comes to the HRE content. Some suppliers develop their own know-how so they can use the HRE only where it is needed for the magnet coercivity. Consequently, this also affects the final magnet price since the amount of Dy and Tb (heavy rare earth) affects the magnet prices. The process will help the suppliers to increase the magnetic properties while keeping the price low. According to industry experts if you want to be successful in the traction motor business you have to use GBD for your magnets.

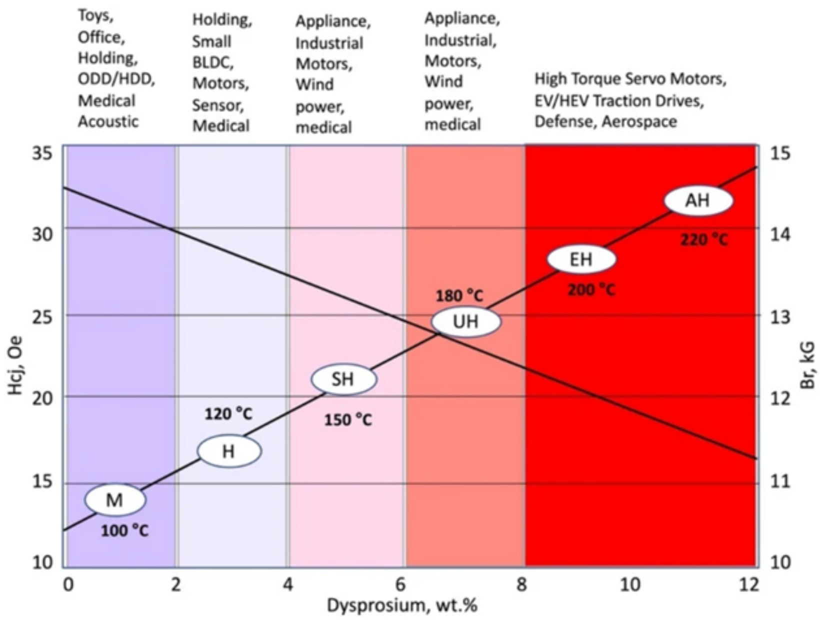

Figure 4.5: *Quantity of Dy required for the NdFeB magnet. Retrieved from Cui et al. 2022*

An alternative solution to the use of RE metals such as Nd in the production of magnets is the development of advanced materials, where these metals are partially replaced (European Commission, 2022). This can be achieved through "doped perovskite manganite oxide nanostructures" that possess similar or better magnetic properties than NdFeB magnets. Another recent development is the magnet-to-magnet recycling (m2m®) process, which involves using the elements from discarded

NdFeB magnets to manufacture new sintered magnets (Prosperi et al., 2018). This process not only recovers the magnetic properties of the starting materials but also enhances coercivity by up to 83% through adding complex additives at different manufacturing stages. This is accomplished by using a sub-process known as grain boundary modification (GBM®), which is mediated by a RE rich "GBM® alloy, to produce a distinctive microstructure surrounding the magnetic grains, consisting of concentric "shells" composed of elements at the boundaries of the grains. This microstructure could be helpful in clarifying how m2m® can produce NdFeBs with up to 40% less Dy while maintaining the same coercivity.

Moreover, tetrataenite, which naturally forms in meteorites over millions of years, has been discovered by researchers to potentially replace rare earth magnets (Ivanov et al., 2023). This indicates that with simple casting, the material can form over a short period of time. Although this approach appears promising, additional research is necessary before determining whether it will work with high-performance magnets. To make this determination, the research team is aiming to work with major magnet producers.

4.2.3 Characteristics of the NdFeB permanent magnet

Fundamentally, a magnet is a tool for storing energy. If correctly built and handled, this energy is initially placed into the magnet when it is first magnetized, and it stays in the magnet indefinitely (Cui et al., 2022). In contrast to batteries, a magnet's energy is never lost and is continuously available to be used. Since a magnet does not directly affect its surroundings net work, instead it uses its energy to repel or draw other magnetic objects, helping to turn electrical energy into mechanical energy. A permanent magnet is special in that, once created, it produces a magnetic flux with no necessary energy input, resulting in no operating cost.

Sintered NdFeB magnet grade matrix, which measure their maximum energy output in mega-gauss-oersteds (MGOe), typically fall between 35 and 52 MGOe (Smith et al., 2022). They are usually identified by their energy product followed by a "N" (e.g., "N35," "N42,") and a suffix that indicates their maximum suggested operating temperature. See figure 4.7 for the different maximum temperature per suffix. HRE (either Tb or Dy) can be replaced with Nd/Pr to work at higher temperature. For instance, in comparison to a "N52" magnet, which has an energy output of 52 MGOe and a maximum operating temp of 80 °C, a "N42AH" magnet, also known as "42AH," would possess an energy output of 42 MGOe and operate in a temp of 220 °C. Figure 4.6 shows an example of how a magnet grading matrix can look like from a supplier.

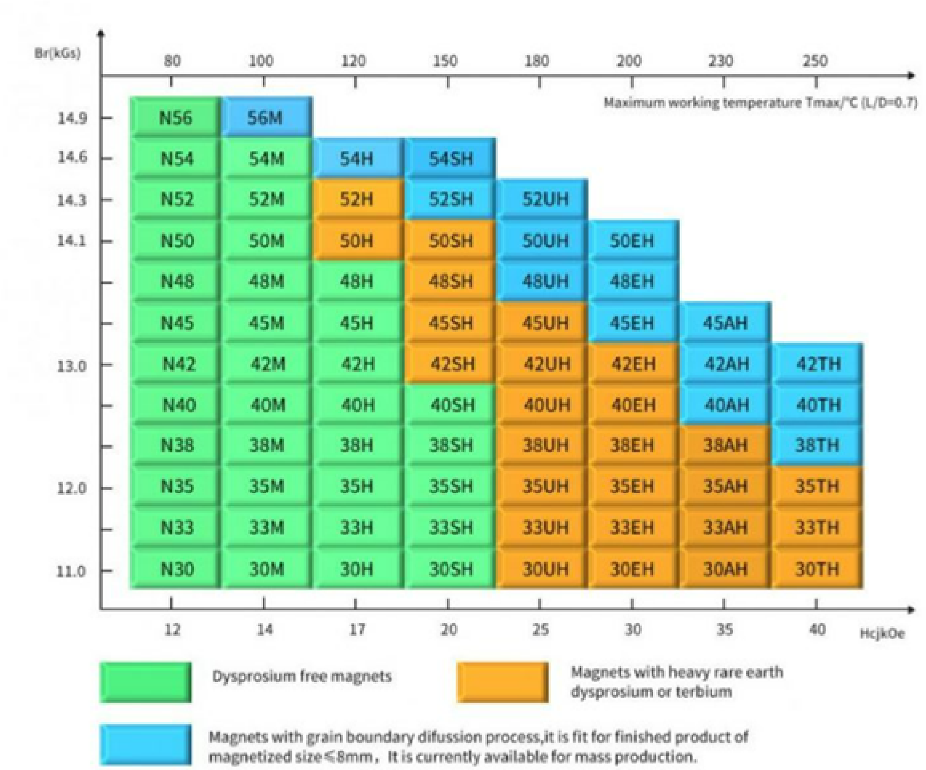

Figure 4.6: *Grade matrix for sintered NdFeB magnet. Retrieved from Rizinia (2020).*

The magnetization of a material is defined as the summation of the electron spins and orbital moments per volume unit (Cui et al., 2022). In the ferromagnets, these orbital moments align over great distances to generate magnetization values that are millions of times higher than those of other materials. A PM is distinguished by its ability to create and sustain magnetic fields despite the presence of an external opposite magnetic field. However, if the amplitude of the opposing field is great enough, the magnetic poles inside the PM will reflect the opposing field, which will demagnetize the PM. This highest opposite field is known as coercivity, or Hc. Magnetic flux density B is connected to the force produced by the magnet, whereas Hc characterizes a permanent magnet's resistance to demagnetizing fields. Permeability, is the total sum of H and M, where M denotes the magnet's magnetization and H denotes the external field that the magnet experiences. When H is 0, the magnet's remanent magnetization, Mr, and residual magnetic flux density, Br, are same. Remanent magnetization is the magnetization left in a ferromagnetic material after an external magnetic field has been removed.

Current EV/HEV traction motor designs need NdFeB grades that can withstand strong demagnetizing fields at temperatures above 180°C (Cui et al., 2022). To boost high temperature coercivity, the conventional commercial solution needs a lot of Dy. Figure 4.7 illustrates the quantity of Dy required for the NdFeB magnet to present the stated coercivity at temperatures particular to various applications. According to these estimations, utilizing the present bulk alloying manufacturing techniques, > 10,000 tons of HREE (Dy or Tb) could be needed by 2030. In 2020, there were around 240,000 tons of rare earth produced worldwide, and the production of Dy accounted for only about 2400 tons, or 1%, of that total. Without significant increases in supply, it seems that in the middle of the decade there will be a severe Dy/Tb shortage. However, the demand of REPM's high temperature qualities may be somewhat lowered with advancements in soft magnetic materials, electrically isolating material thermal conductivity, and motor cooling techniques.

Suffix	No Suffix	M	H	SH	UH	EH	AH
Max operating temp. (C)	80	100	120	150	180	200	220
Approx. Dy content (wt. %)	<0.5%	1.4%	2.8%	4.2%	6.5%	8.5%-11%	8.5%-11%
Approx. Nd+Pr content (wt.%)	29,5%	28.6%	27.2%	25.8%	24.5%	19%-21.5%	19%-21.5%

Figure 4.7: *Relation between max operating time and Dy percentage. Retrieved from Smith et al. (2022)*

A thermally stable magnet is necessary for electrical machines in order to avoid a large flux shift at high motor operating temperatures (Prosperi et al., 2018). The overall reversible loss coefficients of virgin and recycled magnets are comparable. These results demonstrate how the m2m® method can create homogeneous magnets that are specifically designed to satisfy the needs of a particular application such as an electric motor. Moreover, the Canadian magnet manufacturer states that they are developing new magnets called MQ3 with similar magnetic characteristics as sintered NdFeB magnets. The magnets will be high performance magnets with reduced or even zero amount of HRE content and be lower in cost throughout the value chain. These magnets will be used in a variety of applications, including industrial automation motors and traction motors for hybrid electric vehicles.

4.3 Network overview of sintered NdFeB magnets

The following chapter will include an overview of permanent magnet actors and their relationship, Chinese market position and expected volumes by 2030 in the market.

4.3.1 Actors

The PM market is fragmented, with hundreds of suppliers operating at different levels on the supply channels. For example, there are over 800 vendors in the Asia Pacific region (Ormerod, 2022). For NdFeB, there are roughly 20 top-tier, 50 mid-level, and hundreds of third-tier suppliers. As explained by the Rare Earth Industry expert the supply chain for permanent magnets has numerous levels and is opaque, for instance, manufacturer, agents, value adders, and distributors.

It is challenging to estimate an accurate list of permanent magnet manufacturers in the globe since new firms are formed, current ones close or are acquired by others. China (92%), Japan (7%), Vietnam (1%), Germany (1%), and a few additional countries with rather limited capacity are the leading manufacturers of NdFeB magnets, alloys, and powders (Adamas Intelligence, 2020). Major producers of magnets, powders and alloys outside of China includes Shin-Etsu Chemical (Japan), Proterial Ltd. (before named as Hitachi Metals), Vacuumschmelze (German company) with its subsidiary company Neorem (Finland), Magneti (Slovenia) and Less Common Metals (UK). Many companies manufacture magnets in foreign plants (Smith et al., 2022). For instance, Proterial Ltd, Shin Etsu, TDK, and Vacuumschmelze manufacture part of their magnets in China and Shin Etsu manufactures magnets in Vietnam through Shin Etsu Magnetic Materials Vietnam. Japan is the second-largest producer of magnets due to its extensive knowledge in the field, as evidenced by their numerous patent applications in the U.S. and other countries (Smith et al., 2022). See figure 4.8 for a geographical spread of countries specialized in the different steps of the production process of permanent magnets.

Country	Mining	Separation	Metal refining	Magnet alloy manufacturing
China	58%	89%	90%	92%
USA	16%	-	-	1%
Burma	12%	-	-	-
Australia	7%	-	-	-
Madagascar	3%	-	-	-
India	1%	1%	-	-
Russia	1%	-	-	-
Thailand	1%	-	3%	-
Malaysia	-	7%	-	-
Estonia	-	1%	2%	-
Japan	-	-	-	7%
Vietnam	-	-	3%	1%
Laos	-	-	2%	-
Germany	-	-	-	1%
Slovenia	-	-	-	1%
Finland	-	-	-	1%
UK	-	-	1%	-

Figure 4.8: *Geographical spread of countries within the supply chain of permanent magnet production. Inspired from Smith et al. 2022*

The sole operational rare earth mine in the US, Mountain Pass, is owned and operated by MP Materials (Argus Media, 2020). They currently produce a concentrate of LRE, which they sell to China. MP is making significant investments in expanding their separation processing capacity. The US REs project aims to establish domestic capability for the extraction and refining of both heavy and light rare earths, as well as the production of NdFeB magnets, samarium-cobalt magnets, and various rare earth metals and alloys.

Lynas is the only significant RE producer outside of China and fulfills up to a fifth of the world's demand for LRE magnetic materials, neodymium and praseodymium oxide (Argus Media, 2020). Lynas is shipping/delivering RE concentrate from its operations in Australia to Malaysia where it is developing a process to increase capacity and reduce the regulatory risk in Malaysia (Argus Media, 2023). The government of Malaysia is concerned regarding levels of radiation from the cracking and leaching process. The restrictions in Malaysia due to governmental interference may give rise to a supply disruption of NdPr (Burton, 2023). After July 2023, Lynas is not permitted to engage in any activities that will result in radioactive waste in Malaysia (Argus Media, 2023). Moreover, Lynas used its own intellectual property and experience in RE separation for their design phase (Argus Media, 2020). In May 2019, Lynas made a preliminary agreement with US RE technology company Blue Line to establish a JV aimed at creating REs separation capabilities in the US, with the goal of addressing a gap in the supply chain.

During the interviews it was highlighted that different actors are involved in different parts of the magnet production process. Some manufacturers start to produce magnets from metal or alloy while others start directly from ore. The type of manufacturer and their processes determine the number of sub suppliers and their relationships. Some manufacturers have direct contact with mining companies whilst others have direct contact with metal refiners.

4.3.2 Relationships in the market

Several magnet manufacturers highlight that they are aware of the growing market for permanent magnets. A European magnet manufacturer mentions that the number of contacts coming from the OEMs is record high and the interest is higher than ever before. Moreover, the supplier mentions that the automotive market has very strict and clear targets on sustainability and that they want to have a possibility to source permanent magnets independent from China. The European magnet manufacturer follows by describing their customer base. They state that OEMs currently have a small share of the customer base. The company is involved in many different markets, for instance windmills, electronics and automation.

According to a Chinese manufacturing supplier, previously it was most often to have an agent or a distributor in between China and a European customer. However, nowadays, the direct relationship with producers is getting more common. The reason is the co-development for the future electrification and the rising demand of permanent magnet and the development of the magnet for the end-application. As described by a distributor they do not produce magnetic materials, they purchase either finished magnets for distribution or raw magnetic blocks for production of custom magnetic assemblies. They focus on designing the magnet, do post-assembly magnetization, build/sell magnetizers, manage the supply chain/quality of the magnets from China to the international market and build magnetic separation equipment. All the interviewed distributors purchase directly from magnet manufacturers located in China and Japan and whilst some purchase it from Germany. Two distributors mention that they have direct contact with manufacturers and end-users of magnetic products. Furthermore, they mention that they provide engineering support and a vertically integrated production facility for complex and critical magnetic assemblies and custom electrical machines. For instance, a distributor highlights that to have a new customer they demand a collaborative relationship where they invest in the technology together. According to one of the distributors a lot of companies out in the market are distributors even if they declare themselves as a magnet producer.

The distributors highlights that it is difficult for a manufacturer in China or Japan to co-develop with a customer that is not "close". However, another distributor highlights the impact of former relationship with a Chinese magnet manufacturer. The distributor had previous ownership in the manufacturing company and still today they are involved in investment and raw material strategy developments but on paper they buy a magnet as a piece price. The distributor mentions that they have other direct supplier relationships that are very transparent. They know each other's profit and they collaborate to fulfill different customer requirements. For instance, if a European customer purchases a magnet from them the manufacturing company will consign it directly to the customer.

Several magnet manufacturers mentions that they have started to build up relationships with mining actors outside of China to lower their dependency on Chinese supply. According to the actors LRE content can be found from countries such as India, US and Australia and they are therefore in collaboration with them. Some of these mining companies are also open for a joint venture to invest in new technologies and to develop techniques of how to handle HRE content to build a supply chain outside of China. In contrast some manufacturers see permanent magnet as a product where transactional relationship is used. According to a Japanese magnet manufacturer and advanced engineering from Alpha a relationship between a buying firm and a magnet manufacturer is important for sharing knowledge. In their view, magnet manufacturers can provide a prototype of the magnets for the end-customers to enable the development of their own final product.

Recently, MP Materials announced plans to build a magnet manufacturing plant in Fort Worth, Texas, to provide General Motors (GM) with NdFeB magnets for their automobiles (Smith et al., 2022). Initial production would start in 2023, and the facility will manufacture 1000 tons of NdFeB magnets annually, or roughly 1% of the market's actual output (MP materials, 2021). Vacuumschmelze has also revealed its plans to manufacture magnets for GM in the US. However, the size of the plant is still unknown (Vacuumshmelze, 2022).

4.3.3 Chinese market position

China appears to completely control the manufacturing of NdFeB magnets, the separation and manufacturing of REE (Rabe et al., 2017). China's output increased by 118% from 2010 to 2019 with a 9% compound annual growth rate (Ma and Henderson, 2021). However, only a small portion of China's domestic manufacturing is exported. According to customs data, China exported 36,000 tons of RE magnets in 2020, with 13.7 percent of the total going to the US. This is one fifth of the total domestic production in China during 2020 (Xuanmin, 2021). This does not seem to be a conscious attempt to impose export restrictions on magnets, as Beijing attempted with REEs in 2010, which resulted in a World Trade Organization case that China lost (Ma and Henderson, 2021). Instead, China is restricting exports since domestic demand for magnets is expected to increase as the market there begins to embrace EV and wind power. Most of the electric motors are produced globally by Chinese businesses (Bradsher, 2021). Even the manufacture of essential raw materials for electric vehicles, such as lithium, cobalt, and RE metals, has largely been taken over by China.

Additionally, the production of magnets has expanded quickly, resulting in a domestic industry with 200 companies, producing with an annual capacity under 1,500 tons (Ma and Henderson, 2021). Furthermore, only around 15% (23,000 tons) from the total of 160,000 tons, NdFeB magnets manufactured in China in 2018 are classified as high-performance magnets. China consequently seems to be overproducing low-end magnets while having trouble keeping up with high-end (sintered) magnet demand. The high entry patent and cost barrier are the two main factors making it difficult to move up the permanent magnet value chain. The Japanese government's control over the patents for the most sophisticated sintered NdFeB magnets appears to be another barrier to rising the value chain. Chinese businesses are then unable to produce such magnets and, as a result, export them to customers in Western markets are not permitted.

Due to the complexity of the plants and the numerous specialized machines needed, midstream manufacturing of magnets needs a substantial capital expenditure (Ma and Henderson, 2021). Smaller companies simply lack the resources to scale manufacturing or invest in research and development to create high-performance magnets. As of this, just eight Chinese magnet businesses and perhaps a dozen other businesses worldwide have the capability and quality to provide premium end users like Tesla or Siemens. However, China's domination in permanent magnets does not have to remain in the long run. It is evident that China has not presently reached the forefront of the magnet industry, therefore there still seems to be time to expand production elsewhere.

According to one of the Chinese magnet manufacturers in the next eight years, China will decrease its dominance in the global supply of RE going from 80 percent in 2021 to 68% in 2030. This estimate was done together with industry experts. This means China will lose its dominance on the global supply chain. The main reason here is the development of the mining companies outside of China, such as

MP in the United States or Lynas in Australia. These companies are expected to grow.

The rare earth industry expert mentions that China itself is a big market with a lot of magnet manufacturing companies, both mid-and big size actors. Even if the companies partially are connected to the government there is a lot of competition within the country. This competition is due to gaining a share of the export market and access to raw materials. Therefore, they pressure the upstream players and indirectly communicating to the regulatory authorities in China to push for a sustainable raw material cost. Another reason is that a Chinese manufacturer of electrical machine cannot be competitive if they are more expensive than rest of the world. Hence, the government will interfere and pressure the upstream players up to metal making actors in order to stabilize the situation.

4.3.4 Volume of sintered NdFeB magnet by 2030

Approximately 10 million EVs have been sold as of today, while 150 million are predicted to be sold by 2050 (Nakamura, 2018). The majority of these EVs will use permanent magnet motors. If each car uses 1 kilogram of sintered NdFeB magnets, 150,000 tons of NdFeB magnets will be needed just for the traction motors. The demand might increase to 135,000 tons by 2030, primarily due to EVs and wind turbines expansion (Ma and Henderson, 2021). Globally, EVs used roughly 5,000 t of RE permanent magnets in 2019. On a global scale, the amount may expand to approximately 40,000 up to 70,000 t by 2030, depending on the projected growth scenario (Gauß et al., 2021). Furthermore, another source states that the expected global demand for NdFeB magnet in 2030 for EV applications is estimated to be around 114,000 tons (Smith et al., 2022). The demand is calculated based on a total magnet global demand growth scenario that can be rapid in order to reach net zero by 2050, with an average annual growth rate of 12.5 percent during 2030. Based on calculations starting from the volume of 5000 t year 2019 up until 2030 with 114.000 t gives an annual growth rate of 33% during the 11 years.

In 2022, 184,000 tonnes of sintered NdFeB were consumed worldwide (Arafura, 2023). Demand for sintered NdFeB magnets is anticipated to increase by 5.8% annually in the near future, reaching around 322,000 tons in 2032. By 2032, 32% of the overall demand for NdFeB magnets is anticipated to come from EVs. See figure 4.9 for an illustration of the NdFeB magnet forecast by each industry segment.

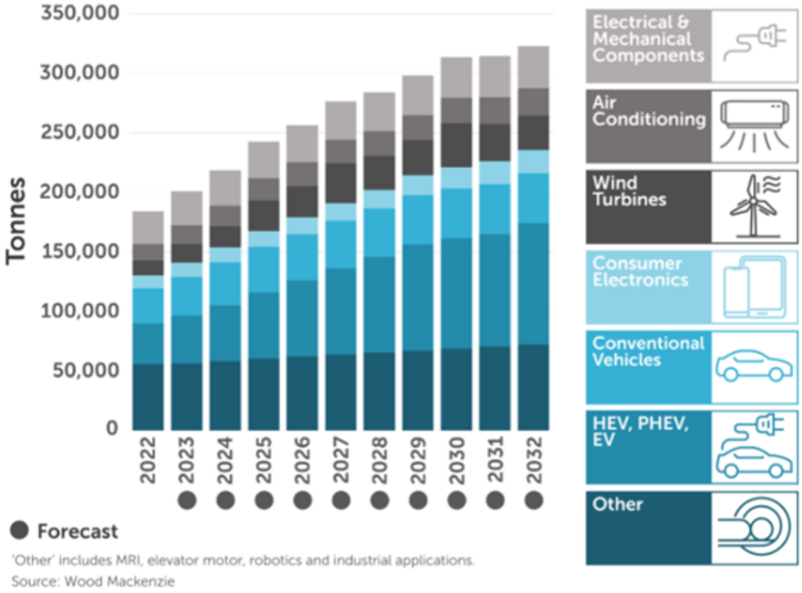

Figure 4.9: *Illustration of the NdFeB magnet forecast for different consumption segments. Retrieved from Arafura (2023).*

The interviewed Chinese and Japanese magnet manufacturers had a production capacity of around 10 000 to 30 000 ton. The most well-known magnet manufacturers in the market had 30 000 t. All the magnet manufacturers also highlighted that they are aware of the increasing demand from the OEMs and therefore they have on-going projects to expand their capacity. The European magnet manufacturers with lower capacity highlight that in order to supply all the requests coming from the OEMs they need long-term contracts with investments since they will not be able to meet the capacity targets.

4.4 Geo-political factors

This section will describe intellectual property, localization and joint ventures in the permanent magnet value chain.

4.4.1 Intellectual property

Large industries that use neodymium magnets, particularly in the USA and Japan, only purchase their magnets direct or indirect from the Japanese business, Proterial, Ltd licensed producers to avoid potential legal issues (Tengye Magnetic, 2023). The Proterial, Ltd patented product license is a significant issue for those companies. In order to comply with legal requirements, the procurement of the NdFeB must be provided from a Proterial, Ltd patent holder. For instance, NdFeB suppliers in Europe, the US, Southeast Asia, and Canada are required by law to pay Proterial, Ltd. a license fee (Amazing magnets, 2023). Unlicensed magnet producers frequently use less standardized raw materials and production techniques, which result in defective products and uneven quality. Buying sintered NdFeB magnets without a license could lead to a future lawsuit from the patent holder. In 2019, 94% of NdFeB magnets were sintered, and the large proportion of those patents were still owned by Japan. While this was ongoing, Proterial was only willing to license its sophisticated sintered magnets technology to eight significant Chinese businesses. This indicates that only 4% of China's 200 or so NdFeB magnet manufacturers can produce high-performance sintered magnets. The demand for global intellectual property protection increased as the market value increased from 2 billion USD in 2000 to 20 billion USD in 2021 (MagPatCo, 2023).

Moreover, Proterial Ltd, have been able to prevent Chinese magnet manufacturers from oversaturating domestic markets by holding U.S. and overseas patents (Smith et al., 2022). Due to the rapidly increasing demand of sintered magnets in the 2000s, China had little alternative but to comply (Ma and Henderson, 2021). In total, 1,413 registered patent applications for NdFeB magnets were published between 2001 and 2021 (Smith et al., 2022). Figure 4.10 illustrates the nation where each technology's initial application was applied. Only 5.7 percent of initial filings were made in the United States, while 9.7 percent were made in China and 60.5 percent were made in Japan. Furthermore, Figure 4.11 shows the top assignees for patents relating to NdFeB magnets. The company with the most patents in this field is Shin-Etsu Chemicals in Japan. US businesses are prevented from competing as a result of foreign companies' aggressive intellectual property enforcement.

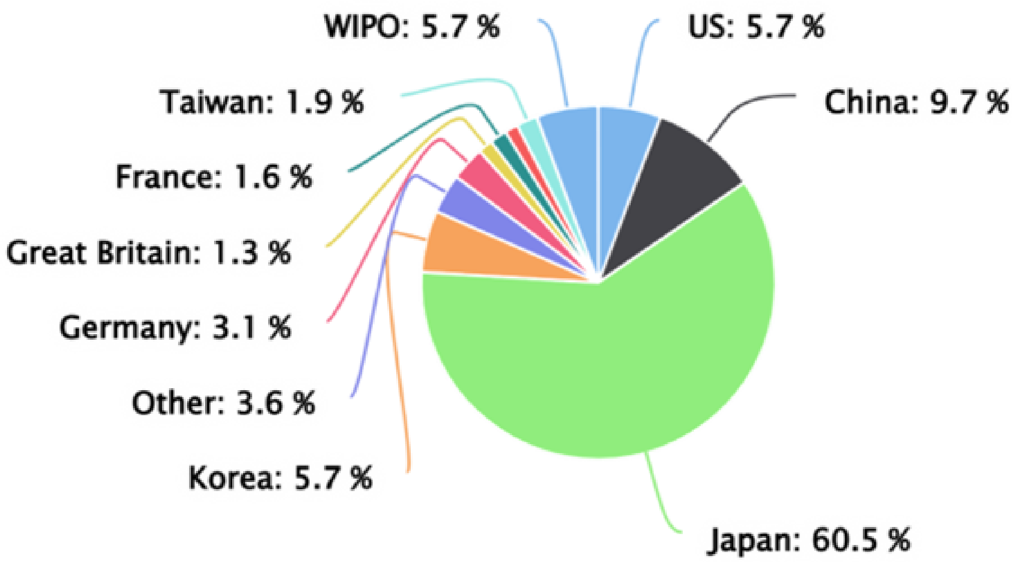

Figure 4.10: *Patent application of NdFeB origin by jurisdiction. Retrieved by Smith et al. (2022)*

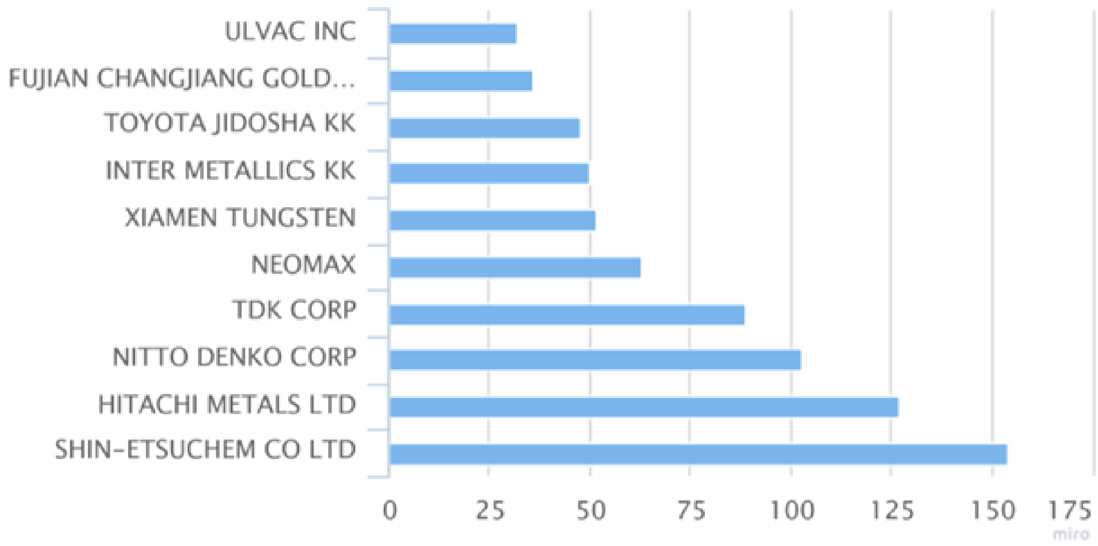

Figure 4.11: *Major actors that have applied for NdFeB magnet patents. Retrieved by Smith et al. (2022)*

For new magnet actors, patents have also acted as a considerable entry barrier. It is challenging for new magnet manufacturers without the license from Proterial Ltd, since it possesses patents for the widely used methods of creating sintered magnets (Smith et al., 2022). In 2012, the International Trade Commission received a complaint regarding four Proterial Ltd patents; the fact that those were expected to expire by 2021 and 2022 may make it simpler for new magnet businesses to operate in the future. However other pertinent patents might have extended expiration dates.

Industry patent expert highlights that the highest concentration of patents is from Japan. The second largest concentrations are in the USA and China. China is intentionally leaved out since they are in a market where they do not prioritize patents. Moreover, the third highest concentration of patents is in the EU. According to the industry patent expert there are several process patents that are still valid and will be valid until 2039. See figure 4.12. The interviewed Chinese, Japanese and European manufacturers highlighted that they have their own process patents for their production processes. Moreover, one of the European recycling companies shared that they have patents on their recycling processes such as green hydrogen-based technology for NdFeB powder.

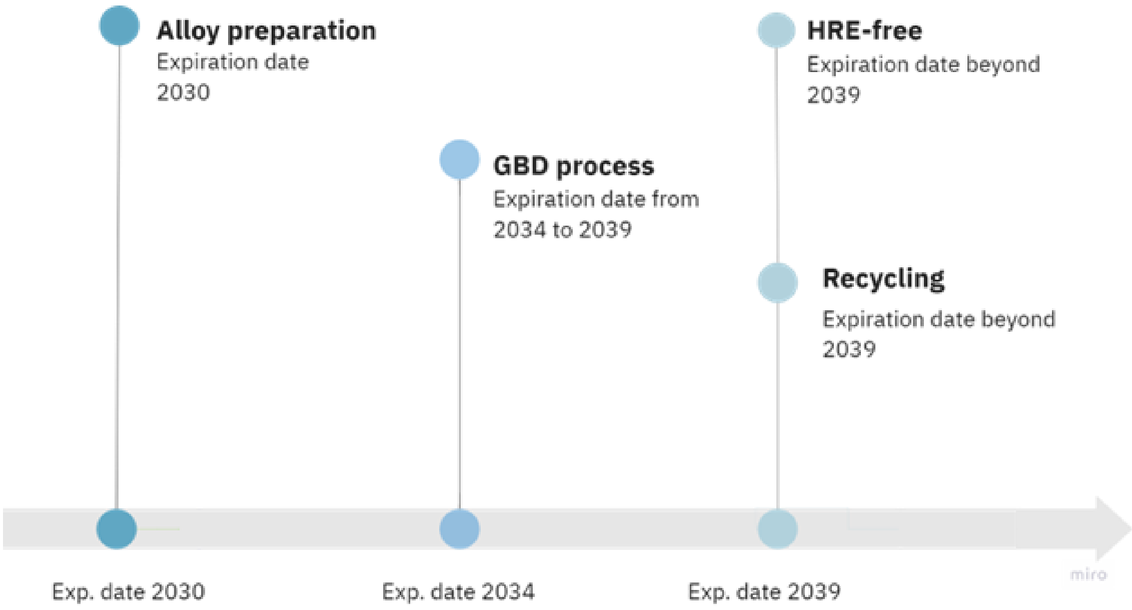

Figure 4.12: *Overview of sintered NdFeB magnet related patents. Retrieved from Google Patent and Patent Scope.*

Furthermore, the industry patent expert mentions that Japan owns the most patents, but they are not able to manufacture at a low price so Chinese actors are pushing the customers to buy their high-end technologies which are patent protected by the Japanese. Japanese companies have a cross licensing agreement, so that means that they can manufacture and distribute without any serious patent issues. For example, if Proterial, Ltd will make a patent, then Shin-Etsu will not have an issue. According to the industry patent expert it is easier to buy from these companies to avoid legal issues, however these companies are expensive compared to the Chinese manufacturers. On the contrary, the European companies like Vacuumschmelze have licenses called exclusive licenses and can sell their magnets worldwide, therefore it is safe to buy from them.

According to the rare earth industry expert some distributors have other patents related to the design consideration. The distributors tier one magnet manufacturer should have patents related to the processes so that the buying firms outside of China avoid issues. One distributor mentions that they for instance have patents related to orientation of each magnet in an assembly to provide higher torque in a motor. Moreover, the distributor highlights that their supplier owns all other process related patents for the magnets that are purchased. This is in order to ensure that it will be no issue for the European and US customers.

Subsequently according to the patent expert when you are communicating with Chinese magnet manufacturers, they can present a certain patent analysis or certain noninfringement opinion, however they do not check the relevant worldwide patents. They have a limited number of patents that they check and basically neglect other patents. These licensed companies approach their customers as being able to manufacture GBD magnets or other types of magnets. However, they are basically not able to sell those magnets on their licensed coverage to all markets. In terms of these high-end magnets like GBD magnets these companies which are licensed by Proterial, Ltd or any other non-licensed magnet manufacturers are in the same category since they present a certain risk. The industry patent expert mentions that after a thorough analysis it turned out that Chinese manufacturer have the patents, but they do not manufacture the magnet as it is disclosed in the patent.

4.4.2 Localization

Companies in China can control the international market for metals, raw materials, magnets and other components with market manipulation, for instance by increasing prices with limiting export or decreasing prices with price dumping (Smith et al., 2022). The Chinese government has several policies and regulations that affect markets, including economic and trade policy (such as tariffs, export quotas, exchange rate targeting and subsidies), economic and trade regulations (such as trade embargoes and price controls, etc.), and environmental regulations (such as emission and clean water standards).

Chen et al. (2018) is skeptical about China's ability to control, manipulate, or dictate pricing. It is suggested that China's pricing advantage stems mostly from cheaper labor costs and relatively less severe environmental rules (even though it has grown in recent years), if prices were to rise considerably, this would encourage (additional) REE manufacturing in other nations (Leal Filho et al., 2023). Yet, the alleged fragmentation of China's industry, with several small and diverse manufacturers and exporters, creates difficulties when negotiating with big foreign buyers. According to Chen et al. (2018), China is now also experiencing a "low-end locking dilemma" in terms of global commerce because the most of its exports are basic materials rather than finished goods. In lower value adding processes, China still has regulatory and price competitive advantages, but it lags in higher value-added processes (Leal Filho et al., 2023). Industrial patents for crucial materials also illustrate the latter, such as REE magnets. However, the researchers Mancheri et al. (2019) arrive at various analytical conclusions on the influence of China's governmental policies. They believe that China's domestic policies dominate the market for REEs internationally and further believe that global standards, China imports of REEs, worldwide stockpiling by nations, and their environmental requirements have a negative impact on the resiliency of the REE supply.

According to a project buyer from Alpha the importance of local-to-local supply is important for the CO2 impact. Two Chinese magnet manufacturer mentioned that the European customers are asking about the magnets outside of China and local sourcing. There are different approaches to tackle this challenge. The first approach is joint venture (JV) with a company outside of China. Secondly, to establish a new plant in Eastern Europe or buy a small magnet company. One of the manufacturers has chosen to build a plant in Vietnam, where there also are mining companies and other companies which separate the oxide into metal. In the first case there is a need to build up a new supply chain for the metal. It makes no sense if the production plant is in Vietnam and the metals are bought from China. In this case, it will not be independent from China. Therefore, it would be necessary to establish a new supply chain within Vietnam. Other suppliers mention that they do not want to be dependent on one single source and therefore it is of importance to have a diversified supply chain. According to the rare earth industry expert this will not happen 100% because the demand will be too high in the future. According to the European recycling company within NdFeB magnets the extraction of RE mining will be a constraint to meet the future market demand resulting in a RE magnet shortage globally before 2030. Moreover, environmental regulations have restricted mining in many countries.

Other manufacturers are also placing production in other locations to meet the demand from the US and European Union. One Chinese magnet manufacturer states that they want to be a global player instead of a Chinese one. The main constraints are the required investments, the licenses and the establishment of local market knowledge in a foreign country. Eventually the pricing for the end user will be impacted due to the location. According to two Chinese manufacturer it is now difficult for a Chinese company to get a license to invest outside of China with the idea of building up a magnet production facility. However, one of the Chinese magnet manufacturer have managed to receive a permission from the government to start a production plant for sintered NdFeB in Mexico that will fulfil the localization requirements for the US customers. This project was straightforward since the US market was very strict about their localization requirements and they were also very quick to make the commitments on the booked capacity. The magnet manufacturer highlighted that this helped them to be very sure about their next strategic steps. Furthermore, this is not the case for the European OEMs since they are not as clear about their requirements and not either willing to commit due to the price difference between China and Europe.

According to several magnet manufacturers the mine industry within China is fully controlled by the Chinese government. The government can control the market day by day. They can decide to stop the export of RE magnets to other markets at any time. All the manufacturers both within and outside of China are buying their HRE from Chinese miners. HRE do only exist within China whilst LRE can also be found in rest of the world. According to one of the European recycling company China holds 60% of the RE mine, 80% of LRE separation and 100% of the HRE separation and 94% of the PM production. Additionally, to meet the demand China imports 40% of the raw material from foreign mining companies. The Canadian magnet manufacturer states that sustainability is high on the agenda for the industry. Therefore, the customers are asking where the source of the raw material is located and if there are alternatives outside of China. However, the manufacturer highlights that it is not possible for them to source completely from other countries, in fact 95% of rare material are coming from China. More precisely, their factory in Europe is running almost completely on raw material sourced from China.

The Chinese and Japanese magnet manufacturer have developed recycling techniques to re-use the HRE and minimize their dependency on Chinese miners, however, the biggest portion is still supplied through China. Even if LRE is available outside of China, they are sent to China for the mid-stream process due to their technology know-how of separation. By using GBD or recycling processes the dependency on China can be lowered. There is only one Chinese manufacturer that reached an agreement with one of the governmental owned miners in China. This actor has priority when buying the raw material. A portion of their production is directly allocated to them. Furthermore, Chinese actors have an advantage of sourcing inside of China due to the tariffs. More about this in section 4.5.

Moreover, the Canadian magnet manufacturer has managed to acquire mining rights in Europe. The supplier will support in terms of technology and financially to develop this source since the amount of RE content seems to be promising for future demand. Since the placement of the mining facility is in Europe the actor follows strict regulations on chemical processes which indicates that they will not use any chemical processes. The manufacturer highlights that this will give them the opportunity to operate in Europe for the whole supply chain of permanent magnets. Moreover, the manufacturer will still supply material from other miners (MP materials and Lynas Rare Earths) and players in the market outside of China. The manufacturer is the only one having the know-how of REE separation in Europe. They are also aiming to open a sintered magnet production facility in Europe close by their separation facility since they have all the technology and capability in Estonia. They can take the material from the mines in Estonia and use it directly for their separation and magnet production.

According to a distributor almost all RE and ferrite magnets are made in China, and there will be a supply issue by 2027 due to potential sanctions or military conflict between China and the US allies. It is not a reality that US companies will manufacture magnets at a competitive price. The Chinese government does not allow investors to pull money out of the country, when you invest in a company the profits will stay there. It is very difficult for individuals or small companies to actually pull their profit out of the country. They want the companies to keep reinvesting.

4.4.3 Joint venture with China

An arrangement between one Chinese enterprise and a foreign investor for a specified goal is known as a China joint venture (JV) (Harris, 2022). The purpose could be finishing a brand-new project or entering the Chinese market. China prohibits foreign firms from operating independently in numerous industries, however, in a few of those sectors, foreign firms can only engage by establishing a JV with a Chinese enterprise. International joint ventures (IJVs), which can be formed at the request or voluntarily by the Chinese government, are one way for foreign-invested businesses (FIEs) to access the Chinese market due to the country's distinct institutional and commercial settings in the country (Yang, 2023). IJVs may succeed or fail based on factors such as the level of partnership commitment, sociocultural distance between partners, product/industry features, and foreign control, in addition to the choice of local partners.

In China, the risk of being foreign is ingrained in institutional, market, and legal uncertainty (Yang, 2023). The government in China implemented several policy initiatives to attract foreign direct investment, creating a dualist legal system where FIEs receive superior legal and regulatory status than domestic businesses. Yet, there are significant issues with local protectionism and market splintering that prohibit FIEs from expanding their sales beyond regions.

The Chinese liability of foreignness can be mitigated by both implementing JV subsidiaries and political relationships. According to Yang (2023), isomorphic pressures ingrained in the political climate of the host country have a significant impact on the optimal form of entry. Sharing ownership with local partners enables the joint company to take advantage of their expertise and social links to further business goals. IJVs are a possible foreign direct investment (FDI) channel for foreign investors, in addition to leveraging local social networks, for a variety of reasons. As indicated by Yang (2023), it is suggested that foreign investors may choose to join domestic companies because of their resource advantages, including land, factories, experienced labor force, equipment and high productivity.

The heavy governmental participation in business activities in China is one of the country's major institutional problems (Yang, 2023). Government officials are enticed and given opportunities to engage in rent-seeking activity through the authority of arbitrary intervention. Government engagement is common in corporate operations and procedures, including, but not limited to, monitoring of labor and environmental rights, tax audit, transportation and logistics, and exporting and importing.

Several interviewed magnet manufacturers outside of China states that they have manufacturing facilities with majority ownership in the form of JV in China. For instance, one European actor states that they have 70% shareholder in the Chinese subsidiary. The precondition for some suppliers was to have a JV where they have a significantly bigger share so they can lead the JV. The manufacturers highlight that there is a risk of influence from China. However, some of them had difficulties to continue their JV since China made it difficult for foreign investors to hold on to companies in China that have anything to do with foreign strategic value, for instance magnets which are classified as high technology goods.

4.4.4 Import and export rates of permanent magnets

In 2021, permanent magnets had about \$1.61B world of trade. Permanent magnet exports increased by 30.4% between 2020 and 2021, from \$1.23 billion to \$1.61 billion (OEC, 2023). All types of permanent magnets, NdFeB, ferrite and samarium-cobalt are included in the data presented in figure 4.13 and 4.14. Top exporters were China (\$781M), Germany (\$126M), South Korea (\$114M), Japan (\$93.4M), and

United States ($48.1M). The top five importers of permanent magnets and items intended to be magnets in 2021 were Germany ($179 million), the United States ($101 million), Vietnam ($93.4 million), China ($88.1 million), and Thailand ($85.6 million). Moreover, during 2021 US imported 75% of sintered NdFeB from China, 9% from Japan, 5% from Philippines and 4% from Germany. For a better overview of import and export shares see figure 4.13 and 4.14.

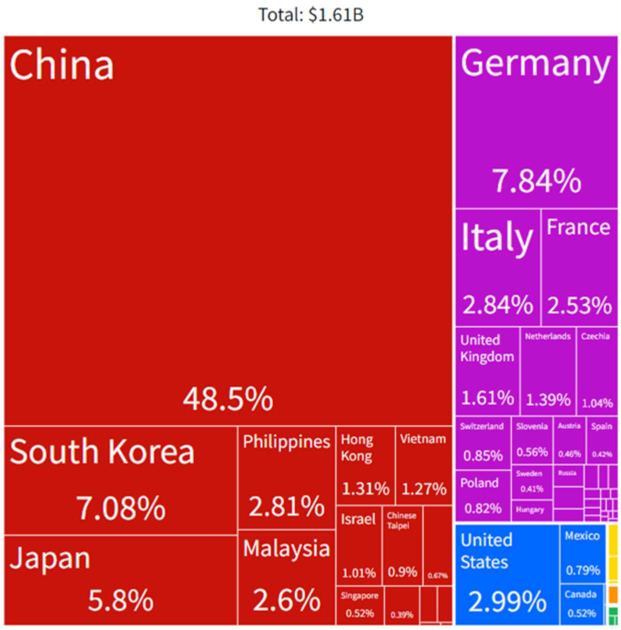

Figure 4.13: *Export share of permanent magnet during year 2021. Retrieved from OEC (2023).*

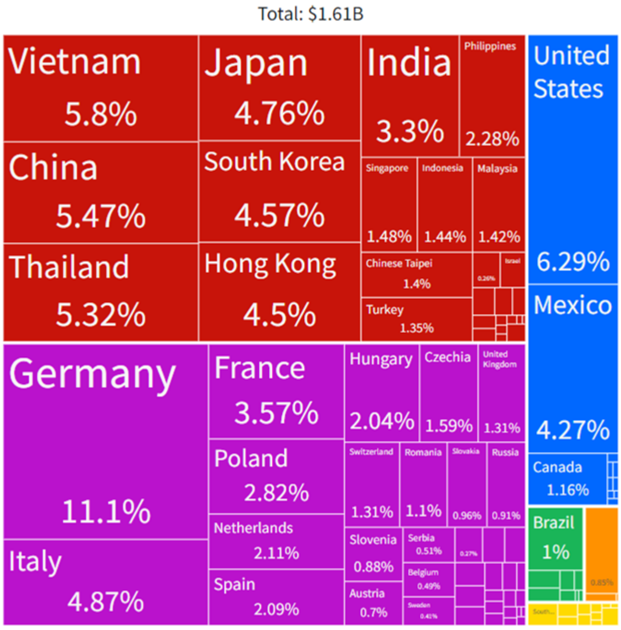

Figure 4.14: *Import share of permanent magnets during 2021 Retrieved from OEC (2023).*

A country's reliance on imports of an item to fulfill local consumption is referred to as "net import reliance" (Smith et al., 2022). Higher values suggest a greater reliance on imported items. It is evaluated by the percentage of total visible consumption that is supplied by imports. However, a large reliance on imports does not necessarily indicate a higher supply chain risk, it can be so if trading partners are also known for having high levels of geopolitical sensitivity and market concentration. See figure 4.15 for a global net trade perspective.

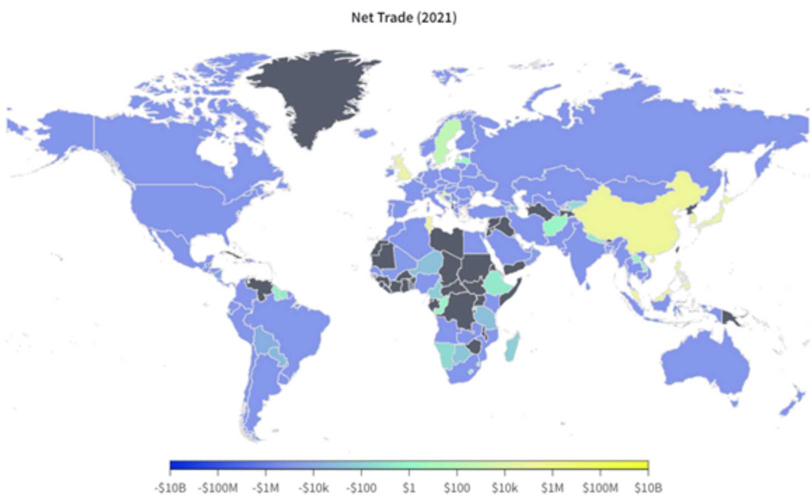

Figure 4.15: *Net trade of permanent magnet from a global perspective. Retrieved from OEC (2023).*

4.5 Price and cost drivers

This chapter will describe the price mechanism and the cost drivers of the sintered NdFeB magnet.

4.5.1 Sintered NdFeB magnet price trend

NdFeB magnets have a restricted supply and thus volatile prices (Jia et al., 2023). Although the magnet only makes up a small portion of the EM's overall weight, the considerable cost makes the entire machine substantially more expensive (Zarkov et al., 2021). Analyzing the price of the permanent magnets is necessary to guarantee fair pricing and strong competitiveness for the EM. The rising demand for REE in past years and the challenges in assuring their supply have an impact on pricing.

Figure 4.16: *Market Price of Dy. Retrieved from (Zarkov et al., 2021).*

Due to Chinese market mishandling during the recent RE crisis in 2011, RE metal prices increased dramatically, which by that time had taken over as the primary supply source (Coey, 2020). Prices for dysprosium (Dy) and neodymium (Nd) in today's dollars per kilogram each went as high as 550 to 3350 USD, respectively. The HRE metals Tb and Dy, which made up 5% (weight) of the higher-temperature grades of NdFeB used for EV at the time, were in jeopardy due to this problem. The Dy/Nd ratios were around 0.16, which is equivalent to the ratio of natural abundance, but using these metals increased the cost of raw materials by double compared to magnets without HRE elements. The conditions were not sustainable, and the quick development of HRE free magnet grades by the scientific community may have ensured the future of PM motor in EVs. Prices for Nd and Dy steadied in 2018 at 70 USD/kg and 280 USD/kg, respectively. See figure 4.16 for the developed market price of Dy. Recently during 2023 Tesla announced that their EVs are HRE free, and many experts presume that it is ferrite magnets (Lee, 2023).

The costs of raw materials for producing magnets are determined in USD/kg, these compositions determine the final cost of the various types of neodymium magnets (Zarkov et al., 2021). Figure 4.17 presents different prices depending on the raw material content for different magnet types.

Magnet type	NdFeB-SH	NdFeB-UH	NdFeB-EH	NdFeB-AH
Working temperature	***150º***	***180º***	***200º***	***230º***
Nd (%)	31	31	31	31
Fe (%)	63	61.5	60	58.5
B (%)	1	1	1	1
Co (%)	1.2	2	3	4
Dy (%)	3.8	4.5	5	5.5
Total (USD/kg)	**57.58**	**62.16**	**65.63**	**69.09**

Figure 4.17: *Different prices for magnet types. Retrieved from Zarkov et al. (2021).*

Using the data from market estimates in 2018, the average (BH)max for each kind of material, the mean price/kg, the price/volume using the material densities, and lastly a price/performance relation by dividing the mean (BH)max by the price/volume can be calculated (Ormerod, 2022). The average price for NdFeB is 70 $/kg calculated based on an average BH max 45 MGOe, density 7.5 g/cm3 and average price of 525 ($/m3 x 10$\hat{3}$) which result in a price performance ratio of 12 price/MGOs. This can be compared to ferrite magnets as shown in figure 4.18.

Material	Average (BH)max (MGOe)	Average Price ($/kg)	Density (g/cm^3)	Average price ($/m^3x10^3)	Price/Performance ($/m^3 per MGOe x 10^3
NdFeB	45	70	7.5	525	12
Ferrite	3.5	6.4	5.0	32	9

miro

Figure 4.18: *Price-performance ratio for NdFeB and Ferrite magnets. Retrieved from Ormerod (2022).*

One of the distributors shared the trend of the sintered NdFeB magnet price for the past year from Asian metal. The data illustrates how four different magnet grades differ in price in USD/kg. The price interval is shown per month, as an average of each day per period. The prices are converted from Chinese RMB to USD based on the latest currency update. Furthermore, the supplier shared the prices for Nd, Dy, Tb, Pr oxide, metal and alloy. The shared numbers can be found in appendix X.

From 2010 to 2012, the price of RE metals and oxides fluctuated greatly (Smith et al., 2022). For example, NdPr oxide prices surged to levels greater than 11 times those of January 2010 and Dy-oxide prices grew to levels greater than 18 times than those of January 2010 before falling sharply. Prices for NdPr oxide have increased by 243% since the start of 2020, whereas Dy oxide costs have increased by 88%. During this time prices remained very constant, with little month-to-month price fluctuations. Based on prices taken from Argus Metal Pages by Smith et al. (2022), figure 4.19 displays price volatility metrics for Nd, Pr, Dy, and Tb oxides. Price volatility is computed as the standard deviation of fluctuations in the monthly averaged prices from January 2010 to June 2020. Smith et al. (2022) found that month-to-month volatility was lower than the average compared to 30 other minerals. However, RE metals still have the potential to experience significant price changes.

Indicator	Neodymium oxide	Praseodymium oxide	Dysprosium oxide	Terbium oxide
Price volatility	0.10	0.09	0.13	0.14

Figure 4.19: *Price volatility measures for oxides. Retrieved from Smith et al. (2022)*

The low use of Dy is important since HREs, for instance Dy, are the most vital and expensive raw materials that are needed to produce NdFeB (Prosperi et al., 2018). There is a global effort to discover ways to decrease the reliance on HREs, and m2m® has already demonstrated significant cost savings. The inclusion of dysprosium is of particular significance for motor applications since NdFeB typically operates at high temperatures. By minimizing the amount of Dy content, the overall cost of the motor can be substantially reduced, as the cost of magnets can account for up to approximately 70% of the total motor cost. Another factor affecting the price is the production costs (Cheng, 2022). The underlying factors include the required equipment, technology used in the processes, material properties, process quantity, product shape, precision and size.

Raw material availability is influenced by a variety of factors, and a rapid rate of growth is not always indicative of a future supply bottleneck (Bobba et al., 2020). This is dependent on the broader supply-demand balance. Demand-driven price increases may make exploration, mining, and refining, as well as substitute and recycling projects, more appealing and financially viable. On the other hand, given that these investments require a substantial capital expenditure over a lengthy period, the current low prices for commodities might make the investment in future production capacity less alluring. A factor in mining operations is the regulatory environment as well as the technical potential for scaling up extraction and refining capacity. Future supply 'flexibility' is determined by all of the factors considered together.

4.5.2 NdFeB prices steered by China

Chinese RE magnet prices are controlled by the government and are driven by a long-term, cross-value chain strategy that aims to establish China as a leader in significant downstream industrial sectors (Gauß et al., 2021). The RE value chain is viewed as a highly strategic asset in China in order to maintain an expanding market share in important downstream industrial ecosystems. The biggest, RE mining and processing firms are state-owned and supported by numerous indirect and direct state subsidies. The most prominent of these is a system of import fees and VAT refunds that is WTO compliant but ultimately make trading in RE anywhere else in the world nearly impossible. RE ores can be brought into China duty-free, but processed RE materials, such as magnets, must pay additional taxes. China wants to shield higher value creation processes from competition.

More significantly, while RE magnets are eligible for a VAT refund when exported, processed RE ores, which include RE alloys, oxides and metals are not (Gauß et al., 2021). As a result, while non-Chinese magnet manufacturers must pay VAT on REE materials to end customers, Chinese magnet manufacturers are exempt from doing so (only the end customer is responsible for paying VAT). This results in a cost disadvantage of 13% on the full price for non-Chinese manufacturers. This poses a serious competitive disadvantage because raw material prices account for up to 90% of the price of the magnet strip casting alloy and 40% to 45% of the cost of the finished sintered magnet. Other significant market-distorting factors include lower social and environmental sustainability standards, as well as access to affordable finance, land, electricity, manufacturing equipment, and a growing academic talent and research community. Except for supplying raw materials to China, non-Chinese businesses along the whole RE value chain have trouble entering the market. Beyond the Chinese market, magnetic materials are primarily supplied for niche market usage.

According to several magnet manufacturers and distributors the Chinese government affects the magnet prices. The government owns the mining companies and therefore the Chinese manufacturers buys the biggest share of the metal from them and that is the reason the Chinese government can have a big impact on the market price of the magnet. The way these prices are developed is through mining companies that mine the ores. The mining companies either sell the material to separation companies that in turn sell the oxides or metals to magnet producers, or in other cases the mining company distribute the material to fully integrated producers of magnets, laser processors, water treatment equipment etc. There exist 200 companies in China working with NdFeB magnets but there are only 20 actors that produce them from the raw material.

One distributor states that the mining companies work with either Argus or Asian metals to develop the prices of the metals and oxides. Asian Metal and Argus are two agencies that reports the market price index for the metal and the oxides. If these mining companies were trying to get a price that is too high, they would get no takers, and so Argus and Asian metals say we have no takers, so they got to lower the price. A price-taker is an entity, either a person or a business, that is obligated to adhere to the prevailing market prices as they do not have enough market influence to impact the market price on their own. All individuals or organizations operating in a market are regarded as price-takers. The stock market price data for oxide, metals and magnets is a result of the number of takers and used to calculate the index price for the current day, which means that the index created by Asian metals is based on the prior day of the Asian trading day. Asian metal prices are determined by taking the volume-weighted average price of transactions conducted during a specific time span.

One Chinese magnet manufacturer mentions that it is more beneficial to buy the metals rather than the oxides. If they buy the oxide, they will need to do the separation step which is an additional cost. The manufacturer is buying the metal from the state-owned actor in China. Moreover, the actor highlights that the oxide and metal market price is the same. The price can fluctuate due to the power of Chinese government. The government can decide to stop magnet production and the export of magnets instantly. Additionally, both Japanese and European magnet manufacturer highlights that recently the Chinese government have lowered the price to make the initiatives outside of China less profitable to secure the Chinese market dominance.

Several magnet manufacturers highlight that the location of the production is correlated with the cost. The government has established a TAX to be paid if you produce outside of China. These TAX regulations enable Chinese manufacturers to have lower magnet prices. If they produce magnets outside of China, the price will be 20-30% higher or even up to 100% more expensive inside of Europe. The most attractive location outside of China according to several manufacturers are Vietnam because of labor cost and local separation companies. According to a European magnet manufacturer the electricity and labor costs are higher in Europe resulting in a price premium for the magnets. The price for a magnet outside of China is therefore higher and is dependent on the volume, the magnet grade, electricity and labor costs. A strategy is driven by the price and the geo-political risks can be mitigated by paying a higher price. A Canadian magnet manufacturer mentions that the VAT is a disadvantage for European magnet producers since a Chinese magnet producer get 13% VAT discount during the export. A European actor is buying material based on VAT conditions whilst Chinese manufacturers are getting the VAT refunded.

According to magnet manufacturers and recycling companies another factor affecting the price is the HRE content. The raw material is driving the price therefore the technologies such as GBD used to minimize the HRE content are important for the price volatility. Moreover, manufacturers mention that recycling is another factor affecting the price. The recycling steps enable the re-usage of the HRE content.

Furthermore, magnet manufacturers mention that they are following the market prices while setting the prices for the customers. They cope with this every quarter by following every three months' price update based on the average price for each element for the last three months by Asian metal. There can also be adjustments for one month. Afterwards the manufacturer and the customer follow an agreed contract with a base price according to these indexes. Another factor affecting the magnet price is the exchange rate. According to one distributor the prices of the raw material (LRE, powder, oxides) in other markets is sometimes the same as the ones in China due to the currency. For instance, today the Japanese magnet price are almost the same as Chinese magnet price. By converting the currency, the supplier receives more accurate prices.

The manufacturing expenses must be considered as a complement to the costs of the materials (Schönfeldt, 2023). This may be demonstrated by looking at the rising costs of energy. In Europe, the cost of energy increased from 7.7 cents per kWh in 2017 to 8.6 cents per kWh in 2022 (for non-household users without taxes) and from 20.9 cents per kWh to 22,0 cents per kWh (for home consumers with taxes and levies). As a result, the use of waste magnet material presents a chance to reduce the manufacturing costs of RE PMs due to cheaper material costs and lower energy consumption from avoiding melting procedures through "hydrogen-based powder metallurgical recycling".

4.6 Sustainability

This section will include the important parts of the environmental, social and corporate governance of the sintered NdFeB magnet value chain.

4.6.1 Sustainability trend

With a goal of keeping global temperature far below 2°C and continuing efforts to keep it below 1.5°C, the Paris Agreement lays out a worldwide framework for preventing severe climate change (European Commission 2023). Additionally, it seeks to assist and improve national efforts to mitigate the effects of climate change. A product or material's sustainability is now considered to be as significant as its chemical and physical qualities (Schönfeldt, 2023). As a result, the circular economy can significantly increase sustainability by reducing the energy and CO2 intensive mining of primary components. Environmental, social, and economic concerns should always be taken into consideration while evaluating sustainability, following the three-pillar theory. Analysis of the sustainability of recycled REPMs has been undertaken in recent years. There are significant environmental challenges associated with the current primary production of REPMs, such as high energy, water and chemical consumption, toxic organic chemicals, inorganic salts and heavy metals, or concentrations of the radioactive materials ThO2 (thorium) and U3O8 (triuranium octoxide), which can be found during the mining, beneficiation, and refining stages of the manufacture of REE. A Chinese magnet manufacturer state that there are strict regulations while working with mining, refining and separation due to the exposure of radioactive materials (ThO2). Radioactive materials are hazardous for the employees working within the production as well as for the environment. Some actors had their licenses for separation withdrawn in Malaysia due to this.

Sustainable growth and a vibrant market economy are among the EU's objectives (Gauß et al., 2021). For European producers of REEs to compete on a worldwide scale, it is necessary to establish a level playing field. Consequently, the fundamental inquiry should not be whether EU producers can rival Chinese producers in terms of a RE product's spot market pricing. In fact, depending on the application, the cost of a magnet made in Europe is currently roughly 20–30% higher than the cost of a comparable magnet made in China. The essential question is simply what it would cost to have accessibility to a sustainable manufactured magnet in terms of economic, environmental, society, and supply risks, as well as the prospective cost of shortages of these materials in the future.

4.6.2 Recycling

Jin et al. (2018) has demonstrated that hydrogen-based magnet-to-magnet recycling can reduce the environmental effect of REPMs by 64–96% as a result of a 99.9% reduction in RE addition compared to initial production. Furthermore, according to Sprecher et al. (2014) research, energy consumption can be decreased by 58-88% and the human toxicity indicator by 81-98% dependent on the recycling procedure. In addition to the environmental responsibilities, the social dimensions of governance, community, infrastructure, health and safety, labor rights, and decent work must be considered (Schönfeldt, 2023). The mining and manufacturing stands for significant impact on the social imprint of REE. The third and most crucial factor from the perspective of the overall industry for the widespread market launch of recycled REPMs is their economics. Production of magnets will be more profitable as the percentage of recycled materials rises. Factors include energy savings since initial mining, refining, and melting operations are not required in a circular economy, which accounts for about 45% of magnet price in raw material savings through recycling.

There has been a price increase during 2017, going between 77 to 159 USD/kg for Nd. The cost of all other REE has previously increased (Schönfeldt, 2023). As a result, the cost of raw materials for a standard sintered NdFeB magnet with one composition (Dy1Nd30(FeB)67Co2, wt.%) grew from 31.6 USD/kg by 2017 to 71.4 USD/kg in 2022, representing a growth rate of 125%. Since there is not a controlled market, it is challenging to calculate the costs for scrap magnets. NdFeB magnet costs, as previously noted, are made up of 45% material expenses and 55% marketing and production costs. In the simplest scenario, the price of scrap magnets is linearly related to the market price of REEs. Given that the price of REE increased by 125% and the scrap magnet price in 2017 was 4 USD/kg, it is reasonable to conclude that the realistic scrap magnet price is 9 USD/kg.

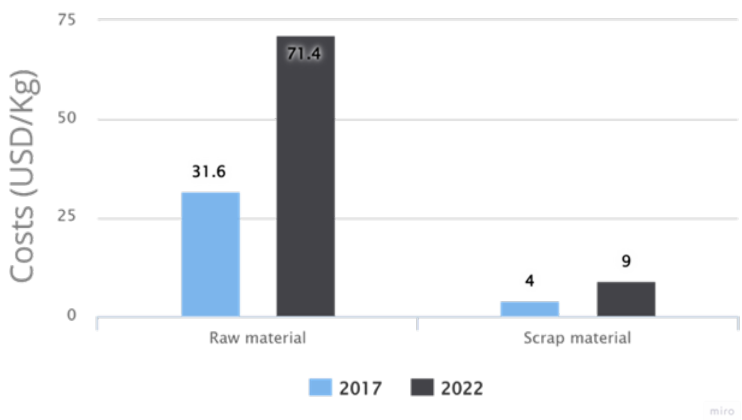

Figure 4.20: *Development of raw material and REE prices in contrast to scrap magnet prices. Retrieved from Schönfeldt (2023).*

Moreover, Shen et al. (2020) emphasizes that we do not currently have adequate information regarding recent trends in the consolidation of domestic REE firms into multiple sizable groups or the sizeable Chinese investments in REEs made abroad. Furthermore, as of the past, China may establish new areas of focus, such as recovering REE from recycled materials found in items that have reached the end of their useful lives and/or retaining some of this material within China due to increased demand (Leal Filho et al., 2023). From the 2000s, China has focused more on addressing issues related to the environmental effects of REE mining, processing, and manufacturing as well as on initiatives to bring more industrial manufacturing into the recognized and regulated domain.

All magnet manufacturers interviewed highlight that they already work with recycling magnets either by having a JV with a company that has the know-how of recycling or by having built their own recycling process within their production plant. Some Chinese magnet manufacturers also acquires recycling companies as a third option. One Chinese magnet manufacturer has signed an agreement with a recycling company to receive their materials from their recycling stream. They are receiving approximately 5000 tons of oxides and that is helping them to produce magnets with exclusively recycled material. According to the magnet manufacturers recycling can reduce the dependency on China by providing HRE from another source. Due to recycling, some suppliers use 30% recycled material for their magnets. Normally the dependency on China is 99% when it comes to HRE content but with recycling it lowers down to 70%. The magnet manufacturers have different strategies and know-how for recycling magnets. Several magnet manufacturers highlighted that they have recently started initiatives for recycling projects whilst other magnet manufacturers have been working with recycling for a while. One Chinese magnet manufacturer states that they have their own recycling process within their plants. They want to have recycling integrated in the factory for two reasons, one to capture the value of waste material with rare earth content and secondly to help customers to recycle their end-of-life products. This is important for them since China has banned the option to import scrap material for recycling, with a new manufacturing location outside of China they can offer that possibility for customers circularity initiatives.

Several magnet manufacturers and recycling companies mention that recycling is also beneficial to lower CO2 emission. The technologies being used to produce the magnets are important to both reduce the CO2 but also to make the magnet as green as possible. One recycling company mentions that when comparing the CO2 emission between recycled RE and a mined RE magnet there is a distinct difference from 6kg CO2 compared to 68kg CO2. The waste generated from the production of magnets is difficult to recycle.

A European recycling company aims to create value by manufacturing magnets from recycled end-of use magnets in Europe close to the customers. They have moved from traditional manufacturing to advanced technology recycling. This recycling technology is also protected by the company through a patent. The company states that their core business reduce the risk of global shortage and dependency on China. As stated during the interview, one important factor is that their customers need to ensure the supply of NdFeB magnets for the long-term. A shortage of permanent magnets for tier 1 will lead to disruptions in the recycling companies' processes which is not desirable if they want to be competitive against China. A Chinese magnet manufacturer do also highlight that OEMs should design for recycling. If the design includes for instance a lot of coating and glue in the rotor, then it is not economical for disassembling and recycling the magnets. From an internal meeting at the case company Alpha, it was seen that the recycling perspective is not yet considered in the design phase.

This type of recycling technology contributes to lower material cost since ores are expensive to extract compared to the usage of scrap material. Furthermore, on the process level it is competitive due to the less processing steps compared to the traditional mining extraction steps. The know-how in RE metallurgy and casting allows them to guarantee high performance and customization. The recycling company highlights that their strategy in securing volumes will be through different sources such as wind turbine manufacturers and OEMs. This will be in three levels, locally with recycling companies, at national level large recycling groups and unions and lastly on an international level with Germany, Belgium and Poland. The recycling company presented two options when it comes to the type of exchange with the OEMs, either they give the recycling company the end-of-life products or scarp material and get back pure RE magnets with an added value for the work, or they just give the oxides or metals to a decided magnet producer. The biggest constraint here is that these companies are not open to collaborate with Chinese magnet manufacturers since that would be against their stakeholder's interest, for instance the governmental initiative to build a supply chain outside of China.

Another recycling company in Europe is developing the know-how of LRE and HRE separation. They state that some actors outside of China have the know-how of mining extraction, but few have the knowledge of separation. Another advantage that the company foresees with recycling is the reduced radioactivity due to less mining activity. Furthermore, they state that recycling is already in place in China, however what is needed is an outstanding technology reducing energy, chemical and water consumption. In other words, Chinese magnets are lower in price but comes with a higher environmental impact. It is up to the OEMs if sustainability is more important than the price increase. The recycling company mentions that they want to hinder mining companies from sending the HRE to China.

4.6.3 Environmental aspects of sintered NdFeB magnet

One Japanese magnet manufacturer mentioned that the energy being used in production is dependent on the country structure. For instance, in Japan the actors need to rely on and use the nuclear energy. The Japanese magnet manufacturer would like to have more green analysis and water analysis. The government in Japan has initiated to give a grant for suppliers who manage to reduce their CO2 emissions.

A European magnet manufacturer highlights that producing magnet is not an environmentally friendly process since the electricity, water, and chemical usage is high. Moreover, according to the Canadian magnet manufacturer dealing with partners outside of China provides more visibility on the market and on the complete supply chain. If you procure material from China, the visibility of the CO2 footprint from the mining process is restricted and this can differ if you look outside of China. The Canadian magnet manufacturer has therefore started to complete a LCA starting from the mining up to the final magnet to create a clear picture of the environmental impact on the value chain. It is of importance to be transparent regarding sustainability goals outside of China. For the Canadian and the European actors, it is important to work with projects, so-called environmentally friendly mining, to use renewable energy. This initiative requires investment and that is the biggest challenge for a magnet manufacturer. This is also hard to convince since there is a lack of visibility regarding the sustainability work in China. There is a challenge to show how better you are working in terms of sustainability if the benchmark is vague.

The rare earth industry expert mentions that the environmental impact is created from the mining, metal and alloy production process and the energy mix being used. For instance, in China, it is common to use coal as energy source and that has a distinct environmental impact compared to the usage of renewable energy. In the value chain the most energy intensity is when producing metals rather than mining. The production of metals and alloys requires hazardous chemicals such as electrolysis. The Japanese magnet manufacturer moved the metal production to Vietnam and Philippines. In Japan there are high standards for producing these metals. In contrary, the environmental impact of mining can be standardized, and everyone can improve it.

According to the rare earth industry expert and several magnet manufacturers the climate challenge is a global issue. The impact of having production or environmental impact in a single place has to be replaced by having multiple places resulting in standards being followed globally. This diversification mean that there will be a big difference in the environmental impact between a Chinese producer and a non-Chinese producer. A higher environmental standard on a global level is required. OEMs can force this transformation by investing in companies both in China and in the rest of the world.

4.6.4 Sustainability regulations

Several magnet manufacturers are working with different certifications and ISO standards to follow some environmental regulations. The most common ISO standards mentioned were ISO14001 and ISO9001. One Chinese magnet manufacturer mentioned that they aim for fully neutral CO2 production by working with a specific green certificate and ESG certification. According to the manufacturer they aim to drive a green revolution since they believe that in general the magnet industry is extremely harmful and “dirty”. The manufacturer works towards this by using their own solar energy for all their factories and having a JV with a wind turbine actor. The JV has created the possibility to have wind farms close to their production factories. Other magnet manufacturers interviewed were not open to sustainability discussions due to lack of knowledge.

Moreover, the rare earth industry expert mentions EU environmental regulations that apply to import goods. When producing in China and exporting it to Europe the companies need to show the environmental impact such as the level of CO2 emission. The companies cannot have the same emission as in China. Further on, the commitment parties need to consider circular economy so that certain portions of their product should have recycled components. This kind of regulation will be implemented in the near future. A Chinese manufacturer needs to comply with the EU regulations. Therefore, the Western companies will try to increase the environmental standards in China.

The European commission has developed a landmark tool called "The EU's Carbon Border Adjustment Mechanism" (CBAM) (European Commission, 2023b). The tool is used to allocate a fair price for the carbon released during the manufacturing of items entering the EU that are carbon intensive. The purpose is to promote cleaner industrial output in non-EU nations. The CBAM's progressive implementation during the interval of 2026-2034 aligns with the elimination of the European Emissions Trading System's (ETS) free allowance allocation to help in the decarbonization of industries in the EU.

Businesses within and outside of the EU, as well as public entities, will be able to make a deliberate, predictable, and appropriate transition thanks to the progressive ramping of CBAM (European Commission, 2023b). During this time, importers of goods covered by the new regulations are only required to report the direct and indirect greenhouse gas emissions (GHG) that are a part of their imports; no other payments or adjustments are required. The scope will after the period of transition cover indirect emissions for some electricity industry sectors, the methodology will be constructed along this transitional phase. The permanent system starting from the first of Jan 2026 will be constructed based on this previous transitional phase. Importers are obligated to report each year how many items were brought into the EU the previous year, together with the inherent GHG. The scope of the product will be revised to determine if other downstream products are covered by the European ETS within the scope of CBAM mechanism. European EV manufacturers are highly important for the competitiveness of EU in order to reduce CO2 with minimal impact on GHG (ACEA, 2021). The purpose of CBAM is to avoid third party country retaliation.

5

Analysis of the sintered NdFeB magnet value chain

This chapter aims to assess the network perspective of sintered NdFeB magnets supported by the collected data. The sub sections will include analysis of sustainability, geo-political, technological, intellectual property and price factors. As a result of the analysis a Kraljic matrix will be constructed.

5.1 Overview of the sintered NdFeB magnet value chain

Due to the different process steps, actors and countries, to get an overview of the empirical data it was necessary to get a full picture of the value chain. This will open up and ease the discussion about geopolitical constraints in further sections. In figure 5.1 it is obvious that the main share in the value creation of the permanent magnet processes is dominated by China and a smaller activity going on in the rest of the world (ROW). As was mentioned before China is now also targeting the final application part of the supply chain to dominate the EV production both when it comes to technology advancement and volumes. The outcome will in our opinion escalate the permanent magnet shortage even more due to the higher domestic demand and lower share of exports to foreign countries.

The main purpose of this report was the downstream actors such as the magnet producers. However, it was determined in the early stages that a holistic view on the network was necessary to understand the complete value chain. As of today, the network is evolving due to the new actors and the changing behaviors of the existing ones. For instance, OEMs are targeting higher purchasing volumes, OEMs such as Alpha are working to develop new relationships with recycling companies to close the loop of end-of-life magnets (midstream). Moreover, magnet manufacturers are reaching out to closer collaborations with mining companies (upstream) to get access to the raw material and to work on the sustainability aspects. All these relations, collaborations and strategies taking place will be affected by the political aspects such as the China versus US, the activities on building supply chain outside of China and the EUs incentives for the sustainability targets. All these aspects will be broken down and analyzed in the sections that are visualized in the framework in figure 5.1.

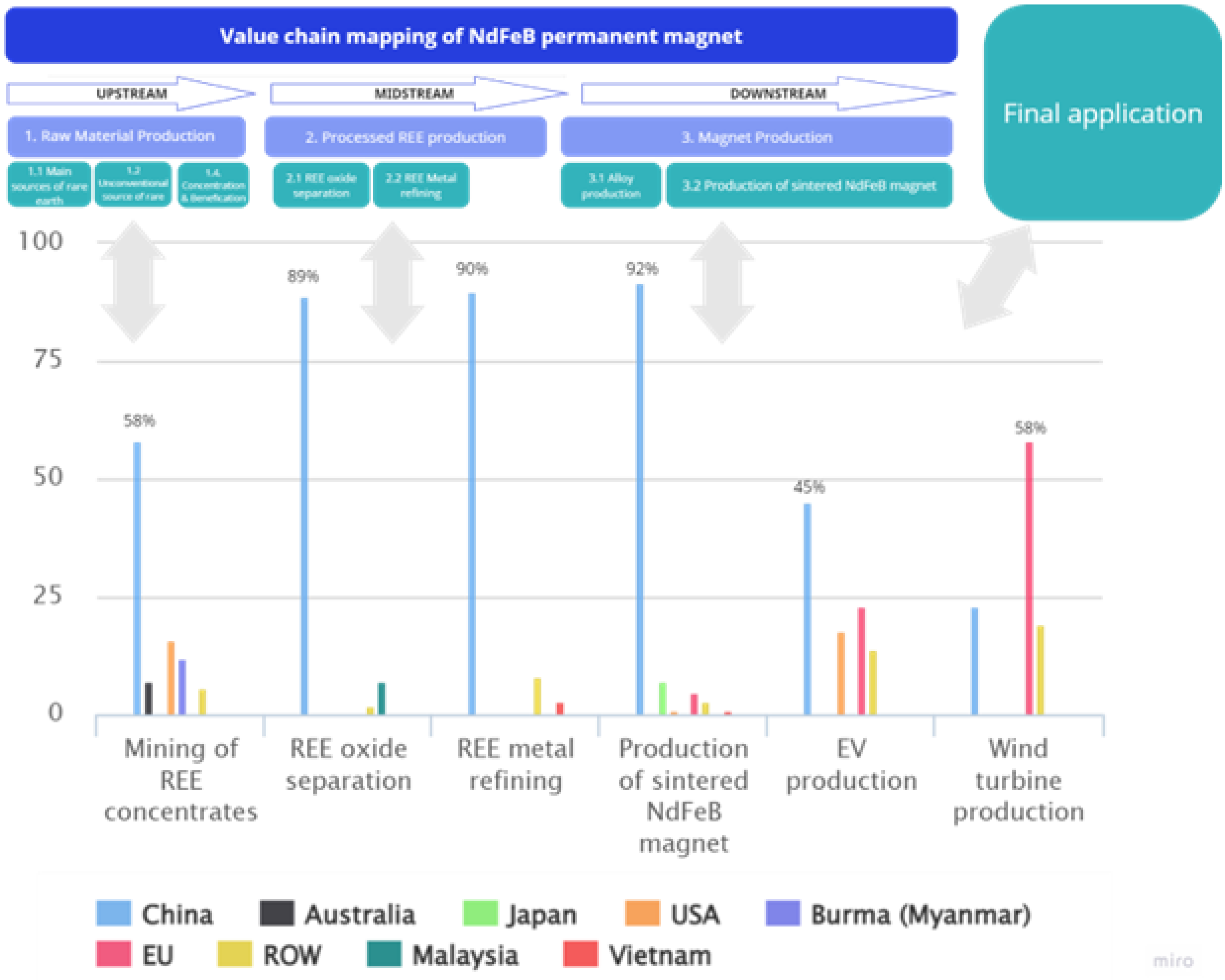

Figure 5.1: *An overview of the value chain, the country's market share and final applications. Data retrieved from Smith et al. (2022).*

5.1.1 The extended permanent magnet framework

The framework in figure 5.2 has been constructed by conducting an analysis on the value chain of permanent magnets. The main areas are divided between processes and actors, followed by a network overview and lastly the externalities. All these areas have been divided into sub- areas as shown in figure 5.2. The different topics have also been complemented with the levels of the network (Micro, Meso, Macro). The sub-areas have been selected based on the main topics identified in the data findings. Moreover, the areas have been selected based on the relevance from an OEMs perspective within the value chain of permanent magnet. From the findings it was evident that the network was highly intertwined and related to several actors between we three network levels.

The first main area "processes and actors" was sub divided into description of the value chain including production processes, magnet characteristics and main actors that were described in the first section in the empirical data. In the second area named as “network overview” includes data about relationships and market trends where demand of the permanent magnet and volumes is an important factor. Finally, external factors such as geopolitical, sustainability and pricing factors were presented.

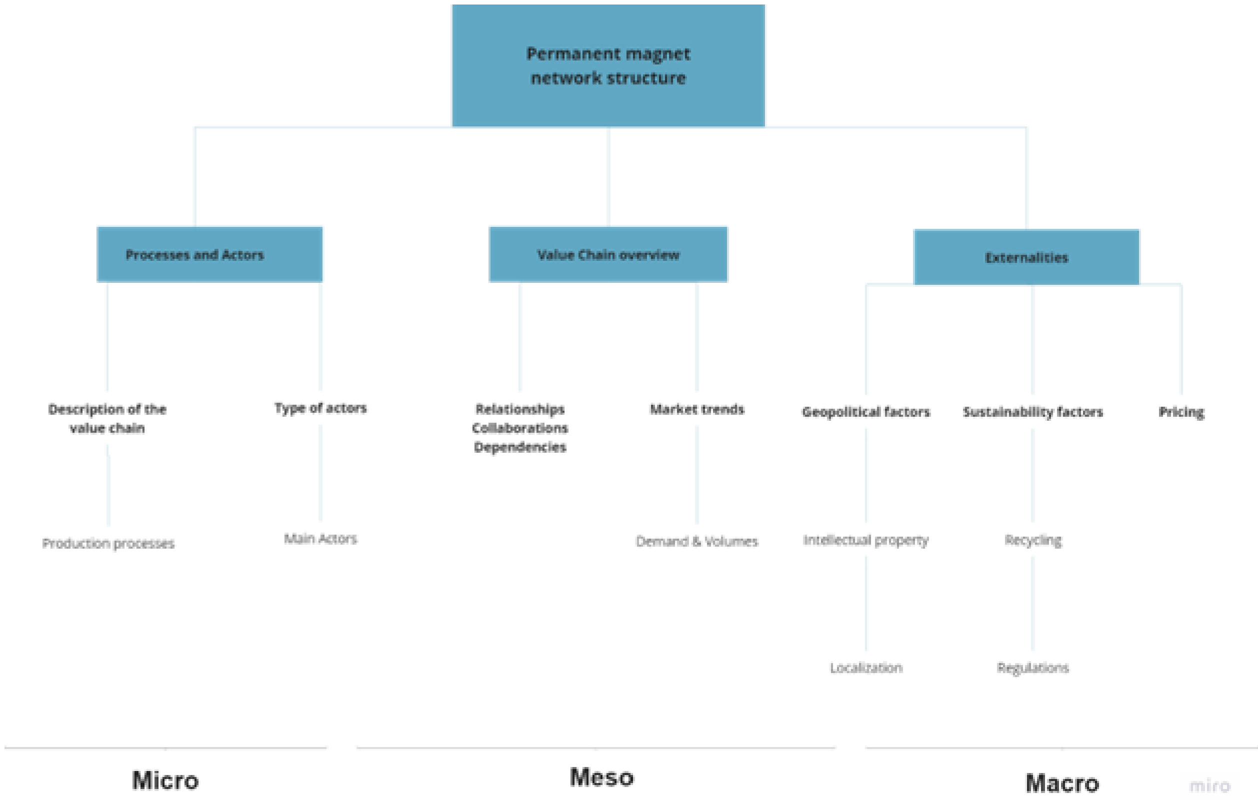

Figure 5.2: *Permanent magnet value chain framework*

5.1.2 The permanent magnet network levels

Individual businesses and organizations make up the micro level (Melander and Lind, 2022). The data collected has shown that firms in the production process of NdFeB are at the micro level. The actors in the different parts of the value chain of NdFeB are individual firms. These are firms such as magnet manufacturers, industry organizations, mining companies, metal refiners and recycling companies. From a micro level perspective, understanding user dynamics throughout the innovation process requires an in-depth understanding of potential future customers (Melander and Lind, 2022). At the micro level, resources owned by these firms are essential for their value creation. Individual firms in the downstream value chain are driven by the demand from different end-user application markets. There are several markets that require permanent magnets and the rapidly growing demand during the last years is driven by the automotive sector such as Alpha. Further, OEMs want less HRE content in their magnets and higher sustainability priorities. Downstream actors such as magnet manufacturers are working with developing specific process techniques to lower the HRE content. Individual companies such as the buyers and suppliers in the micro level need to understand the common requirements to co-develop the market for permanent magnet.

The meso level are networks and business relationships and inter-organizational interactions (Melander and Lind, 2022). Business networks are described by the links between buyer-supplier relationships, and how actions in one relationship affect other ties in the network. Based on the data collection, the companies active in the value chain have several different links to each other. These companies co-operate with each other depending on their position in the value chain. Upstream actors collaborate with mid-stream actors who then collaborate with downstream actors. Subsequently, downstream actors are then the first contact for the majority of end customers (for instance Alpha). Some magnet manufacturers (downstream actors) also have direct contact with upstream actors, in this case mining companies. Interaction can be initiated by a variety of factors, such as problem-solving, adaptability, discussion, or preparation for upcoming market demands (Melander and Lind, 2022). The resources that can be obtained through business connections serve as a crucial foundation for business growth. This is to facilitate their collaboration and influence each other to work and follow the same regulations, trends and developments for the expected demand growth coming up within the value chain of permanent magnets. According to several manufacturers, these collaborations give rise to working towards long-term goals such as a supply chain outside of China.

As Melander and Lind (2022) mention, by participating in a network the businesses can share and integrate knowledge. By participating in a network, businesses can define standards for their industry, conduct pilot projects, and commercialize products in addition to sharing and integrating knowledge. Both Japanese, Chinese and European manufacturer highlighted the importance of knowledge sharing within the value chain stream. For the manufacturer it is of importance to have good relationships in the form of long-term collaboration with the mining companies to ensure accessibility to raw material. This is the reason behind one Chinese magnet manufacturer have signed an agreement with one governmental owned miner in China. Two Chinese magnet manufacturer as a JV with recycling companies. One of the manufacturers has acquired a recycling company so they can manage in-house recycling within their plant. The advantage of this collaboration is to gain know-how of recycling processes and early design adaptation for recycling.

According to Melander and Lind (2022) businesses are being pressured to invest in innovative sustainable solutions by government regulations and public awareness of the environment among consumers and public actors. EU has announced environmental regulations that will be applied to imported goods. When producing in China and exporting to Europe companies needs to show their environmental impact such as CO2 emission. Moreover, they need to consider circular economy so that certain portions of their product should have recycled components. In addition to this the European commission has developed a landmark tool called "The EU's Carbon Border Adjustment Mechanism" (CBAM) (European Commission, 2023b). At the macro level businesses must navigate societal shifts in customer demand and behavior as well as governmental actions and decisions (Melander and Lind, 2022). One Chinese magnet manufacturer has taken governmental actions by developing their sustainability work. The manufacturer has a specific green certificate and ESG certification. The manufacturer works towards this by a JV with a wind turbine actor. The JV has created the possibility to have wind farms close to their production factories to use renewable energy. Figure 5.3 gives an illustration of the network levels in the permanent magnet value chain as a result of different actors, initiatives and relationships.

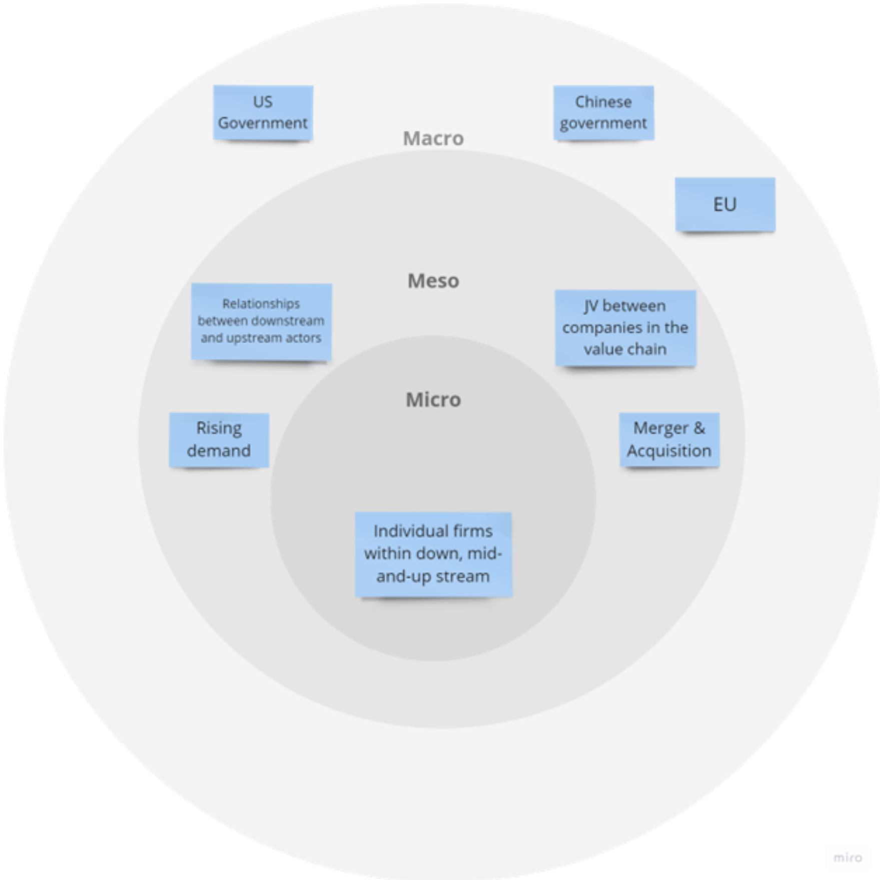

Figure 5.3: *Micro, meso and macro level of the permanent magnet value chain.*

5.1.3 Interdependencies in the network

The network model by Dubois et al. (2004) has been used to better visualize the dependencies between firms in the network. These include all market members such as manufacturers (Firm A1, A2, A3), mining-and refining companies (Firm F1,F2, F3, F4), recycling companies (Firm B), government and industry associations (Firm C, D, H) and OEMs (Firm E). As was discussed previously all these actors are interdependent through links in the form of relationships, activities and resources. The network is thus complex and includes many influencing factors that an OEM needs to be conscience about. In accordance with Ford et al. (2003), it is recommended to concentrate on supply network management rather than attempting to control them. It is therefore important for an OEM (Firm E) to understand and manage the supply side according to the current and future knowledge about the permanent magnet network.

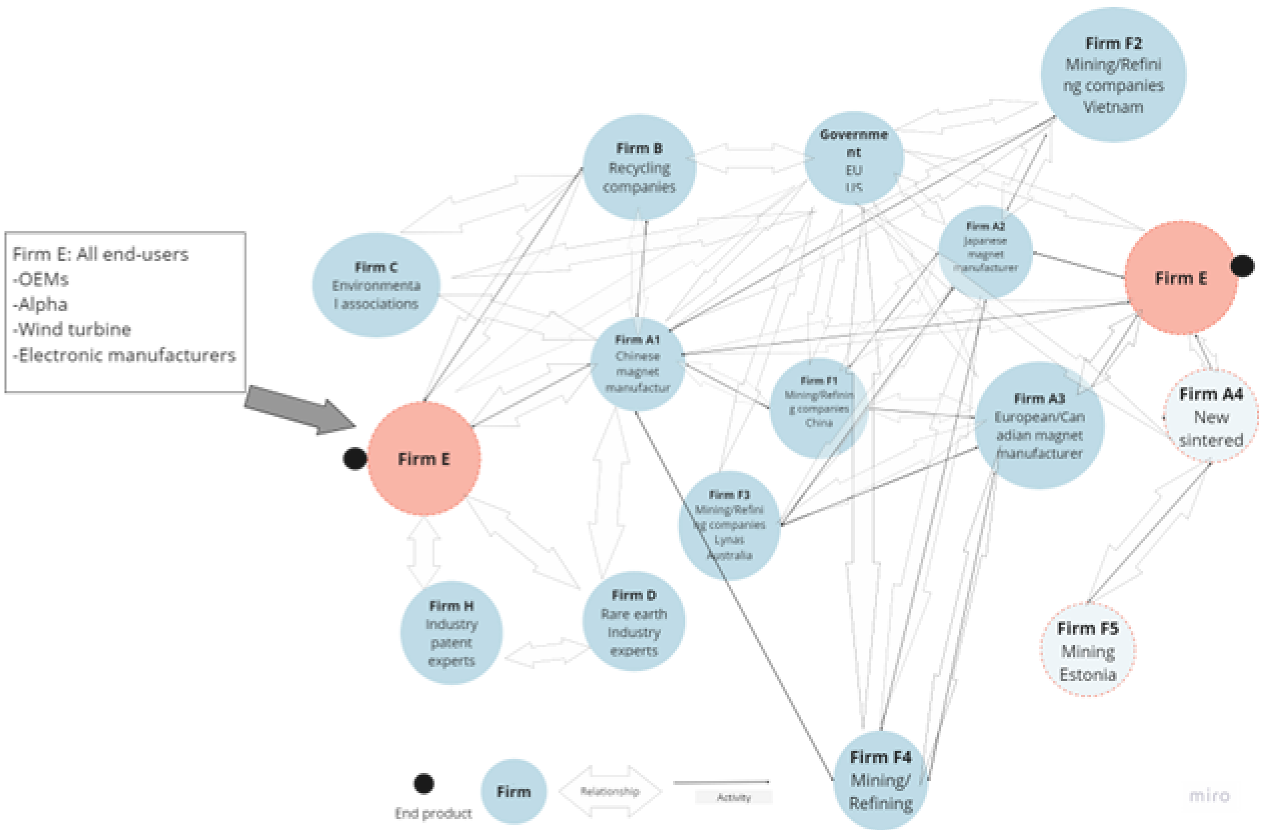

Figure 5.4: *Relationship, Activity and Resource analysis of the permanent magnet network.*

Due to the interdependence, each modification may have an influence on another part of the supply chain, and therefore on another actor (Dubois et al., 2004). As mentioned by two magnet manufacturers, they have the liquidity to invest in more resilient supply chain outside of China but then they will need commitment from the customers side and that is not happening today. OEMs are afraid of committing to this kind of new investment in Europe. US companies on the other side has been very straight forward and determined that they are willing to do what it takes for the supply options outside of China. As a result, a Chinese manufacturer invested in a new production location in Mexico. The reason was to fulfil the localization requirements from the US customers. This relationship creates a new activity between the firms resulting in a common resource. From a broader network perspective, it is required to have a two-sided commitment for the relationship between OEMs and magnet manufacturers to work together. This initiative also results in new activities between the manufacturers and the customers (Firm E) to source the magnets from a new location. The upcoming sintered NdFeB magnet production plants in Europe create the same kind of new activities. The Canadian magnet manufacturer (Firm A4) initiative for a new production plant in Estonia enables new relationships to be created with buying firms (Firm E) that are aiming for local-to-local relationship. This interdependence creates an emerging firm in the network (Firm F5).

When some of the activities incorporated in the supply chain share the same resources it can result in changes that have an effect on the following end products (Dubois et al., 2004). Although organizations may change counterparts and do so occasionally, the important questions tend to center on how integration best can work with current counterparts (Wynstra, 1998). Initiatives coming from the government (macro) control the development of green energy and sustainable solutions. The laws and regulations from the higher level of the network (macro) result in a changed dynamic in the network, thus affecting the relationships further down in the meso and micro level. Chinese magnet manufacturer expresses that this has given rise to initiatives to contact recycling companies, moreover, to start collaborating with wind turbine company to create green energy for their production factories. One of the Chinese magnet manufacturers stated that they will offer 100% recycled magnet for some customers, and they are looking at alternatives to make this a standard and official on a global scale. Another magnet manufacturer states that their competitors are focusing more on sustainability, and they can see that the trend is shifting. The big magnet players become a benchmark for other magnet producers to follow thus creating a new dynamic in the network.

Dubois et al. (2004) highlight that with relationships, they can also communicate with clients and suppliers to make changes that might enhance some aspect of their performance. These improvements may lead to relationship-specific investments that link organizations together. The magnet manufacturers state that they are aware of the new customers' requirements for greener products and sustainable solutions. Moreover, A European manufacturer mentions that the automotive market has very strict and clear targets on sustainability and that they want to have a possibility to source permanent magnet local-to-local. To follow the responsibility that the suppliers are taking new activities and relationships are created with sustainability associations that elevate the ESG standards for the industry.

Melander and Lind (2022) mention that companies may lack the resources or knowledge necessary to create and implement innovative sustainable solutions. Regulations may therefore encourage businesses to seek out in networks to interact with other actors. Furthermore, new relationships are created with industry experts within the permanent magnet market to understand how the market is evolving and what the competitors of the magnet manufacturers are active in. Several magnet manufacturers highlight that they are aware of the growing market for permanent magnets and the rising requests from the OEMs. The creation of rapidly higher demand for permanent magnets on macro level will consequently affect the micro and meso level to a certain extent. The whole network will then be in a new phase where all relationships, resources and activities evolve. Several magnet manufacturers mention the importance of global relationship between different organizations in the mid-and up-stream value chain. For instance, as mentioned by the recycling companies' governmental initiatives from the EU have helped them to grow. There is global pressure from macro level to have a diversified supply chain. Therefore, firms in the up-stream value chain such as MP materials are investing in moving up the value chain to reach processes in mid-and downstream.

As Dubois et al. (2004) states, the way a firm behaves with respect to their counterparts will likely depend on how the business views the products that come from its similar activities. Due to the way the activities are organized, all the supply chains that lead to its final products make use of resources that are also active in other chains. MP Materials announced plans to build a magnet manufacturing plant in Texas, to provide General Motors (GM) with NdFeB magnets for their automobiles (Smith et al., 2022). Vacuumschmelze has also revealed its plans to manufacture magnets for GM in the US. As new projects are developed outside of China the relationships will change focus, China will not be the only dominating player. Therefore, OEMs and other customers will create new relationships with these new developing mining companies that will be able to offer separation and metal refining. The Chinese government is aware of this and is therefore striving to make the businesses outside of China less profitable.

The relationship between magnet manufacturer and mining companies and recycling companies is to develop new sources and solutions for the end-users of the sintered NdFeB magnets. Several magnet manufacturers mentions that they have started to build up relationships with mining actors outside of China to lower their dependency on Chinese supply. Some of these mining companies are open for a JV to be able to invest in new technologies to develop techniques of how to handle HRE content to be able to build a supply chain outside of China. Moreover, two Chinese and one Japanese magnet manufacturer highlight that they already work with recycling magnets either by having a JV with a company that has the know-how of recycling or by having built their own recycling process within their production plant.

5.2 Technological know-how and collaboration

The design and the properties of the sintered NdFeB magnet are highly important for the performance of the EM. According to Taherdoost and Brard (2019) the criteria technical or technology is useful when a company needs capable technological support from their suppliers in order to consistently deliver high-quality goods or services, support productive research and development projects, and guarantee future advancements. For a sintered NdFeB magnet manufacturers are using different process steps to achieve high performance NdFeB. There exists different technological know-how within the downstream processes that differ manufacturers and distinguish them from a technological perspective. Some of the manufacturers have the know-how of the whole production process needed for a complete sintered NdFeB whilst others have limited knowledge. For several manufacturers NdFeB is classified as a strategic product while for others it is a standard commodity product. This indicates the different viewpoints on the importance of technological advancement for magnetic properties.

Better manufacturing techniques including grain boundary diffusion (GBD) and dual alloy method, which mixes ferro-dysprosium (DyFe) and NdPr metal, have been widely used by manufacturers to reduce the amount of heavy rare earths (HRE) in NdFeB (Smith et al., 2022). According to the Rare earth industry expert, if you want to be successful in the traction motor business you have to use GBD for your magnets. However, the magnet technology is not only limited to the magnet itself but also the optimization together with the electric machine application. The shift that can be seen right now is the influence of China's initiative to reach high level of the magnet value chain such as the end application innovation where permanent magnet is a key part of. During the interviews with Chinese, Japanese and European magnet manufacturers, it was seen that this type of governmental initiative is reflecting the new targets for magnet manufacturers to also start doing some assembly and design of products for the customers and leaving the sole magnet sell and buy transaction. Several manufacturers were very knowledgeable in the motor design area and not limited to magnetic properties. The importance of the permanent magnet is thus influencing how the material is being advanced to reach higher value applications. Magnet manufacturers and customers such as OEMs are driving this technological evolution in this electrification journey ongoing mostly in Europe and US. At the same time the need for RE metals may decline as technology develops because companies may find substitutes for REEs in materials or technologies. The cost of RE metals could drop as a result of this.

According to Van Weele (2018) there are different advantages of early supplier involvement. Short-term benefits include improved quality, less product costs, quicker development times, and lower development costs. These advantages can be attained by utilizing specialized goods and technological know-how supplied by the supplier. During the interview it was noticed that the magnet manufacturers develop their own know-how in order to use the HRE only where it is needed for the magnet coercivity. The development of HRE free magnet or less HRE content sintered NdFeB magnets can be achieved by utilizing the supplier's technological know-how of advanced technology. One Chinese magnet manufacturer mentioned that they are developing their current GBD process to improve and evolve the magnet properties. Moreover, the Canadian magnet manufacturer states that they manufacture magnets with similar magnetic characteristics as sintered NdFeB magnets. According to the actor, these magnets will be high performance magnets with reduced amount of HRE content and be lower in cost throughout the value chain.

In many industries, suppliers contribute more to innovations than manufacturers themself (Van Weele, 2018). For large manufacturers, the question of how to unleash the innovative ability of suppliers is of utmost significance. According to a Chinese magnet manufacturing direct relationship with producers is getting more common than having a distributor. The reason is the co-development for the future electrification and the rising demand of permanent magnets to develop the magnets for the end-application. All the interviewed distributors purchase directly from magnet manufacturers located in China and Japan and whilst some purchase it from Germany. The R&D potential required to support the customer's new product development activities may be underappreciated by the supplier's side (Van Weele, 2018). An effective producer is not usually a skilled product developer, and vice versa. The transfer of knowledge and experience between the customer and the supplier necessitates a significant investment in time and energy. Two distributors mention that they have direct contact with manufacturers and end-users of magnetic products. Furthermore, they mention that they provide engineering support and a vertically integrated production facility for complex and critical magnetic assemblies and custom electrical machines. For instance, a distributor highlights that in order to have a new customer they demand a collaborative relationship where they invest in the technology together. The distributors highlights that it is difficult for a manufacturer in China or Japan to co-develop with a customer that is not "close". However, another distributor highlights the impact of former relationship with a Chinese manufacturing supplier.

Earlier supplier engagement in product development led to shorter development lead times, improved product quality, quicker time to market but it can also increase development costs, product costs, and intellectual property issues (Van Weele, 2018). Magnet manufacturer can provide technological support by having a direct relationship with the buying firm (end-customer). The manufacturer can give prototype of the magnets for an electrical machine so that the end-customers can develop accordingly. Moreover, a direct relationship is important to follow the development in the market and make sure that the supply and demand is in balance. The availability of raw materials is important to meet the expected demand, which can be achieved by having a close relationship to ensure that the buying firm will be supplied. This is of great importance due to the expected supply shortage in the coming year. A magnet supplier relationship with the ability to co-develop to optimize the magnetic power and at the same time secure supply of raw material is significant for an OEM. A magnet manufacturer can also by their know-how help to redesign sintered NdFeB magnets where Nd is replaced as the European Commission has suggested as an alternative activity (European Commission, 2022). In contrast, some magnet manufacturers see permanent magnets as a product where transactional relationship is used. It can then be less beneficial to have this kind of manufacturer as the relationship is not viewed as valuable. However, the degree of collaboration willingness is also influenced by the volume bought by the buying firm and the customer base that the supplier has.

ISO standards include a wide range of tasks, including producing products, managing processes, delivering services or materials (ISO, 2023). During the interviews it was stated that several magnet manufacturers are following ISO standards. Standards are the condensed knowledge of those with subject-matter expertise and a familiarity with the requirements of the businesses they represent, including manufacturers, vendors, purchasers, customers, trade groups, users, and regulators (ISO, 2023). ISO 14001 and ISO 9001 are the most commonly used standards. These quality management standards can be used to increase productivity and decrease product failures. Environmental management standards can be used to support waste reduction, environmental impact reduction, and sustainability (ISO, 2023). ISO 14001 is one of these standards that mandates that a business considers all environmental issues pertinent to its operations, including waste management, resource use, air pollution, sewage and water problems, soil contamination, and climate adaptation and mitigation. ISO 14040:2006 is a standard related to LCA, which means that the execution of LCA should be ISO compliant (ISO, 2023). A European magnet manufacturer mentioned that they have started to complete a LCA starting from the mining up to the final magnet to create a clear picture. The usage of LCA should be a common practice in the permanent magnet value chain.

5.3 Sustainability requirements

From the empirical data it was evident that producing magnets is not an environmentally friendly process. Partners outside of China provides more visibility on the market and on the complete supply chain. It is important for an OEM to make sure that the magnet manufacturing companies have performed complete LCA, that they are using raw material from environmentally friendly mining companies and lastly that they are using renewable energy. The purpose of such requirements is to lower the risk of unsustainable usage of electricity, water and hazardous chemicals. As Van Weele (2018) highlights there is a need of CSR to ensure that companies supply chains work in accordance with established standards and norms for human rights, as well as regional labor and environmental regulations. A Chinese magnet manufacturer state that there are strict regulations while working with mining, refining and separation due to the radioactive materials such as ThO2 (thorium). The radioactive materials are hazardous for the employees working within the production as well as for the environment. It is required to have management paradigm transformation and higher awareness of professional training emphasizing ESG through the value of rigorous, globally recognized professional certifications (IASE, 2023).

The goal within CSR is to create business solutions that meet the needs of the current global population without compromising the needs of the next generation (Van Weele, 2018). Companies can demonstrate their expertise in environmental sustainability with a certificate in ESG (IASE,2023). Another sustainability related certificate is so called green certificate. This green certificate is official proof that a company has generated a level of green electricity (European Environment Agency, 2023). One Chinese magnet manufacturer mentioned that they aim for fully neutral CO2 production by working with a specific green certificate and ESG certification. The manufacturer is among the first to reach carbon neutrality through declaration certificate. In contrast, other magnet manufacturers interviewed were not open to sustainability discussions due to lack of knowledge.

The "profit" part in CSR provides recommendations for a company's long-term, sustainable financial growth. The idea behind increasing profitability is that the business also pays attention to relevant key stakeholders including customers, suppliers and shareholders. In the permanent magnet market, most countries have negative result of their net trade value, as it is today the profit part of this industry is not sustainable and many countries are being dependent on very few exporters mostly China. This is also one of the root causes for the expected global shortage before 2030. Since the raw material spike the manufacturers are aiming to find new ways to re-use and gain back the material at the end-of-life products. This will imply better profitability and lower environmental impact. The Chinese magnet manufacturer states that they have recycling integrated for their Mexico factory. This is important for them since China has banned the option to import scrap material for recycling, with a new manufacturing location outside of China they can offer that possibility for customers circularity initiatives.

Sustainable growth and a vibrant market economy are among the EU's objectives (Gauß et al., 2021). Moreover, the rare earth industry expert mentions EU environmental regulations that apply to import goods. When producing in China and exporting it to Europe the companies need to show the environmental impact such as the level of CO2 emission. Any initiatives aimed at maximizing the use of raw materials, energy, and other natural assets are included in the CSR "planet" component. The "planet" aspect includes waste disposal, recycling of scrap, reverse logistics and surplus materials. Additionally, it involves reducing carbon emissions. Several magnet manufacturers and recycling companies mention that recycling is also beneficial to lower CO2 emission. They have therefore developed recycling technologies in order to reduce the CO2 impact. Furthermore, the landmark tool CBAM by European commission has an aim to promote cleaner industrial output (European Commission, 2023b). However, the sustainability aspect regarding magnets is not only important from a CSR and ESG perspective but also to fulfill upcoming legal requirements from the government such as the CBAM where OEMs like Alpha will be obligated to report their GHG emission. Therefore, the sourcing of permanent magnets will be highly sensitive from a sustainability perspective due to the high CO2 emissions contribution from the magnet processes. If the government sets higher standards for sustainability, magnet manufacturers might face greater costs.

A European magnet producer highlights that it is difficult to trace the environmental impact in the mid-and-up stream value chain of permanent magnets. It is therefore difficult to benchmark with a non-chinese actor since the traceability is not there. There are initiatives on developing a standard for traceability. ISO/AWI 17887 is one of the standards under development which is devoted to the permanent magnet field (ISO, 2023). This standard will represent the ability for a company to trace RE throughout the supply chain, from REE to finished permanent magnets. Furthermore, to improve the quality of life for people living in mining areas another ISO standard will be developed.

5.4 Geo-political factors in the permanent magnet value chain

This section includes analysis of localization, intellectual property, resiliency and transilience in the permanent magnet network.

5.4.1 Localization

The idea of risks associated with disruption of the supply chain has changed from focusing solely on demand-side risks to now considering supply-side and control risks, as well as ever-increasing risks brought on by the globalization of supply chain and the greater emphasis on single sourcing (Gatenholm and Halldórsson, 2022). There are governmental initiatives to lower the dependency on China and build a supply chain with limited or no dependency on the Chinese government. The main initiatives are coming from EU and US but other countries are also seeing the dependency and want to act against it. The researchers Mancheri et al. (2019) believe that China's domestic policies dominate the market for REEs internationally and further believe that global standards, China imports of REEs, worldwide stockpiling by nations, and their environmental requirements have a negative impact on the resiliency of the REE supply.

The requirement from the customer side is becoming more obvious for the supply market, and manufacturers are therefore placing production in other locations to meet the demand from the US and European Union. Designing supply chains to be adaptable and able to respond to changes in demand is a usual response to these disruptions (Gatenholm and Halldórsson, 2022). This can be done by introducing new items, altering volume, controlling transactions in manufacturing and delivery, or customizing product and service characteristics to fit the needs of customers. Both Chinese, Japanese European and Canadian manufacturer highlighted their strategies for different production locations outside of China such as Vietnam. The question is not whether or not to replace China since the EU demand is far over the supply, even if the suppliers can produce permanent magnet with a higher price, it will only cover a part of the demand. An additional type of resilience introduced by Azadegan and Dooley (2021) called macro-level resilience is when businesses, including rivals, work with organizations like the government or industry associations to handle or control a longer-term supply risk. A Canadian magnet manufacturer has managed to acquire mining rights in Europe (Estonia). The magnet manufacturer highlights that this will give them the opportunity to operate in Europe for the whole value chain of permanent magnets.

One recycling company highlights that their strategy in securing volumes will be through different sources such as wine turbine manufacturers and OEMs. This will be in three levels, locally with recycling companies, at national level large recycling groups and unions and lastly on an international level with Germany, Belgium and Poland. The biggest constraint here is that these companies are not allowed to collaborate with Chinese magnet manufacturers since that would be against the governmental initiative to build a supply chain outside of China. This is an example of meso-level resilience initiative taking place in the permanent magnet market. This kind of initiative is a way to prevent the long-term supply risk and control over the RE material. Another type of resilience introduced by Azadegan and Dooley (2021) is micro-level resilience which emerges when suppliers and buyers work together directly to prevent and recover from supply risk. This level of resilience can be exemplified with the collaboration between MP mining company and GM to build a sintered NDFeB manufacturing plant. Moreover, VAC is also planning to produce permanent magnets for GM in US.

Information-sharing and leveraging between actors are two other well-established approaches for supply chain resilience (Gatenholm and Halldórsson, 2022). Several interviewed magnet manufacturers outside of China states that they have manufacturing facilities with majority ownership in the form of JV in China (Yang, 2023). For instance, one European manufacturer states that they have 70% shareholder in the Chinese subsidiary. The Chinese liability of foreignness is mitigated by both implementing JV subsidiaries and political relationships (Yang, 2023). Sharing ownership with local partners enables the joint company to take advantage of their expertise and social links to further business goals. Contrary, a distributor had difficulties to continue their JV since China made it difficult for foreign investors to hold on to companies in China that have anything to do with foreign strategic value, for instance magnets which are classified as high technology goods. Information sharing and transparency is therefore more difficult due to the geopolitical differences in different countries. The US and China political war inhibits the development of resilient magnet supply chain. Consequently, most projects aiming to build supply chain outside of China is outperformed by lowering the price as an initiative from the Chinese government.

5.4.2 Intellectual property in the permanent magnet network

External factors, which include variables such as legislation, are often beyond the supplier's scope of influence that may have an impact on a product's availability both now and in the future in a particular market (Van Weele, 2018). The permanent magnet patent related topics are one of the external factors that have an effect on the network. It needs to be considered in order to identify the availability of the different types of sintered NdFeB magnets and the possible risks for the final application customers. The demand for global intellectual property protection increased as the market value increased from 2 billion USD in 2000 to 20 billion USD in 2021 (MagPatCo, 2023).

Network dynamics creates a particularly challenging strategic field (Menell, 2019). Although the innovation related patents have expired there is a list of active process related patents until 2039 that need to be considered due to the impact on the permanent magnet network dynamics. These patents include processes for HRE-free, GBD, alloy preparation and recycling. The interviewed Chinese, Japanese and European manufacturers highlighted that they have their own process patents for their production processes.

The researchers show how patents affect global trade, foreign direct investment, licensing, and eventually growth (Maskus, 2002). There are motives to be concerned about firms with greater intellectual property protection exercising market power. The evidence highly indicates that intellectual property rights imply a crucial foundation to promote local innovation, technology transfer, and the growth of the economy in the long term. The degree and the duration of the impact is uncertain but the current state with for instance GBD process shows that the same scenario can be repeated if one actor in the network will establish a new more effective process for the sintered NdFeB magnet process technology. The risk is correlated to different magnet technological requirements due to cost pressures and sustainability, for instance to use GBD to lower the cost and the HRE content. New benchmark technologies will push other actors in the market to follow in order to be competitive. Low knowledge in the patent area and the technical factors represents a risk for the magnet buyers. If the buyer has a supplier with a license agreement it is important for them to have an alternative source if there are any patent infringement cases. It is essential for the suppliers to give full liability in terms of products with no or limited risk.

Actors can often pick different strategies when they compete in the network (Menell, 2019); first to gain control over an entirely new proprietary standard to get a market domination; secondly to adopt a current standard through license or imitation. Lastly to collaborate with other businesses in the sector to create an open or practically open standard, whether contractually, through formal associations of businesses, governmental standardization authorities or informally. The Proterial Ltd license is one way for the Japanese to spread the GBD process as a market standard to be used for every manufacturer. This has also a positive effect for Japanese manufacturers since they can disclose in the license that magnets cannot be sold in the Japanese market and in that protect their market. They can also outsource part of their magnet processes to China with a more profitable price compared to the labor cost. These license agreements are also exposed to a high level of risk as several Chinese manufacturers of NdFeB magnet inside China do not always comply with the intellectual property rights (IPRs).

It is more beneficial to think of IPRs as rules governing the conditions of dynamic and static competition rather than ways for establishing legal monopolies (Maskus, 2002). The emerging recycling companies in Europe with their patented solutions for reuse of sintered NdFeB will play an important role in the future of the sintered NdFeB magnet market. Right now, China is prohibiting import of scarp materials however this dynamic can change whilst the recycling operations will develop in Europe. One possible outcome could be that China will notice the drawback of losing control over the material that is sold to domestic markets such as Europe and US. At the same time, customers are taking initiatives to build a closed loop for their products containing magnets. Recycling technology and know-how is evolving in Europe and therefore the dynamics of competition and strategy to get hold of the raw material will change over time.

While IPRs do result in market power, the effects on competition differ significantly depending on the countries, products, and technologies (Maskus, 2002). The industry patent expert mentions that after a thorough analysis it turned out that the Chinese manufacturer with patents do not manufacture the magnet as disclosed.

This entails a major risk when you buy magnets from China. What would be the liabilities of these Chinese companies from this perspective is to indemnify their customers. Subsequently according to the patent expert when you are communicating with Chinese magnet manufacturers, they can present a certain patent analysis or certain noninfringement opinion, however they do not check the relevant worldwide patents. These licensed companies approach their customers as being able to manufacture grain boundary diffused magnets or other types of magnets. However, they are basically not able to sell those magnets on their licensed coverage to all markets. In terms of these high-end magnets like GBD magnets these companies which are licensed by Proterial or any other non-licensed magnet manufacturers are in the same category since they present a certain risk. The magnet buyer really has to understand what is being bought. The level of protection varies depending on the scope of the granted rights, the competitor's ability to develop non-infringing technologies and products and the availability of supply source substitutes (Maskus, 2002). The buyer needs to do a certain analysis and ask the manufacturer to perform pattern analysis and to provide evidence that they are not infringing any patents. This analysis can also be done through a third-party audit. Manufacturers must run responsible and open communication with the customers, since they are usually misleading different opening addresses like the limitations of the Proterial Ltd and Shin-Etsu license. This market dynamic also affects the distributors, they need to ensure the intellectual property aspects of their tier one suppliers in order to give full liability to European and US customers.

If the OEMs have a supplier with patent infringement it will eventually be harmful for the markets where the end-product is sold. There is a risk for huge lawsuits on the magnet suppliers when the magnet is bought out of China and eventually it will lead to a supply risk for the OEMs especially if it is from a single source with no diversification. For a successful and sustainable buyer-supplier relationship, it can therefore be beneficial to perform a patent analysis with technical parameters included.

5.4.3 Permanent magnet network transilience

It has been observed that discontinuities can either be controlled consciously, whether forced or voluntary or left unmanaged by external factors (Gatenholm and Halldórsson, 2022). For a transilience permanent magnet value chain, it is of importance to identify the un-managed discontinuities within the chain, as visualized on the left side of fig X. China dominates the market by having know-how in separation processes which affects their control over the HRE prices and the proportion of magnets that is supplied outside of China. The domestic market is prioritized. Another case is the effort from the Chinese supply market to move in the value chain to also dominate in the electric motor production. One possible outcome of this political game can result in higher domestic demand of permanent magnets and decreased portion of export to international customers. This can then result in shortages of supply to foreign countries while the demand is spiking. As a European magnet manufacturer states the supply side will be an issue with the higher demands coming from customers. The manufacturer highlights that to supply all the requests coming in they would need long-term contracts with investments since they will not be able to meet the capacity targets.

Furthermore, discontinuities are considered to be external in nature, meaning that the point of the disruptive event introduces an unmanageable interval (Gatenholm and Halldórsson, 2022). The electrification targets are increasing due to the Paris agreement and therefore the rising demand from the OEMs. The demand side is not aligned with the supply market capabilities, both when it comes to capacity and the local-to-local, even though there are initiatives ongoing there is more work that needs to be done in order to build a resilient supply chain and also align the permanent magnet supply chain with the electrification transformation until 2030 and onwards. The Chinese government makes it difficult for international investors to enter the Chinese permanent magnet market thus customers cannot invest in business with suppliers. This is due to the fact that permanent magnets are classified as strategic. This factor is an additional demand side unmanaged discontinuity.

Moreover, for OEMs that have not been in the EV sector for a long time, there is a greater need for technical support in the design phase to determine the grade of magnet and also to implement recycling into the early stages of the EM design. The OEMs will require more time and effort from their supplier compared to other sectors such as electronics and wind turbine customers that have been in the market for a long time and have reached a higher maturity level.

Gatenholm and Halldórsson (2022) introduced the phase of manageability which is actions implemented during the crisis to minimize the unmanaged interval. They are subdivided between deliberated voluntary or forced managed organizational discontinuity. The deliberate forced factor amongst the magnet actors is the decreased interaction with agents and distributors. Due to the high environmental pressure from governments some mining companies are forced to shut down the mining activities such as what happened in Malaysia. Pressures from government and customers have also led to deliberate voluntary with a supply chain outside of China. Chinese, Japanese and European manufacturers have started to take initiatives to build a diversified supply chain by building new production facilities in other locations such as Vietnam, US and Mexico. Another deliberate voluntary is that a Chinese manufacturer have started to prioritize markets and customers where they are committed to capacity. Manufacturers take this initiative to mitigate future disruptions, to make sure that their customers are willing to cooperate.

The release phase starts when the present supply network can no longer meet the evolving demands (Gatenholm and Halldórsson, 2022). Mode 1 refers to reestablishing and focusing on existing supply chain structure, which does not need a significant rearrangement and can instead quickly change to conservation and exploitation. To meet the upcoming disruptions the first step as mentioned by several magnet manufacturers is to focus on the current supply chain by increasing the existing capacity to meet the future permanent magnet market demand. Product-based service may be generally referred to as offerings that are delivered throughout the product's lifetime, such as repair, maintenance, and refurbishing. Gatenholm and Halldórsson (2022) argue that the degree of severity of discontinuities noticed by product-based-service (PBS) supply chain organizations necessitates transilience rather than just resilience. Some processes require fast restoring while others also require simultaneous radical changes. As of today, it is visible in the permanent magnet value chain, that it is in need of both resiliency in the form of alternative sourcing locations and higher capacity to meet the demands. While a greater degree of radical change is also needed in the form of new technological solutions to replace the expensive raw materials or completely revolutionary magnets with similar properties that can be an alternative to NdFeB. Although we can see some examples of ongoing initiatives that are not yet fully launched, the market is behind the expected demand from managed and unmanaged discontinuity.

The transformative aspect of resilience is divided into two other modes: extending the normal by improving or adding the product-based service offering (mode 2) or embracing a new normal state by drastically modifying the PBS offering (mode 3) (Gatenholm and Halldórsson, 2022). The organization exploits new consumer behavior and/or the changing business landscape to liberate resources and reorganize. In the permanent magnet market, the "normal" can be extended by improving or adding the know-how of separation as it is happening for MP in the US and a Canadian manufacturer planning to produce sintered NdFeB in Europe. This results in a reorganization of the network where the existing mining companies move up in the value chain. Moreover, adding recycling processes in the existing value chain as some Chinese manufacturer already have done is also changing the network structure. In mode 3, a more radical change such as the introduction of the new magnet variant with tetrataenite or MQ3 is offering a replacement to the current NdFeB. The production of these will not require the usual standard process and thus give rise to a change in the entire network. These changes will give a complete reorganization of the permanent magnet network in a radical way for magnet manufacturers, customers (OEMs), distributors, miners and refiners. As a result, a transilient supply chain of permanent magnet with lower dependency on China for customers such as Alpha.

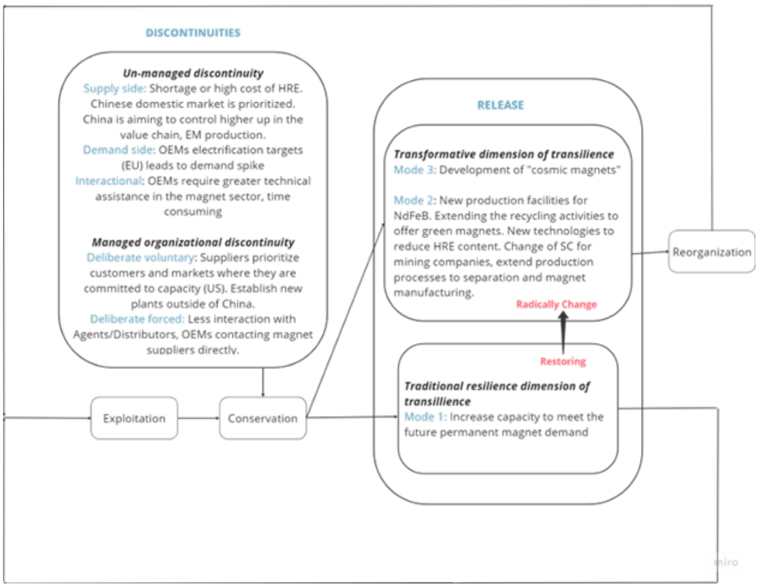

Figure 5.5: *The permanent magnet network interpreted with the transilience framework.*

Manufacturing SC resilience strategies mostly focus on the product and material flow, using flexible suppliers and information sharing between actors, prepare backup sources and inventory buffers, finally to share the risks with other actors and having multiple sources (Gatenholm and Halldórsson, 2022). The rivalry between OEMs is high due to the strategic level of electrification and the importance of gaining market share. The actors such as OEMs and permanent magnet manufacturers mainly in China have therefore not established transparent information sharing. Time to market for the OEMs is very important at the same time that the EM market together with permanent magnet is a rather new area for OEMs. Since the OEMs are not the biggest customers for the magnet suppliers the option of having multiple sources is not preferable from a volume perspective since that would make the buyer power an even lower share. Furthermore, from a technical perspective the standardization level cannot remain the same for all EM if magnets are sourced from different suppliers due to the differing cutting and magnetization processes. However, from a resiliency and price perspective the most desirable sourcing strategy would be to have for instance 20% from a European magnet manufacturing supplier and the 80% remaining from a Chinese supplier. In the purpose of balancing between price and risk than sourcing from a single geographical location in China. Multiple sourcing implies less reliance on net imports from one single market and less probability for a SC to be concentrated in geopolitically sensitive locations.

5.5 Capacity and volumes

Ho et al. (2018) illustrates different criterias to think of when selecting the best optimal supplier. One of the most common is manufacturing capacity. The purpose of a successful supplier selection is to identify the ideal supplier who can offer the buyer the necessary goods at the right time, price and quantity (Taherdoost and

Brard, 2019). The demand for magnets is expected to increase. All the magnet manufacturers highlighted that they are aware of the increasing demand from the OEMs and therefore they have on-going projects to expand their magnet production capacity. Moreover, Taherdoost and Brard (2019) highlight that when producing products with the same standards and quality, it is challenging to keep the same strategy while dealing with varied financial situations and customer reputations. Both the European and Canadian magnet manufacturers with lower capacity highlighted that to supply all the request coming from the OEMs they need long term contracts with investments since they will not be able to meet the capacity targets. Moreover, the global demand for NdFeB magnets is anticipated to increase by 5.8% annually in the near future, reaching around 322,000 tons in 2032 (Arafura, 2023). It is of great importance for buyers to consider the suppliers production capacity to mitigate supply shortage of sintered NdFeB magnets. The volumes mentioned above represent the share of the total EV market, however, there will also be competition inside the same segment which means it will be even more limited capacity for each actor. Therefore, the competition is fierce, and the buying firm needs to consider that in their supplier selection strategy. At the same time, the other segments will probably also grow, and their demand will exceed the automotive industry with a big margin. The volume and capacity are highly correlated to the venerability of the firm's future demand. On the contrary side the whole volume and capacity can change if the replaced technological advancements like for instance HRE free magnets will be the most used together with more efficient processes. Furthermore, if the prices would increase globally due to geo-political activities, higher volumes would be produced outside of China to cope with the demand.

5.6 Price mechanism and correlations

Zarkov et al. (2021) and Prosperi et al. (2018) state that the sintered NdFeB magnet is a small portion of the EM's overall weight, and the cost can make up to 70% of the entire machine cost. Analyzing the price of the permanent magnets employed in the machine's construction is necessary to guarantee fair pricing and strong competitiveness.

External factors also include changed price of raw material, labor cost, product innovation or legislation (Van Weele, 2018). These factors are beyond the suppliers' influence, but they will determine the price of the produced end-product. To understand the price mechanism of NdFeB in the market it is important to analyze the historical price data and the price volatility together with the correlations between raw material and magnets. As earlier described by magnet manufacturers and distributers during the interviews these prices are closely followed by Argus metal and Asian metals index. The price of the raw material, i.e. oxide, metal and alloy, has a major impact on the final sintered NdFeB magnet. Several magnet manufacturers and the rare earth industry expert highlight that the location of the production is correlated with the cost. As the Chinese government has established a TAX system, the magnet manufacturers get 13

As known, the prices of RE oxides and metals fluctuated greatly during 2010 to 2020 which gave rise to volatility of the prices for NdPr and DyFe, which then also affected the magnet prices (Smith et al., 2022). Both distributors and Chinese, Japanese and European manufacturers confirmed this by explaining the different prices that oxide, metal and alloy have and had during the last period. Van Weele (2018) states that external factors can influence a product's price indirectly by shifts in the supply dynamics. According to several manufacturers the Chinese government owns the biggest mining companies in China with a big share to Chinese manufacturers. This provides the Chinese government to have a big impact on the market price of the magnet since they are setting the oxide and metal prices. This leads to volatile prices which then also creates a change in the supply and demand dynamic in the value chain. According to European magnet manufacturer and one distributor China can practically stop the export of magnets. It will then have an impact on the magnet price.

Van Weele (2018) also indicates that shifts in the market structure can have an indirect impact on the products' price. As mentioned by Chinese, Japanese and European manufacturers China is dominating the sintered NdFeB magnet value chain. Their power in HRE processing has an impact on the global market structure. They can determine the volume targets at any given time, and the share of export and import to international markets. Consequently, this creates shifts in the market structure depending on the Chinese governmental political targets. The most impacting factor on the final sintered NdFeB magnet price is the raw material (oxide, alloy). Moreover, a European manufacturer also indicated that the Chinese government are lowering the prices of the magnets to counteract developments in other countries that aims to produce sintered NdFeB magnets outside of China. China is aware of the international activities to lower the dependency and their strategy can shift according to the current state and the success of competitors.

Currency risks have to be addressed when purchasing from foreign suppliers (Van Weele, 2018). Another factor affecting the magnet price is therefore the exchange rate, resulting in a market structure where the raw material prices in the market is the same as the one in China. For instance, one distributor mentions that today and during the last year Japanese magnet price are almost the same as Chinese magnet price due to the currency changes. Since RE metals are traded as commodities globally, swings in exchange rates have an impact on the price. More specifically when purchasing magnets from countries with high magnet export value such as China and Japan (OEC, 2023). Domestic prices for RE metals could increase or decrease depending on the value of the local currency.

Prices for dysprosium (Dy) and neodymium (Nd) went from 550 to 3350 USD, respectively (Coey et al., 2020). The Dy/Nd ratios were around 0.16, which is equivalent to the ratio of natural abundance, but using these metals increased the cost of raw materials by double compared to magnets without HRE elements. The price development of last year for sintered NdFeB magnet (different grades), oxide and alloy has been depicted in fig x and x. It can be seen that the magnet prices are correlated with the alloy prices. During February 2022 the price for NdPr and DyFe increased and as a result the magnet prices also increased. Furthermore, between August and September 2022 the prices for magnets decreased because of the decreased NdPr price and partly the falling DyFe price. After September 2022 until today the prices have stabilized with small up and down turns following the alloy prices. As was depicted in fig 5.6 irrespective of the magnet type Nd represents the second biggest share in the magnets, about 31%. As a consequence, the correlation between magnet and NdPr alloy is stronger than DyFe. The price is less influenced since Dy stand for a smaller share (about 5%). The low use of Dy is important since HREs, for instance Dy, are the most vital and expensive raw material that are needed to produce NdFeB (Prosperi et al., 2018). However, DyFe is far more expensive, about 2-3 sometimes 4 times more expensive than NdPr. The data can be retrieved from Appendix B.

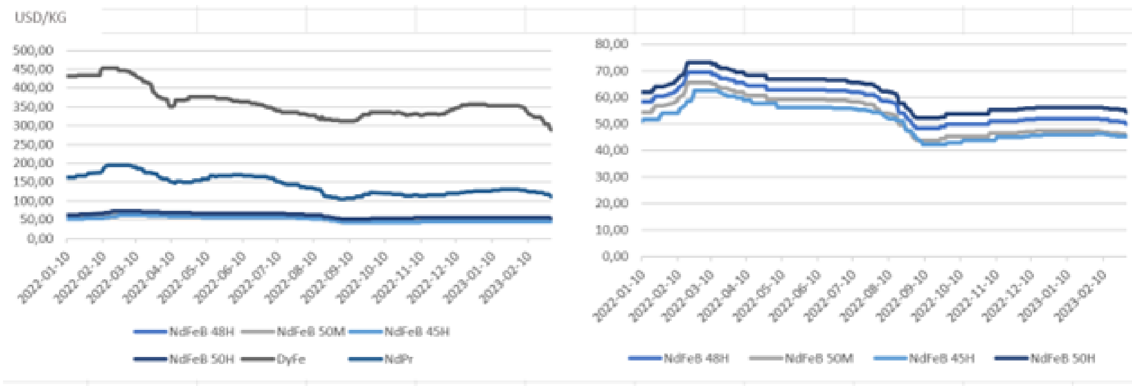

Figure 5.6: *Visualization of correlation between four magnet grades and the Alloy DyFe and NdPr.*

Tb is less important for the price fluctuation of the magnets, i.e. a lower level of correlation is seen. According to Smith et al. (2022) the most common metals used for producing magnets are NdPr, pure Nd, and ferrodysprosium (DyFe), while Tb metal being less used. This can be the reason behind why Tb has less price impact for the final magnet price.

Another layer of analysis is the oxide versus magnet correlation depicted in fig x. The correlation seems to follow the same trend as magnet versus alloy correlations in fig 5.7. This similar correlation can be due to the price differences between the oxides and alloys. For instance, Nd oxide price was 110 (March 2023) and at the same time NdPr price was also 110, these can be found in Appendix B. Dy oxide was 340 USD/kg and DyFe was about the same price during March 2023. As one Chinese manufacturing company stated, there is no motives for a manufacturer to buy the oxides and pay for an additional process step when the alloy can be purchased for the same price.

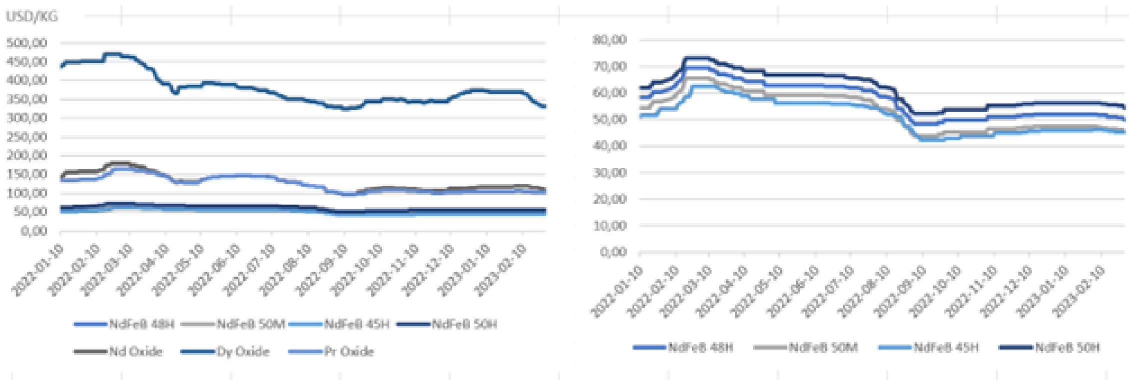

Figure 5.7: *Visualization of correlation between four magnet grades and the raw material oxides.*

5.6.1 Price volatility

From 2010 to 2012, the price of RE metals and oxides fluctuated greatly (Smith et al., 2022). For example, NdPr oxide prices surged to levels greater than 11 times those of January 2010 and Dy-oxide prices grew to levels greater than 18 times than those of January 2010 before falling sharply. Prices for NdPr oxide have increased by 243% since the start of 2020, whereas Dy oxide costs have increased by 88%. During this period prices remained constant, with little month-to-month price fluctuations. Based on prices taken from Argus Metal Pages by Smith et al. (2022), the first row in figure 5.8 displays price volatility metrics for Nd, Pr, Dy, and Tb oxides. The oxide, metal and alloy price volatility index were compared to the calculated volatility for the past year to get a more up to date situation of the fluctuating prices. The results of the calculations are visualized in fig 5.8. The oxide price volatility from 2020 decreased from 0.10, 0.09, 0.13, 0.14 to 0.04, 0.03, 0.02, 0.03. This is probably due to the stable situation of the prices. Moreover, metal and alloy follow the same volatility deviation due to the correlation between the raw material and the composition of the metal. RE mining and magnet producers need to keep track of the fluctuations in RE prices so they can mitigate by supply strategies and production adjustments in order to secure market share and profitability.

Price volatility from year 2010-2020	Neodymium oxide	Praseodymium oxide	Dysprosium oxide	Terbium oxide
Smith et al. (2022)	0.10	0.09	0.13	0.14
Price Volatility year 2022-2023	**Neodymium**	**Praseodymium**	**Dysprosium**	**Terbium**
Oxide	0.04	0.03	0.02	0.03
Metal	0.04	0.02	0.02	0.03
Alloy NdPr & DyFe	0.04	0.02		
Magnet Grade	**50H**	**45H**	**50M**	**48H**
Price Volatility year 2022-2023	0.02	0.02	0.02	0.02

miro

Figure 5.8: *Price volatility index for oxide, metal and magnet comparison between the year 2010-2020 compared to 2022-2023.*

Price volatility for the different magnet grades is calculated as 2%, as shown in figure 5.8. The volatility index indicates similar values as the oxide, metal and alloy volatility. This can indicate that the correlations mentioned earlier are aligned for the different raw material and semi-finished magnets on the oxide, metal and alloy level. The change of upstream RE prices has a greater impact on midstream producers of REPMs. By making bulk purchases of raw materials, large manufacturers may reduce the effect of RE price volatility on their operations or by extending the supply chain upstream to guarantee the purchase of RE components at a price that is extremely competitive. Several actors are involved in the value chain and are willing to develop their knowledge in up, mid and downstream. This can then result in new investments that can change the market dynamic and cause price volatility. If China continues to control the market, the prices will follow a similar trend.

5.6.2 Price related to demand

RE metals are in relatively short supply, but demand is rising. The price of RE metals will be impacted by any circumstance that impacts the available supply of RE, such as interruptions in production, export limits, policy changes, etc. Sintered NdFeB magnets price fluctuations are significantly influenced by the market demand. If the demand declines, the supply of magnets on the market might exceed the demand, resulting in a price decrease. Contrarily, if there is a shortage of supply, magnet prices could increase. Van Weele (2018) states that external factors can influence a product's price, for instance indirectly by shifts in the demand dynamics. Several magnet manufacturers highlight that their customers and rising regulations will influence the demand for recycled sintered NdFeB magnets. Furthermore, magnet manufacturers mention that recycling is another factor affecting the price. The recycling steps enable the re-usage of the HRE content. The more HRE content, the more expensive magnet price. Schönfeld (2023) highlights that production of magnets will be more profitable as the percentage of recycled materials rises. Factors include energy savings since initial mining, refining, and melting operations are not required in a circular economy, which accounts for about 45% of magnet price in raw material savings through recycling. This is dependent on the broader supply-demand balance (Bobba et al., 2020). Demand-driven price increases may make exploration, mining, and refining, as well as substitute and recycling projects, more appealing and financially viable. Moreover, the restrictions in Malaysia due to governmental interference may give rise to a supply disruption of NdPr (Burton, 2023).

5.7 Kraljic matrix for permanent magnets

Kraljic Matrix is a purchasing portfolio model, which includes a matrix classifying the goods bought by a corporation into four categories based on two key factors: the profit impact and the degree of supply risk (Garzon et al., 2019). In the Kraljic Matrix, permanent magnets can fall under the category of "non-critical item" since it is a high-volume material that is part of a bigger application. However, for the buying firm of a sintered NdFeB the preconditions are different compared to other permanent magnets that are abundant. Sintered NdFeB magnets are a critical component for electric machines, and their quality and reliability are essential to the performance of the motors. The supply of these magnets may also be limited, as they are not widely available and require specialized manufacturing processes. The raw materials Nd, Pr, Tb and Dy included in the sintered NdFeB are classified as a strategic and critical raw material (European Commission, 2023a). These materials are subject to a supply risk in the future.

Non-critical items have minimal technical or commercial issues (Van Weele, 2018). There are numerous alternative suppliers, and they typically have low prices per item. Ferrite magnets and bonded NdFeB can be found outside of China and the prices are considerably lower than sintered NdFeB. The manufacturing processes for these magnets are less advanced and less related to the Chinese know-how. Therefore, these items can be seen as a non-critical item since they are easier sourced than sintered NdFeB, there are several supply alternatives available in the market. Ferrite is an example of a HEE free magnet and due to that it can also be seen as a strategic, bottleneck or leverage item depending on the usage and availability of suppliers.

HRE free magnets can be considered as strategic items if they are essential to the organization's operations and contribute significantly to its profitability. If the supply of HRE free magnets is limited, and there are few alternatives available, they could be classified as bottleneck items. This means that the supply risk is high, and any disruption in the supply chain could have a severe impact on the organization's operations. If there are several suppliers of HRE free magnets, and the organization has bargaining power to negotiate prices, these magnets could be classified as leverage items. In this case, the organization can use its bargaining power to negotiate better prices, delivery terms, or quality standards. In conclusion, the classification of HRE free magnets in the Kraljic Matrix depends on their importance to the organization's operations and the supply chain's availability and stability.

The assessment of supply risk considers factors including availability, supplier diversity, competitive demand, make-or-buy opportunities and substitute potential (Garzon et al., 2019). As a strategic item, the company would need to invest significantly in managing the supply of sintered NdFeB magnets. This could include developing long-term relationships with reliable suppliers, implementing quality control measures to ensure the performance of the magnets, and potentially investing in research and development to find alternative materials or manufacturing processes to decrease the HRE content. Strategic items are high-tech and high-volume items that are frequently given to customers according to their specifications (Van Weele, 2018). There is a single supply source, which would be extremely costly to change in the near future. A large portion of the cost of the final product for the company comes from strategic products. Overall, the categorization of sintered NdFeB magnets in the Kraljic Matrix would depend on their importance to the company's operations and the level of risk associated with their supply. For a company producing electric machines, these magnets should be considered as a critical and high-value item that requires significant investment and management.

For a firm buying magnets that is an early development, the magnet is of strategic importance due to the expected supply risk in the market. The expected supply will not reach the demand, especially for the EVs as they have a significantly smaller volume compared to other sectors of the market and thus less power. Moreover, the supply side of sintered NdFeB is condensed in the Chinese and Japanese market which result in less options to diversify the supply chain for the buying firm. As of today, it is not possible to replace the sintered NdFeB performance with another type of magnet, for instance in HEV applications. There are no options for OEMs to bring magnet production in-house thus making the buyers dependent on suppliers to source the magnets from. Sintered NdFeB magnets are not widely available and require specialized manufacturing processes. The supply of these magnets can be limited, particularly during times of high demand or disruptions in the supply chain. This makes them a critical item that requires careful management to ensure a reliable supply. For a company producing electric machines, the quality and availability of sintered NdFeB magnets are crucial to the performance of their products and their overall business success. Moreover, as permanent magnetized sintered NdFeB for technical reasons is not preferred to be sourced by several suppliers due to the required standard in all machines to have the same quality and effect, it contributes to limitations to diversify to several suppliers of the few alternatives outside of China.

The profit impact of a specific supply item can be expressed in terms of the volume purchased, as a proportion of overall purchase expenses, or as an impact on the product quality or company growth (Garzon et al., 2019). The profit impact is the impact of purchasing on financial results. The financial impact of buying on the bottom-line increases as the volume or the amount of money invested increases. The share of a permanent magnet in an EM can vary depending on the type and design of the motor. The permanent magnet can make up a significant portion of the machine's overall weight and size. The size and strength of the magnets can vary depending on the desired performance characteristics. Since sintered ferrite and bonded NdFeB cannot be used due to its lower power as a standard in heavy duty EM but only in smaller motors and sensors, these fall under non-critical. To conclude, the sintered permanent magnet is a large share of the EM cost which makes the purchasing strategy of high importance to the final application. The EM has a high impact on financial results and as sintered NdFeB is a large portion of the motor it provides justification for classifying the magnet as a strategic sub product for an OEM, see figure 5.9.

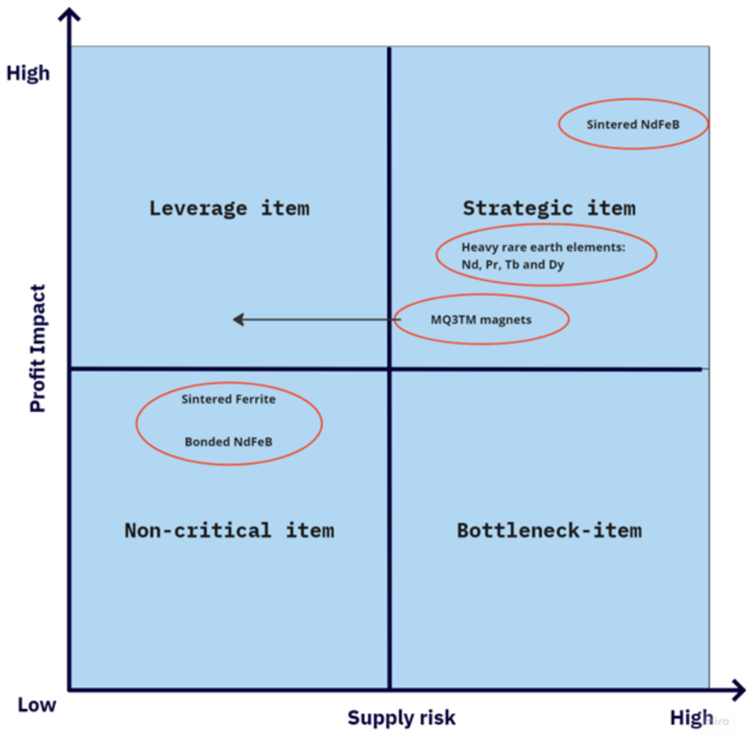

Figure 5.9: *Kraljic matrix for permanent magnet*

New substitutes such as the MQ3 magnet will impact the downstream level and thus the meso level dynamics. At the initial stages when commercializing the new magnet, it will be set as an average supply risk due to the restricted product availability found from a single supplier. However, the supply risk will be lower compared to sintered NdFeB since this supplier is in Europe and thus not influenced of the

Chinese market. When this type of magnet enters the next stages of the commercialization process the magnet will be an industry standard and more actors will offer this through agreed licenses which will decrease the dependency on one supplier. However, this commercialization will take time to enter the market and be accepted by the demand side in the value chain.

Given that MQ3 magnets are a new substitute for sintered NdFeB magnets and do not contain REE, they may be considered as a strategic item. This is because there is a new technology with the potential to disrupt the market and reduce dependence on REE. This quadrant requires a long-term procurement strategy, as the supply market is complex and the impact on the business is high. Companies need to invest in research and development, build strong relationships with suppliers, and closely monitor the market to ensure continuity of supply. MQ3 can potentially also have a significant impact on a company's profit margins. Strategic items are typically high in financial and operational significance and require a long-term procurement strategy. This is because they have the potential to create significant value for the company if they are successfully adopted but may also carry a high level of risk if the market does not respond as expected. The exact impact of MQ3 magnets on a company's profit margins will depend on several factors, including the size and complexity of the company's supply chain, the availability of alternative technologies, and the overall market demand for REE. However, given the potential benefits of adopting new technologies that reduce dependence on REE, MQ3 magnets could have a positive impact on a company's financial performance over the long term. As a result, the position of MQ3 is placed on the right side of the mid-level supply risk as a strategic item for the buying firm.

After the new technology's commercialization process evolves, the item's position will change to the leverage category, as shown in figure 5.9. Leverage items are purchased in huge quantities and make up a sizable portion of the cost of the final product (Van Weele, 2018). The magnet contains almost no HRE which is a drive for lower price but still a higher price due to the production expenses in European manufacturing location as a result of for instance higher labor cost compared to the Chinese labor expenses. Therefore, the profit impact will be higher than sintered ferrite and bonded NdFeB but still lower than sintered NdFeB.

6

Important criterias for sourcing sintered NdFeB magnets

In this section, the result of the analysis and discussion will be used to define the important areas to consider when sourcing sintered NdFeB magnets.

6.1 Sintered NdFeB supplier criteria's

The analysis and discussion provide the basis for defining criteria that are important to address when a buying firm is sourcing a permanent sintered NdFeB magnet. The three main areas addressed in the framework in Figure 5.2 provided a basis for selecting the appropriate sub factors. The selected critieras are 5 areas that are presented in figure 6.1.

1.	Technological requirements
2.	Sustainability criteria
3.	Geo-political criteria
4.	Price criteria
5.	Volume and capacity requirements
6.	Strategy criteria

Figure 6.1: *Summary of criteria for NdFeB permanent magnets*

6.1.1 Technological requirements

Technological requirements and collaboration are an important criterion since the properties and design of sintered NdFeB magnets are crucial for the performance of EM. Magnet manufacturers use various techniques such as grain boundary diffusion and dual alloy method to achieve high-performance of NdFeB. To reduce the amount of heavy rare earths (HRE), the manufacturers develop their own know-how and utilize the supplier's technological advancements. The Chinese government's initiative to reach a high level of magnet value chain has driven the technological evolution in electrification. A direct relationship between magnet suppliers and end-customers is important to follow market development and secure raw material supply. By co-developing with customers, magnet suppliers can optimize the magnetic power and redesign sintered NdFeB magnets to replace Nd with an alternative. A buying firm therefore needs to ensure that a magnet manufacturer has the right know-how for their end application. It is essential to have the right manufacturing processes used to deliver the desired performance such as different magnet grades or alternative substitutes of sintered NdFeB. The criteria are of importance to ensure that the magnet manufacturers know how to develop magnets and improve their performance by having a good knowledge of their processes. It is important to understand how the supplier works with this and that they have a transparently structured system for this type of technical exchange with their customers. The level of know-how of the supplier and the willingness to invest in research and development is therefore an important criterion when determining the suppliers for an OEM (the buying firm).

6.1.2 Sustainability criteria

Sustainability is another important factor to analyze when selecting suppliers. The production of magnets is not an environmentally friendly process. It is important for the buying firm to ensure that magnet manufacturers perform complete Life Cycle Assessment (LCA) and use raw materials from environmentally friendly mining companies, as well as renewable energy. This helps to lower the risk of unsustainable usage of electricity, water, and hazardous chemicals. In addition, the need for CSR to ensure that companies' supply chains work in accordance with established standards and norms for human rights, as well as regional labor and environmental regulations needs to be ensured. Furthermore, there are upcoming legal requirements such as the Carbon Border Adjustment Mechanism (CBAM) that will obligate manufacturers to report their greenhouse gas emissions, which makes sourcing of permanent magnets highly sensitive from a sustainability perspective. Therefore, considering sustainability criteria such as CSR, LCA, renewable energy use, and environmental regulations is crucial when selecting a supplier of permanent magnets.

Recycling is important to consider when selecting a permanent magnet supplier for a few reasons. Firstly, recycling can help the manufacturer gain back the raw material from the end-of-life EM, thereby reducing the dependency on limited raw material resources and reducing the environmental impact. This can result in better profitability for the manufacturer in the long run. Secondly, if the manufacturer offers recycling options to its customers, it can support their circularity initiatives and help them reduce their own environmental footprint. Finally, with China banning the option to import scrap material for recycling, having a manufacturing location outside of China that offers recycling can be advantageous for customers looking to source from a more sustainable supply chain to close the product loop. By considering a supplier that has integrated recycling practices in its operations, buying firms can demonstrate their commitment to sustainability and potentially gain a competitive advantage in the market.

6.1.3 Geopolitical criteria

The next criteria to address when selecting a supplier is geo-political factors. The risks associated with the disruption of the supply chain, which have shifted from focusing solely on demand-side risks to now considering supply-side and control risks, as well as risks brought on by the globalization of the supply chain and the greater emphasis on single sourcing. Governments are initiating actions to lower dependency on China and build a supply chain with limited or no dependency on the Chinese government. Manufacturers are placing production in other locations to meet the demand from the US and European Union. Designing supply chains to be adaptable and able to respond to changes in demand is a usual response to these disruptions. Different types of resilience, including macro-level and micro-level resilience, are introduced by Azadegan and Dooley (2021), and they emerge when businesses, including rivals, work with organizations like the government or industry associations to handle or control a longer-term supply risk. It also provides examples of meso-level resilience initiatives taking place in the permanent magnet market. However, geopolitical differences in different countries make information sharing and transparency more difficult, inhibiting the development of resilient magnet supply chains.

Some magnet manufacturers outside of China have joint venture manufacturing facilities in China, with the majority ownership held by the foreign company. This approach helps to mitigate the challenges faced by foreign companies in China, such as the "liability of foreignness," and allows the joint company to leverage the expertise and social connections of local partners to achieve business objectives. One European manufacturer is cited as an example, stating that they have a 70% shareholder in their Chinese subsidiary. If the selected supplier is a Chinese actor, the benefits can be gained from a JV to get access to the material and technical know-how within the Chinese market. This benefit can also be gained by having a European supplier that have the same ownership and knowledge within the Chinese market.

Understanding the risks associated with a supplier's supply chain is important when selecting a supplier because it can impact the reliability and resilience of the supply chain. The risks can come from various sources such as demand-side, supply-side, control, and geopolitical risks, and can lead to disruptions in the supply chain that can affect the availability and cost of products or services. It is not only risks associated with downstream suppliers but also to consider the risks coming from the mining sub suppliers on the upstream level. By considering these risks, businesses can make informed decisions when selecting a supplier and take steps to mitigate the risks through strategies such as diversification of suppliers and collaborating with other external organizations such as associations specialized in the industry. Ultimately, a supplier with a reliable and resilient supply chain can help businesses to meet their needs and maintain continuity of their operations. Due to the technical requirements and the quality aspect, it is preferable to select a supplier that offers several supply locations and thus creates diversification without increasing the number of magnet suppliers.

Moreover, it is important to look at how the supplier works with intellectual property. If a buying firm has a supplier with patent infringement it will eventually be harmful for the markets where the end-product is sold. There is a risk for huge lawsuits on the magnet suppliers when the magnet is bought out of China and eventually it will lead to a supply risk for the buying firms especially if it is from a single source with no diversification. For a successful and sustainable buyer-supplier relationship, it can therefore be beneficial to perform a patent analysis with technical parameters included.

6.1.4 Price Criteria

Another important criterion to consider is price. The cost of these magnets can make up a significant portion of the overall cost of the EM, and the price of the magnets is closely tied to the price of the raw materials used to make them, which can be volatile and influenced by a variety of factors such as government policies and global supply and demand dynamics. Buying firms need to be aware of these factors and choose a supplier who can provide fair pricing and a stable supply chain. They also need to consider currency risks when purchasing from foreign suppliers and the impact of exchange rate fluctuations on the price of the magnets. By taking these factors into account, buying firms can make informed decisions when selecting a supplier and ensure that they are able to offer competitive pricing to their customers.

The volatility of rare earth (RE) metals and oxides prices and their impact on midstream producers of RE permanent magnets is also of importance. Buying firms should consider the supply strategies and production adjustments made by their potential suppliers to mitigate the effect of RE price volatility on their operations. The ability of suppliers to make bulk purchases of raw materials and extend the supply chain upstream to guarantee the purchase of RE components at a competitive price is also an important consideration. By choosing a supplier with a reliable supply chain and pricing strategy, firms can secure their market share and profitability.

6.1.5 Volume and capacity requirements

The demand for magnets is expected to rise, especially for EV and wind turbine applications. The global demand for NdFeB magnets is estimated to reach 135,000 tons by 2030, and magnet manufacturers are expanding their production capacities to meet this demand. Suppliers' production capacity is critical to avoid supply shortages, especially for sintered NdFeB magnets. Buyers must consider the supplier's production capacity when selecting a supplier to ensure that they can meet their demand. The competition is fierce, and the buying firm needs to consider this while developing their supplier selection strategy. Prices may increase globally due to geopolitical activities, but the capacity can change if new technological advancements, like HRE free magnets, become commercialized.

To conclude, another important criterion to think of is the volume and capacity level of a supplier. The criteria will highlight the importance of a supplier's manufacturing capacity in mitigating potential supply shortages of sintered NdFeB magnets. The global demand for these magnets is expected to continue increasing, and some manufacturers may struggle to meet the growing demand without significant investment in their production capacity. Therefore, buying firms need to consider a supplier's production capacity and long-term investment plans to ensure a stable and reliable supply of these crucial components for their EM.

6.1.6 NdFeB as a strategic product

It is important for a buying firm to consider the Kraljic Matrix classification of the purchased products when selecting a supplier, especially when sintered NdFeB is classified as a strategic item. The classification is dependent on the buying firm's strategy and risk tolerance towards the permanent magnet value chain. If the risk tolerance is high, the classification of permanent magnet may change to bottleneck or non-critical item. Although from our findings the risk tolerance should be low and the NdFeB should be targeted as a strategic product to meet the electrification and sustainability targets. If instead other types of magnets were purchased for the EM (ferrite, bonded NdFeB) the risk tolerance can be low, and the products may be classified as non-critical due to the abundance.

The classification enables the understanding of the supply risk and profit impact of the item, which in turn affects the OEM's operations and profitability. By considering the classification, the buying firm can determine the level of investment and management required for the item's reliable supply, including developing long-term relationships with suppliers, implementing quality control measures, and investing in research and development to find alternative materials or manufacturing processes. The buying firm can also assess the bargaining power it has to negotiate better prices, delivery terms, or quality standards based on the classification. Overall, the Kraljic Matrix provides a framework for the firms to make informed decisions about supplier selection, risk management, and investment strategies, which can ultimately impact the success of their business.

7 Conclusion and recommendations

The conclusions are presented in this chapter by considering the aim and research questions that were developed in the study's initial stages. Lastly, highlighting key areas that require additional investigation in the future permanent magnet field.

7.1 Conclusion

The aim of the report was to describe and analyze the permanent magnet value chain, identifying its trends, actors and other factors influencing the sourcing strategy for Alpha. Furthermore, to analyze the most important factors for Alpha to consider while sourcing sintered NdFeB magnets and identify the challenges related to it. The research questions helped to reach the aim of the thesis. The actors and their interdependencies within the value chain were answered in both RQ1 and RQ2. The remaining parts were covered by the extensive and detailed analysis of the interviews. Important areas to consider were analyzed, including the trends and challenges in the permanent magnet value chain.

The constructed research questions RQ1, RQ2 and RQ3 are linked to each other and provide a basis to clarify the network of sintered NdFeB magnets and furthermore a basis for specific criteria for a buying firm to consider for their sourcing. RQ1 enabled further development of answering RQ2 and RQ3. The first question was answered by describing the processes in the value chain from mining to a final sintered NdFeB magnet. The process assessment was important in order to understand the actors, relationship, and the bottlenecks in the value chain. The conclusion is that the magnet industry is a niche market, and it is essential to understand the building blocks of the value chain to get a helicopter perspective.

Moreover, RQ2 concluded that the network of the permanent magnet value chain is structured at the micro level, by individual businesses and organizations making up the value chain. These include magnet manufacturers, industry organizations, mining companies, metal refiners, and recycling companies. At the meso level, these businesses are linked together through buyer-supplier relationships and inter-organizational interactions. The companies cooperate with each other depending on their position in the value chain, with upstream actors collaborating with mid-stream actors, who then collaborate with downstream actors. Downstream actors, such as magnet manufacturers, are often the first point of contact for end customers, such as OEMs. Business relationships and activities serve as a crucial foundation for business growth, facilitating collaboration and influence to work and follow the same regulations, trends, and developments for expected demand growth in the supply market of permanent magnets. Collaboration within the network allows for the sharing and integration of knowledge, defining industry standards, and gaining access to raw materials. The network is also influenced by external factors such as government regulations and public awareness of the environment among consumers and public actors.

By answering RQ3, it is concluded that sintered NdFeB magnet is classified as a strategic product. Lastly, RQ4 outlines important criteria for selecting a supplier of permanent magnets. The first criterion is technological requirements, emphasizing the importance of design and properties of sintered NdFeB magnets for the EM performance. The second criterion is sustainability, including complete LCA, CSR, recycling and environmental regulations. The third criterion is geopolitical factors, which involve supply chain disruption risks, information sharing, intellectual property and transparency. The fourth criterion is price, which should be considered alongside other criteria such as supplier location. A supplier with a reliable and resilient supply chain can help businesses meet their needs and maintain operational continuity. Businesses should consider various factors while selecting a supplier of permanent magnets. By selecting a supplier with a reliable supply chain, businesses can maintain continuity of their operations, and by considering recycling and sustainability, they can ensure that they are acting responsibly.

7.2 Future research recommendations

This study concentrated on a particular permanent magnet type and its final use in electrical machines. To construct a more nuanced study with more case studies than Alpha's perspective, several industries that use permanent magnets can be analyzed. This can provide a holistic perspective, and the result will be more general for several industries such as wind turbines, electronics and other applications. Another subject that requires further research is whether competitors deal with permanent magnets and how their strategy is designed to build a resilient supply chain. This involves comparing Alpha to its competitors in order to draw any valuable conclusions.

Another perspective that could not be explored in depth was the extent to which there is new research and development of substitutes to sintered NdFeB magnets that could have an important impact in the near future. Although alternative solutions have not been commercialized as of today. There are several new innovations that could change the entire network and its stakeholders. It is of interest to investigate these and draw conclusions if it is possible to identify early adopters in the market. This study provides a basis for Alpha and other OEMs to consider the sintered NdFeB network and how they should adapt their strategy. The results can be used as an initiator for other in-depth analyses of the different building blocks that have been addressed in this study.

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A
Appendix A

What is your core business?

Do you have a code of conduct, if so, is it possible to share?

How do you position yourself in the permanent magnet supply chain market?

-What part of the value chain of permanent magnet are you working with (upstream, midstream and downstream)?

-How far down in the permanent magnet value chain do you have visibility?

What challenges in the permanent magnet market do you see in the coming years?

Do you have any geopolitical challenges?

What business model do you have?

What processes do you work with to produce permanent magnets?

What kind of permanent magnets are included in your product portfolio?

Do you see any differences when producing different strengths of the magnets? -What are the main cost drivers in your process? -What step in the process are your main bottlenecks?

Do you own any patents, or do you buy licenses for the processes and the magnets?

B

Appendix B

INDICATOR	Neodymium oxide	Praseodymium oxide	Dysprosium oxide	Terbium oxide
Price volatility	**0.04**	**0.03**	**0.02**	**0.03**

Volatility measure of RE oxides.

INDICATOR	Neodymium metal	Praseodymium metal	Dysprosium metal	Terbium metal
Price volatility	**0.04**	**0.02**	**0.02**	**0.03**

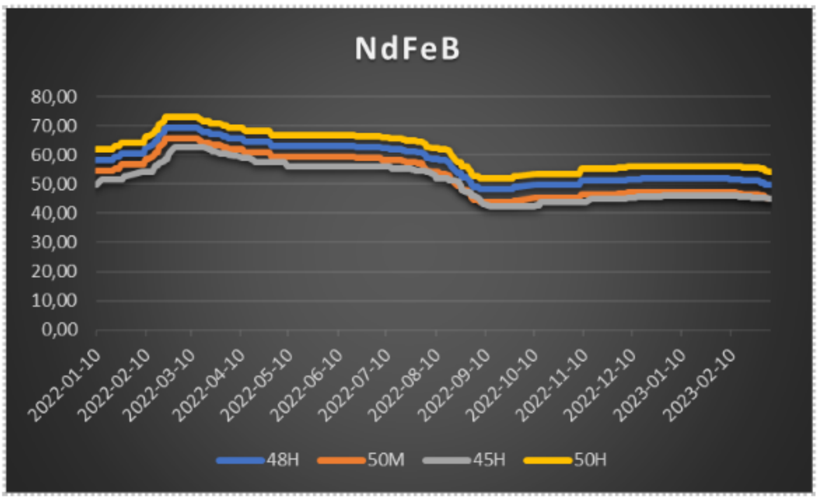
Volatility measure of RE metals.

INDICATOR	NdPr Alloy	DyFe Alloy		
Price volatility	**0.04**	**0.02**		

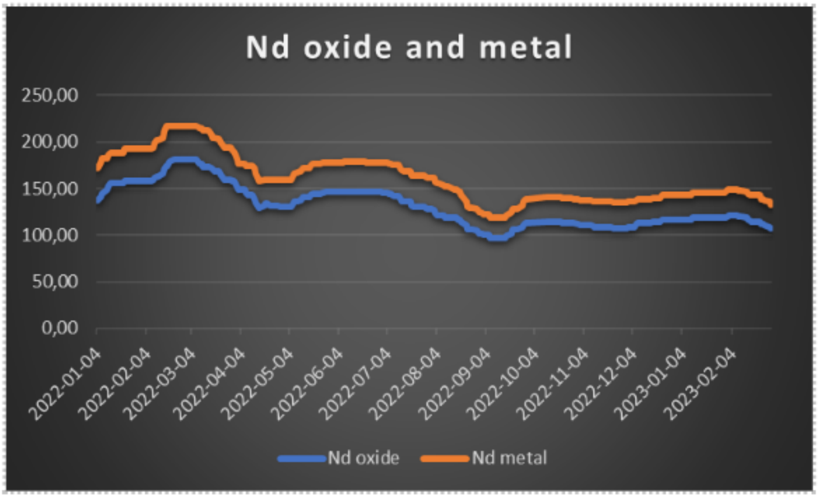
Volatility measure of RE alloys. Data retrieved from from one interviewed supplier

INDICATOR	NdFeB 50H	NdFeB 45H	NdFeB 50M	NdFeB 48H
Price volatility	**0.02**	**0.02**	**0.02**	**0.02**

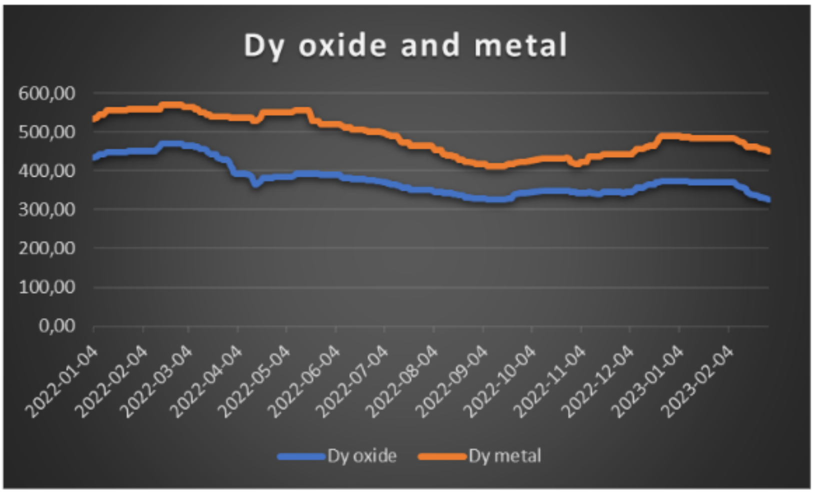
Volatility measure of RE magnets.



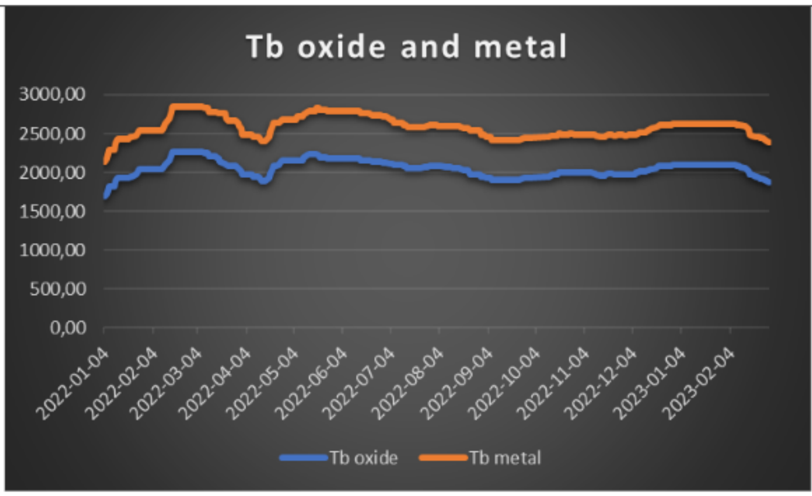
Magnet price for different grades



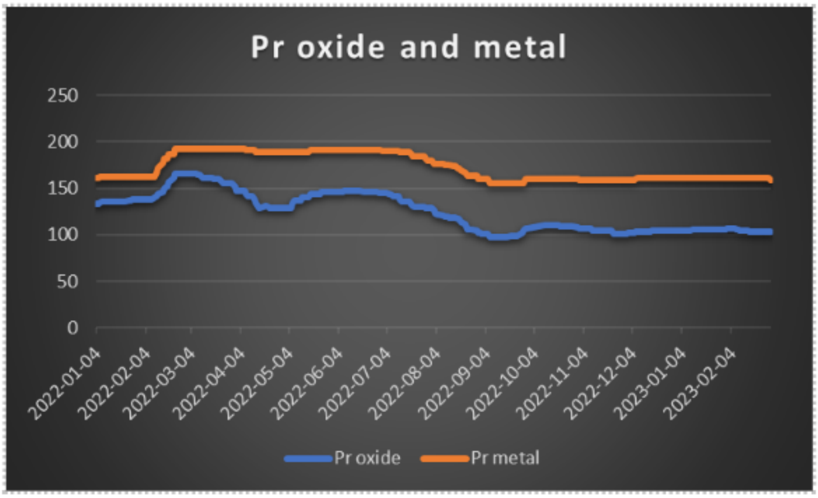
Nd oxide and metal price



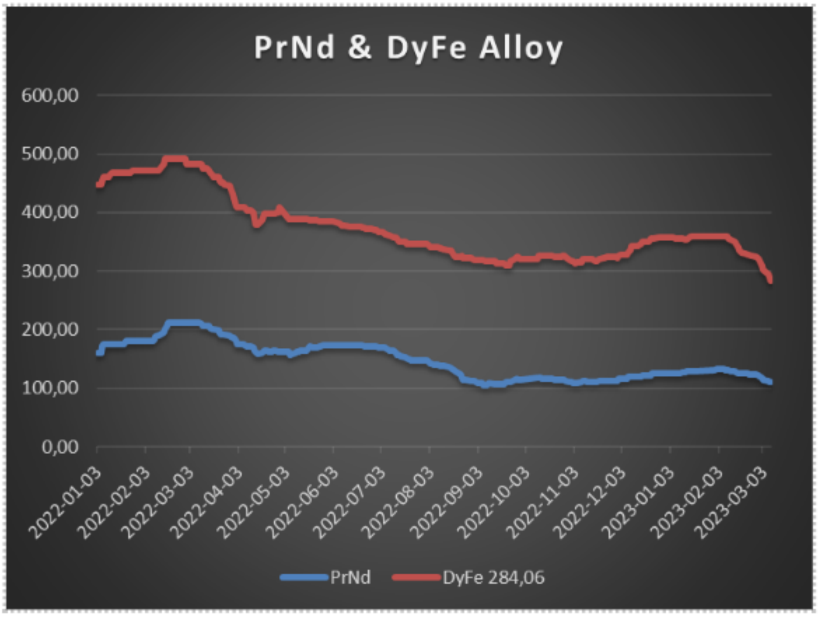
Dy oxide and metal price



Tb oxide and metal price



Pr oxide and metal price



PrNd and DyFe alloy price

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