Exploring circular economy strategies to reduce dependency on Critical Raw Materials in the defence sector

A case study on NdFeB magnets

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Exploring circular economy strategies to reduce dependency on Critical Raw Materials in the defence sector

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Master thesis submitted to Leiden University and Delft University of Technology in partial fulfilment of the requirements for the degree of Master of Science in Industrial Ecology

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Preface

Before you lies the master thesis 'Exploring circular economy strategies to reduce dependency on Critical Raw Materials in the defence sector - A case study on NdFeB magnets'. It has been written to fulfil the graduation requirements of the Master of Industrial Ecology at Leiden University and Technical University Delft. I was engaged in researching and writing this thesis from February to June 2024.

My interest in sustainability, design, defence and international relations has been a cornerstone of my choice to perform this research. The multifaceted nature of these fields and their profound impact on global sustainability have inspired me to delve deeper into understanding how industrial systems can be designed to promote ecological balance while enhancing societal resilience. This thesis represents my effort to contribute to this dialogue, aiming to bridge the gap between industrial practices and sustainable development within an international context.

This work is written primarily for the academic and professional communities involved in industrial ecology, defence studies, and international relations. It is also intended for policymakers and designers who want to integrate sustainable practices into industrial and defence systems. My goal is to provide insights that can inform better decision-making processes, promoting collaboration across disciplines to achieve a more sustainable future.

I would like to express my gratefulness to those who have supported me throughout this academic journey. Firstly, I would like to thank my first supervisor, David Peck, whose guidance and expertise have been instrumental in shaping this thesis. The discussions during our meetings were very valuable, as was the network I was allowed to use. I am equally grateful to my second supervisor, Benjamin Sprecher, for your critical attitude that managed to lead me out of tunnel vision by offering challenging new perspectives which have enriched my research and broadened my understanding.

I am also thankful to the numerous individuals who have contributed to this work. Special thanks goes to the interviewees who generously shared their knowledge and experiences. Your contributions have been essential to the depth and breadth of this research.

Finally, I would like to thank my partner, family and friends who have supported me throughout this process. In special, my student colleague, Serra Anker. With whom I have spent many hours discussing and brainstorming lifting our theses to a higher level.

While I have strived to approach this study as objectively as possible, I acknowledge the limitations inherent in my background and perspective. Coming from a business administration background my analysis may lean towards the social dimensions of industrial ecology. Additionally, being from Western Europe I recognise that my worldview is shaped by this context, which may introduce certain biases. Regardless of these limitations, I did my best to conduct this research in as fair and proper manner as possible providing a balanced and comprehensive examination of the topic.

I hope this research serves as a useful resource for future research and practical applications.

Enjoy the reading.

Lyanne Wagemans
Leiden, June 11, 2024

Executive summary

This research explores the intersection between circular economy strategies, critical raw materials (CRMs) and the defence sector, especially focusing on Neodymium-Iron-Boron (NdFeB) magnets. The significance of CRMs in modern defence applications and the associated risks of geopolitical and supply chain disruptions underscore the necessity for a secure supply. Circular strategies are crucial not only for securing a stable supply of CRMs but also for their potential to significantly reduce environmental impacts. This study aims to determine the effectiveness of various circular strategies in securing a stable supply of CRMs, thereby enhancing national security and promoting environmental sustainability.

To address the research question, a mixed-methods approach was employed. Secondary data collection involved a review of scientific and grey literature, while primary data was obtained through interviews with experts. The conceptual framework was based on the 9R framework of circular strategies, chosen for its comprehensive coverage of all value retention options, from smarter product use and manufacturing, and lifespan-extending practices to the useful application of materials. This framework was adapted to the context of CRMs. The analysis was conducted using the backcasting method to develop strategic pathways for implementation.

From the results, it is clear that NdFeB magnets are crucial to the defence sector due to their exceptional magnetic properties. This makes them indispensable in various defence applications, such as in motors, sensors, and communication devices. The reliance on CRMs like neodymium and dysprosium for the production of NdFeB magnets poses a significant risk due to their limited supply and geopolitical concentration. The study identified effective circular strategies on all 10 levels of value retention. This includes modular design, which facilitates easier disassembly and reuse, and advanced recycling techniques like hydrogen decrepitation, which efficiently reclaims materials. These strategies are already being implemented in the civil sector and can be adapted for defence applications to enhance sustainability and resource efficiency.

To implement the circular strategies in the defence sector, barriers and enablers are highlighted on four levels: cultural, regulatory, market and technological challenges. Culturally, the defence sector has a somewhat conservative approach in which operational effectiveness is considered most important. Awareness about sustainability and CRMs can be created through programs, training and role modelling. Secondly, the defence sector is heavily regulated with stringent standards for performance and safety. Therefore, policies are important to ensure that circular practices comply with existing standards and incentives should be created. On the market level, commercial considerations are said to be the hardest challenges which should be taken care of in procurement processes. Lastly, adopting circular strategies involves technological innovations for which investments and development are crucial. Collaboration among various stakeholders is essential to the implementation. A detailed implementation plan is provided including measures to overcome the barriers alongside an indication of time.

The research concludes that implementing circular strategies on NdFeB magnets within the defence should be improved as many more benefits can be gained from further implementation especially with regards to lowering dependence on CRMs. By adopting these strategies, the defence sector can not only secure a more reliable supply of critical materials but also contribute to broader sustainability goals. The circular strategies could be tailored to fit specifically into the defence sector by addressing unique challenges and leveraging opportunities.

Keywords*: Defence, NdFeB magnets, Critical Raw Materials, Circular Economy Strategies, Strategic Autonomy*

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List of Acronyms

ASD	Aerospace, Security and Defence Industries
CRMA	Critical Raw Materials Act
CRM	Critical Raw Material
EDA	European Defence Agency
EIT	European Institute of Innovation & Technology
EU	European Union
EV	Electric Vehicle
HCSS	Ten Hague Centre for Strategic Studies
HDD	Hard Disk Drive
HREEs	Heavy Rare Earth Elements
IE	Industrial Ecology
IMCCS	International Military Council for Climate and Security
LREEs	Light Rare Earth Elements
MOD	Ministry of Defence
MRI	Magnetic Resonance Imaging
NATO	North Atlantic Treaty Organisation
NdFeB	Neodymium-Iron-Boron
NIDV	Netherlands Industries for Defence & Security
PGMs	Platinum Group Metals
PSS	Product Service System
REE	Rare Earth Elements
TAP	Technology Action Plan
TNO	Netherlands Organisation for Applied Scientific Research
UAV	Unmanned Aerial Vehicle
USA	United States of America

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Introduction

1. Introduction

In an era marked by escalating geopolitical tensions, the stability of global supply chains has become a subject of concern. During the past decades, various global disturbances took place which affected the global economy and the geopolitical landscape. In 2022, the Russian government ordered the entry of military forces into Ukrainian territory (Ratten, 2023). Not much later, in 2023 the conflict between Palestine and Israel escalated. As a consequence, international relations are disrupted and awareness within the EU is created of the exposure to geopolitical risks in key supply chains (Le Mouel & Poitiers, 2023). In the meantime, the world faces unprecedented environmental challenges. Climate change continues to escalate, manifesting in severe weather events and impacting global ecosystems, economies and communities. These environmental crises have spurred an urgent need for sustainable practices, particularly in terms of resource efficiency.

Critical raw materials (CRMs) are at the intersection of these geopolitical and environmental issues. CRMs, such as rare earth elements used in high-tech applications, are pivotal due to their essential roles in various sectors including renewable energy technologies, electronics and defence (Kumari & Sahu, 2023). The strategic importance of these materials is underscored by their concentrated supply chains, often located in geopolitically sensitive regions. This concentration poses risks of supply disruptions which can have ripple effects on global security and economic stability. The Critical Raw Materials Act (CRMA) by the European Union addresses these issues by ensuring the secure and sustainable supply of CRMs, emphasising diversification, recycling, and innovation (European Commission, n.d.-c).

Given the environmental impact associated with the extraction and processing of CRMs, it is imperative to explore strategies that not only reduce dependency on these materials but also enhance environmental sustainability. Lowering the dependency on CRMs can decrease the leverage that supplier nations hold, contributing to more stable supply chains and promoting geopolitical stability. Simultaneously, implementing resource-efficient strategies aligns with the global agenda such as the Paris Agreement to mitigate environmental degradation, promoting a more sustainable and resilient economy (European Commission, n.d.-d). In the context of defence, the dependency on CRMs becomes even more critical (C. C. Pavel & Tzimas, 2016). These materials are located in numerous defence components such as Neodymium Iron Boron (NdFeB) Magnets which are part of applications like electric motors and missile guidance systems to communications and surveillance technologies (Grasso, 2013). Ensuring a stable and secure supply of CRMs is not only a matter of economic importance but also of national security ((European Commission, n.d.-c). Reducing reliance on these materials or finding sustainable alternatives, is therefore a strategic imperative for defence sectors worldwide.

While literature already examines the strategic importance and vulnerabilities associated with CRMs only a few studies have explored the intersection of CRMs with circular economy principles within the context of the defence sector (Mathieux et al., 2017). Existing literature thus far primarily focused on the civil sector without considering the unique demands and security considerations of military applications (Gaustad et al., 2018; Kumari & Sahu, 2023; Rademaker et al., 2013). Of these, only a few have looked at multiple value-retaining options (Habib, 2019). This research aims to bridge this gap by developing an understanding of how circular strategies can be specifically implemented to reduce CRM dependencies in defence. Specifically, this research contributes to the field of Industrial Ecology (IE) by demonstrating how IE principles can be applied to the defence sector to enhance their environmental sustainability. Other strategies for increasing resilience could also be examined such as diversification and stockpiling (Sprecher et al., 2015). As the main focus is to enhance environmental sustainability, only strategies will be examined related to circularity.

Societally, the study addresses urgent global challenges related to vulnerable supply chains, climate change and geopolitical tensions. By enhancing the resilience of defence sectors through circular strategies this research directly contributes to national security and economic stability. The findings aim to influence policymaking and strategic planning within and beyond the defence sector, advocating for broader adoption of circular economy principles to foster resilience against supply disruptions and contribute to environmental sustainability.

This thesis therefore explores the intersection of CRM dependency and environmental sustainability within the defence sector, examining how circular strategies can be applied to reduce CRM use and dependency while improving the environmental sustainability of the defence sector. Therefore, the research question of this study is: *'What effect can circular strategies have on securing critical raw materials supply for the defence sector in the case of NdFeB magnets?'*

Sub-questions include:

1. What makes NdFeB magnets and their CRMs particularly significant in the defence sector?
2. What circular strategies are known in the civil sector for NdFeB magnets in their main defence applications?
3. How can these strategies be implemented within the defence sector?

To answer these questions, the thesis begins with background literature on CRMs. It proceeds with a conceptual framework which forms a basis for this research. In the methodology chapter, the approach will be outlined for data collection and analysis. Results are then presented and discussed with the three sub questions discussed in the subchapters. The discussion chapter interprets the results, discussing implications concerning the initial research question. The final chapter summarises key findings and draws conclusions based on the research question whereafter it offers practical and theoretical recommendations.

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Literature background

2. Literature background

2.1 Critical Raw Materials

Over the past decade, the notion of "critical raw materials" has increasingly informed discussions and found a way into the public debate (Hofmann et al., 2018). These discussions mostly entail topics on economic as well as environmental concerns over limited resources and strategies proposed to cope with these limitations (Haumann, 2018). Therefore, this section will highlight the most important aspects relating to CRMs to form a basis for the rest of the research.

The criticality of materials is not a new concept. In the 19th century, there was a shortage of wood which could have led to a severe energy crisis (Sombart, 1928). Due to certain people pointing out the importance of wood for the maintenance of economic and public well-being, the resource use was tightly administered which prevented a major crisis (Haumann, 2018). One of the first uses of the term 'critical materials' was by the U.S. government when they enacted the 'strategic and Critical Materials Stockpiling Act of 1939' in which they determined the degree of dependence and the risk of a material shortage occurring (Peck, 2019). The criticality of materials is significantly important for the defence industry as it influences the ability to supply army forces which is a deciding factor in the war's outcome.

2.1.1 Defining CRMs

Historically materials deemed as critical were very diverse but currently have been defined much more specifically via specific frameworks. In the field of study for raw material criticality, economic and technical dependency on a certain material as well as the probability of supply disruptions for a stakeholder group within a certain time frame are evaluated (Schrijvers et al., 2020). To test this criticality, various factors for example geological, technological or environmental levels can be examined. However, there is not one true assessment of the identification due to the diverse perspectives of studies (Schrijvers et al., 2020). Therefore, there does not exist one global list of agreements since it varies significantly by geographics (Peck et al., 2015). The United States (US) for example has defined the criticality of minerals as a function of two variables: importance of uses and availability as said by Graedel et al. (2015). Also, other countries such as Japan, The Netherlands, China, South Korea, Australia, Canada, Germany, France and Finland have assessed the criticality of materials (Hatayama & Tahara, 2015; Peck et al., 2015). Even organisations such as NATO have established lists tracking the most critical materials (Juutilainen & Grikinytė, 2024).

The main parameters used by the European Union to determine the criticality of the material are economic importance and supply risk (European Commission, n.d.-b). Economic importance aims at providing insight into the importance of material for the EU economy in terms of end-use applications and the value added corresponding EU manufacturing sectors and supply risk reflects the risk of a disruption in the EU supply of the material based on the concentration of primary supply from raw materials producing countries, considering their governance performance and trade aspects as mentioned by the European Commission (n.d.-b). Hence, CRMs are those raw materials that are economically and strategically important for the European economy but have a high supply risk (Ferro & Bonollo, 2019).

This research will limit itself to the definition provided by the European Commission. Therefore, the examined list of CRMs is the one focused on the European Union. This list, created by the European Commission, is subject to regular review and update. So far 5 lists have been published of which the latest in 2023 contains a list of 34 CRMs of which three are materials groups: Heavy Rare Earth Elements (HREEs), light rare earth Elements (LREEs) and Platinum Groups Metals (PGMs), see Figure 1 (European Commission, n.d.-b).

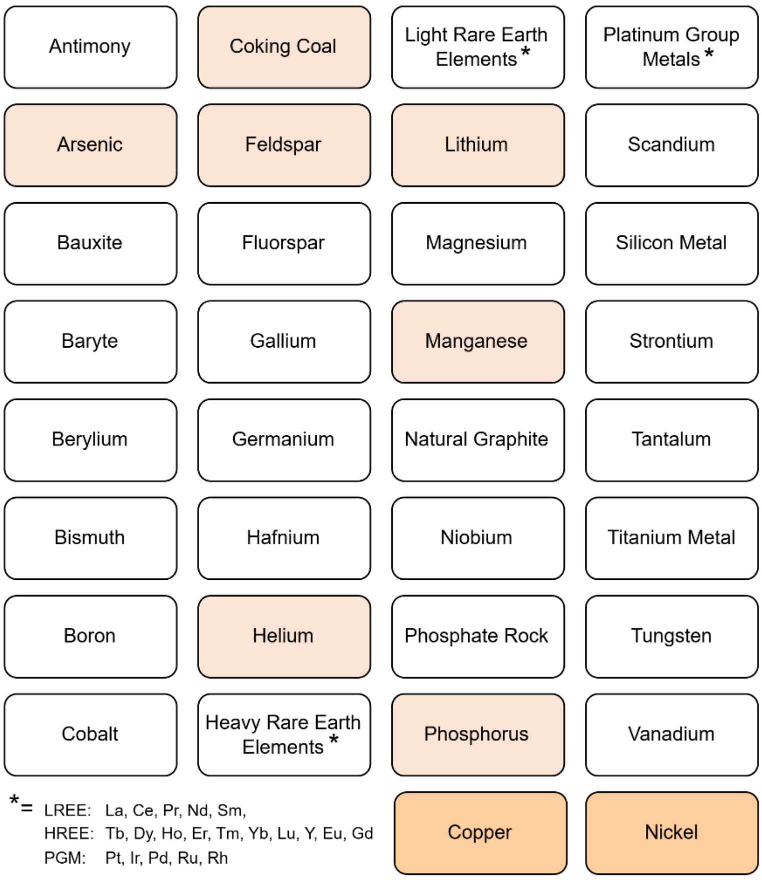

Figure 1- Raw Materials Considered to be Critical* by the European Commission (n.d.-b).
= The CRMs In orange are also considered Strategic. In **bright orange, materials are considered strategic but not critical.*

As indicated in the Figure, the material group HREE consists out of dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium and yttrium. The LREE include cerium, lanthanum, neodymium, praseodymium and samarium. Lastly, Iridium, palladium, platinum, rhodium and ruthenium belong to the PGM (Grohol & Veeh, 2023).

To provide an example of one of these CRMs, the case of Germanium will be further explained. Which frequently appears to be assessed as highly critical (Schrijvers et al., 2020). Germanium is required in various strategic industrial sectors within the EU such as renewable energy, e-mobility, defence and aerospace (Lewicka et al., 2021). Germanium is extracted employing complex processes from zinc residues done by, on a global basis, over 20 producers in countries such as the United States, Taiwan, Belgium, China, Russia, Germany and Canada (Moskalyk, 2004). The most important applications for which Germanium is used are high-speed electronics for cell phone communications and high-efficiency solar cells for space and terrestrial use (Bosi & Attolini, 2010). This example explains both the supply risk and the economic and strategic importance of these materials.

2.1.2 Importance of CRMs

The CRMs listed in Figure 1, are considered to be essential within broader future scenarios. They shape expectations about the technologies central to future development such as the current scenario focusing on the idea of sustainable growth (Haumann, 2018). Related to this is the increasing demand for green technologies in recent years in which CRMs such as tellurium, indium and REE play a crucial role (Haumann, 2018; Jones et al., 2020).

The main trends in Europe affecting raw materials firstly involve the shift towards sustainable energy via photovoltaic and wind technologies (Hofmann et al., 2018). These technologies require the use of various CRMs such as Neodymium, Dysprosium, Copper and Indium (Carrara et al., 2020). The second trend is promoting and adopting electric vehicles (EVs) to revolutionise transportation. In the upcoming years, mass adoption of EVs is anticipated which is primarily fuelled by policy incentives, increasing incomes, and technological progress (Jones et al., 2020). However, the success of this transition heavily relies on the availability and affordability of the necessary raw materials. As mentioned by Ortego et al. (2018) the rarity of vehicles increases with the level of electrification due to the increased use of critical metals, in particular, the increased use of Copper in-car electronics and Cobalt, Lithium, Nickel and rare earth metals (Lanthanum, Neodymium and Praseodymium) in Li-Ion and NiMH batteries. Lastly, the progression of information and communication technology along with sensor technology affects CRMs (Santillán-Saldivar et al., 2021; Schrijvers et al., 2020). Hence, for the EU to have a stable economy CRMs are crucial.

Next to this, CRMs are also viable in ensuring national security. The defence sector uses a great amount of raw materials of which 40 materials are deemed critical or soon-to-be critical by (Girardi et al., 2023). For example, niobium and vanadium are used for high-performance alloys in aircraft and fighter jets lightweight alloys are used which contain Beryllium (C. C. Pavel & Tzimas, 2016). Next to this, CRMs are used in many other applications such as weapon systems and technological advancements.

2.1.3 Key issues related to CRMs

As explained above, for products to fulfil specific functions, many of them require a variety of specific elements whose total reserves in primary deposits on the planet are limited in quantity and unevenly distributed, respectively requiring significant efforts for exploration and investments in their exploitation (Hofmann et al., 2018). Due to socio-political, economic, geological availability and ecological reasons the availability of CRMs needed for the transition to a more environmentally and economically sustainable society is at risk. Therefore, our technological progress and quality of life rely on access to various raw materials. This section will highlight the two main issues which are supply risks related to geopolitical issues and the environmental and social impacts of extraction.

Supply Risk and Geopolitical Issues

Throughout history, the transportation of metals across long distances has highlighted the world's dependency on foreign resources. This is because our supply of metals and minerals is dependent on mining which is tied to geological formations that are unevenly distributed between countries (Buijs et al., 2012). This historical precedent highlights the ongoing challenge of balancing resource distribution and accessibility. However, this challenge has taken on new dimensions in contemporary times. Currently, the increasing consumption and rapid shifts in the global economic, financial, and political landscape contribute to significant supply-demand imbalances for certain raw materials, leading to price volatility in material markets (Hofmann et al., 2018). These changes introduce uncertainties across industries, impacting technology development and market strategies. CRMs, in particular, are subject to these fluctuations and can thus be decisive for the success of emerging technologies (Ziemann et al., 2013).

Take the example of rare earth metals, for which 97% of the global supply is produced by China (Massari & Ruberti, 2013). In addition, as mentioned by Lewicka et al. (2021) the most striking dependencies next to the rare earth metals are borates (98% from Turkey), niobium (85% from Brazil), platinum (71% from South Africa) and cobalt (68% from Congo). An overview of the concentration of CRM extraction per region can be found in Figure 2.

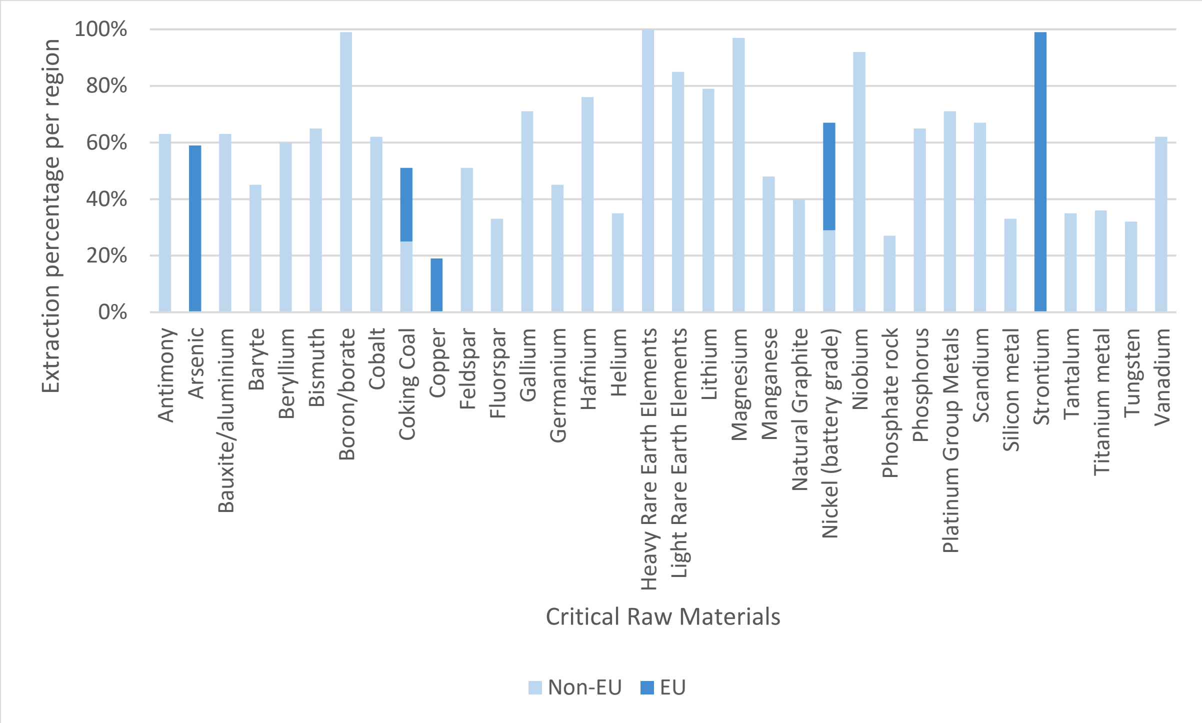

Figure 2 - Extraction per CRM per country (European Council, 2023)

The concentration of CRMs may lead to vulnerability for the EU as the vast majority is extracted outside of its region which provides power to the countries in which the materials are located.

Environmental and Social Impact of CRM Extraction

The extraction and processing of the CRMs often relate to environmental burdens as well as frequent negative social impacts. Environmental impacts relate to impacts on the atmospheric air, subsoil, relief, soil, groundwater and surface water levels. For example, for REE mining the atmospheric air impacts are mostly related to hydrochloric acid, steam use and electricity when looking at the total GHG footprint (Haque et al., 2014). In addition, mining activities also result in the introduction of metals in particulate form into aquatic ecosystems affecting groundwater and surface water levels (Salomons, 1995). Furthermore, due to population growth, continued industrialisation and increased material prosperity, the most abundant and easily accessible reserves are depleted and will lead to an increase in the environmental impacts associated with CRMs (Powell-Turner & Antill, 2017). But not only during the activities the environment is negatively affected. Also, post-extraction there remain disadvantages due to the landscape being exposed to large volumes of waste that pose serious pollution hazards to agriculture (Festin et al., 2019). More specifically the soil conditions of the post-mining landscape are dry, acidic and nutrient-poor (F. Schulz & Wiegleb, 2000).

To provide a more detailed image of the environmental impact, the case of Rare Earths will be explained as these are forecasted to increase strongly in upcoming years (Langkau & Erdmann, 2021). In order to extract rare earths various steps need to be taken such as the extraction using the acidic route, roasting the rare earth ore, washing and filtering, leaching and further separation stages (Haque et al., 2014). In these steps, the major contributors to the total greenhouse gas footprint of rare earth processing are hydrochloric acid, steam use and electricity (Haque et al., 2014). Next to these impacts, the extraction of rare earths also significantly impacts photochemical oxidation, ozone depletion, human toxicity, global warming, ecotoxicity terrestrial, ecotoxicity aquatic, eutrophication, acidification and fossil fuel depletion, now and in the future (Langkau & Erdmann, 2021).

While mining generates income and employment opportunities in local areas, it also introduces various social drawbacks. To go more into detail, negative impacts of employment relate to the occurrence of child-, forced-, and compulsory labour but also factors such as poor and dangerous working conditions, low wages, accidents and fatalities relating to working conditions as mentioned by Mancini & Sala (2018). Furthermore, another concerning consequence of mining is the environmental impact affecting human health (Mancini & Sala, 2018). Such as the contamination in and around mines which leads to a 1.4 times higher inhalation dose and health risks for adults (Yadav & Jamal, 2018). But also more indirect effects have great impacts on society such as the effect of noise and vibration which can lead to irreversible consequences (Aleksandrova & Timofeeva, 2021).

These negative environmental and social impact ensures that mining has a bad image across many countries. This changing societal acceptance of resource extraction operations and increasing pressures on industry performance is called Social License to Operate (Moffat et al., 2016). This can act, for example, as a potential bottleneck in the process of increasing domestic production in the EU (Mancini & Sala, 2018).

2.1.4 Regulatory landscape

Due to the importance of CRMs and the issues related to them mentioned above, reliable and unhindered access to certain raw materials is a growing concern within the EU and across the globe. Therefore, various policies have been announced in the regulatory landscape which often aim to increase strategic autonomy.

As the first list of CRMs was already introduced in 2011, various initiatives have been established since then. One of these initiatives is the EIT RawMaterials. The EIT (European Institute of Innovation & Technology) Raw Materials project IRTC ("International Round Table on Materials Criticality") was established, bringing together international experts in round table dialogues to tackle the questions surrounding methodology, application, and future development of raw material criticality assessments (Schrijvers et al., 2020). More currently, this has led to the Critical Raw Materials Act (CRMA) which addresses challenges faced by the EU in the strategic sectors of decarbonisation, digitalisation, aerospace and defence (Hool et al., 2023). The CRMA is part of a broader plan including the Green Industrial Plan and the Net Zero Industry Act (Hool et al., 2023). The CRMA aims to strengthen all stages of the European value chain of critical raw materials by diversifying EU import to reduce strategic dependencies, improving the EU's ability to monitor and mitigate the risks of disruption to the supply of critical raw materials, and improving circularity and durability (Ursache, 2023). This act by the European Union (2024), mentioned the defence sector various times to be one of the strategic sectors for which CRMs are an indispensable input.

Also in other countries, various policies have been set in place. In the UK this policy is called the UK Critical Minerals Strategy, which aims to improve the security of the supply of critical minerals (U.K. Department for Business and Trade & U.K. Department for Business, Energy & Industrial Strategy, 2023). Also to the U.S., it is essential for their economic prosperity and national defence to secure the supply of critical minerals, for which they have introduced the A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals (U.S. Department of Commerce, 2018). Important to note is that over the years many more regulations and organisations have been dealing with CRMs, but the most important ones were discussed.

2.2 NdFeB magnets

Permanent magnets play an essential role in modern society as they are included in many energy-efficient appliances such as hybrid and electric vehicles and wind turbines but also in consumer products (McCallum et al., 2014). One of these permanent magnets is the neodymium-iron-boron (NdFeB) magnet which was developed in the 1980s when the lanthanum terbium-iron-boron (LaTbFeB) alloy was discovered to have special properties (Du & Graedel, 2011).

Since the invention of NdFeB magnets in 1983, they have evolved into indispensable components, playing an essential role in today's society (Jin et al., 2016, 2018). Over the years they have replaced other types of magnets in the many applications of modern products that require strong permanent magnets (Shewane et al., 2014). By the 1990s, rare earth magnets such as NdFeB magnets were cheap and plentiful but due to the rapid escalation of demand for hybrid electric cars and wind-powered electric generators the use of these magnets ignited (McCallum et al., 2014). Nowadays, NdFeB magnets account for two-thirds of the permanent magnet market for which a compound annual growth rate of 9.5% from 2021 to 2026 is forecasted (J. W. Heim & Van der Wal, 2023; Kaya, 2024).

Examples of these markets are for example electronics which encompasses a broad range of products such as computers, CDs, DVDs, hard drives and cell phones (J. W. Heim & Van der Wal, 2023). For the transportation sector, they are also crucial since electric vehicles and e-bicycles contain these permanent magnets in their motors as mentioned by Heim & Van der Wal (2023). Another significant industry is the medical industry in which these magnets are used for example in MRI devices (Huang et al., 2019). But also to transition to a greener society they are crucial as they are included in green technologies such as wind turbines. An overview of the global demand per sector is provided below in Figure 3.

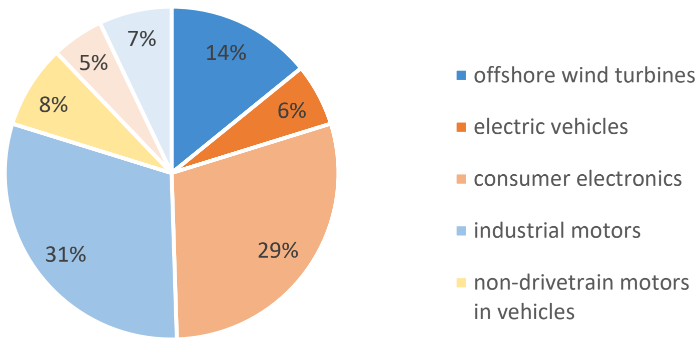

Figure 3 - Global demand for NdFeB magnets per end-use sector (Smith et al., 2022)

To provide more information on NdFeB magnets, first, the properties and structure will be discussed followed by an elaboration on their supply chain analysis.

2.2.1 Properties and Structure

NdFeB magnets (also known as Neodymium or Neo magnets) are made from an alloy of neodymium, iron and boron to form the Nd2Fe14B tetragonal crystalline structure (Shewane et al., 2014). An example of a NdFeB magnet is provided in Figure 4.

Figure 4 - NdFeB magnet (Shewane et al., 2014)

Properties

As mentioned by Kaya (2024), these magnets have more significant advantages than other ferrite and Sm-Co magnets. The study of Harris & Jewell (2012) compared different kinds of permanent magnets showing the excellence of NdFeB magnets in high maximum energy product, high saturation magnetisation and high coercivity. The first is noted by Coey (2002) as these magnets have the remarkable ability to deliver magnetic flux into the air gap of a magnetic circuit without requiring continuous energy expenditure. This characteristic makes NdFeB magnets highly efficient in various applications, providing power-to-weight advantages (McCallum et al., 2014). In addition, NdFeB magnets can be used to invent a new method of energy generation by using the magnetic field of a magnet and converting the magnetic energy into kinetic energy without using any kind of fuel and overcoming the energy generation problem such as building a magnetic turbine (Shewane et al., 2014). The high saturation magnetisation relates to the maximum amount of magnetisation a material can achieve when subjected to an external magnetic field. NdFeB magnets offer the strongest magnetic field per unit which is two-and-a-half times that of the competitor magnet which is made from Samarium-Cobalt (Jin et al., 2018; Powell-Turner & Antill, 2017). The latter, coercivity, indicates the ability of a magnet to withstand demagnetisation under the influence of an externally applied field (Harris & Jewell, 2012). However, the curie temperature of NdFeB magnets is poor. Therefore, for applications at which the magnets are exposed to elevated temperatures, the magnets usually contain significant levels of Dy (Harris & Jewell, 2012).

Other highlights of the NdFeB magnets are related to them having a compact structure, lightweight and small size (Calin & Helerea, 2011). The magnets vary in size, from under 1 gram in small consumer electronics such as mobile phones to around 1 kilogram in electric vehicles, and can reach sizes as large as 1000-2000 kilograms in the generators of modern wind turbines or MRI scanners (Schulze & Buchert, 2016; Yang et al., 2017). In addition, although the rare earth elements in the magnet are very expensive in comparison to other permanent magnets the main constituent is iron, which is significantly cheaper than cobalt which is used in Samarium-Cobalt magnets (Powell-Turner & Antill, 2017; Shewane et al., 2014).

Structure

As the name suggests, the structure of NdFeB magnets consists of Neodymium, Iron and Boron. To obtain high remanence and maximum energy product Nd atoms are coupled with ferromagnetic Fe atoms. The element B is added to this which consists of 1% of the magnet to have a stable magnet. However, the typical composition consists of more than just these three elements.

The properties and structure of a magnet can be tailored to suit specific applications through production methods and compositional adjustments. The two types of NdFeB magnets are sintered and bonded magnets. As mentioned by (Horikawa et al., 2021) sintered magnets are produced using powder metallurgy techniques to achieve anisotropic and fully dense sintered magnets resulting in a high maximum energy product. In contrast, bonded magnets have a lower maximum energy product but have the advantage of obtaining nearly net-shaped products which are created by blending Nd-Fe-B magnet powders, often produced through techniques of melt-spinning (Horikawa et al., 2021).

The magnets can be altered by adding or substituting elements to improve conditions of the magnets such as the temperature stability and the coercivity. This leads to different compositions of the NdFeB magnets. For example, Kaya (2024) described the typical composition as 60–70% Fe, 20–30% Nd, 0.5–7% Pr, 0.2–6% Dy, 0.3–1% B, 0.1–0.9% Al, and 0.4–3% Co. Whereas Heim & Van der Wal (2023) described NdFeB magnets to also contain praseodymium (Pr) and the occasional inclusion of terbium (Tb). The level of Dy differs as the temperature stability increases if significant amounts of Nd are substituted by Dy (Velicescu et al., 1996). However, this results in a substantial increase in the cost of the magnet as Dy is more scarce than Nd (Brown et al., 2002). Therefore, in applications where the NdFeB-type magnets are subject to high temperatures the magnets contain notable amounts of Dy

(Harris & Jewell, 2012). In addition, the partial substitution of Nd by Dy can also increase the intrinsic coercivity considerably (Harris & Jewell, 2012). To improve coercive stability at elevated temperatures sometimes Tb and Pr are also added, which allows for better magnetic properties (J. W. Heim & Van der Wal, 2023; Morimoto et al., 2016; Schulze & Buchert, 2016). Lastly, very small amounts of Cu, Co and O also improve the coercivity, high-temperature capabilities and corrosion resistance without reduction of remanence as mentioned by Kim & Camp (1996).

2.2.2 Supply Chain Analysis

In 2020, the worldwide demand for NdFeB magnets was 119 000 tons which is expected to grow to 387 000 tons by 2030 and over 750 000 tons by 2050 in the scenario of net zero carbon emissions (U.S. Department of Commerce, 2022). By Ormerod et al. (2023) the NdFeB magnet market is even expected to grow to 450 000 tons in 2030 and is projected to increase even further by 2050. Whereas Schulze & Buchert (2016) predict the demand to grow even higher in the high-demand scenario which was calculated upon the expected growth of the industries with NdFeB applications. Either way, the NdFeB magnet market is expected to grow tremendously. Which is mostly related to the popularity of the technology in green technologies.

Currently, the estimated in-use stock of NdFeB magnet is estimated to be 97.1 gigagram (Du & Graedel, 2011). This stock is located in the end-use sector of NdFeB magnets which are among others off-shore wind turbines, electric vehicles, consumer electronics and industrial motors (J. W. Heim & Van der Wal, 2023). These are both for the civil and defence sectors. About 5% of this demand stems from the defence sector (U.S. Department of Commerce, 2022). The expected life spans of the product in which they are located vary between 20 years for wind turbines, 15 years for household appliances and 10 years for computers (Du & Graedel, 2011). However, the substantial majority are in the wind turbines which have not yet reached the end of life.

The production of NdFeB magnets was researched by Yang et al. (2017), which showed that in 2015 China produced over 80% of all these magnets. Japan had a share of about 10%, the U.S. 3% and Europe 1% (Yang et al., 2017). Producers in China are Tengye and Ningbo Yunsheng (Ningbo Yungsheng, n.d.; Tengye, 2021b). In Japan an example of a company is Shin-Etsu. They produce high-quality NdFeB magnets that offer the highest performance in all applications (Shin-Etsu, n.d.). Noveon, is the sole domestic producer of NdFeB in the U.S. and supplies high-performance magnets for, for example, the needs of the Department of Defence (Noveon, n.d.-b). In Europe, more specifically in Germany, a producer is Vacuumschmelze (n.d.).

When examining the supply chain, not only is it important to determine who the producers are but it is also important who supplies the raw materials. To produce NdFeB magnets, depending on the required composition of the magnet various raw materials are needed such as Boron, Cobalt, Dysprosium, Terbium, Neodymium, Praseodymium. All these elements involved in the production of NdFeB magnets are currently deemed as critical by the EU which poses challenges to sustaining the increasing demand. Boron and Cobalt are deemed as ‘regular CRMs’. Dysprosium and terbium are categorised as HREE’s while Neodymium and Praseodymium are classified as LREE’s. Both kinds of REE’s are currently considered among the most important materials in both the U.S. and E.U. due to their significant economic value and supply risks as mentioned by Kaya (2024). NdFeB magnets utilise a significant share of rare earths with 30% of the total rare earth mine output being used for the production of permanent magnets (Schmid, 2019).

The dominance of countries in the extraction and processing of the CRMs involved in the production of NdFeB magnets currently lies outside of the EU. Boron is mostly mined and processed in Turkey, Cobalt is mainly extracted in the Democratic Republic of Congo but is mostly processed in China where also dysprosium, terbium, neodymium and praseodymium are extracted and processed (Grohol & Veeh, 2023). In Figure 5, an overview is provided.

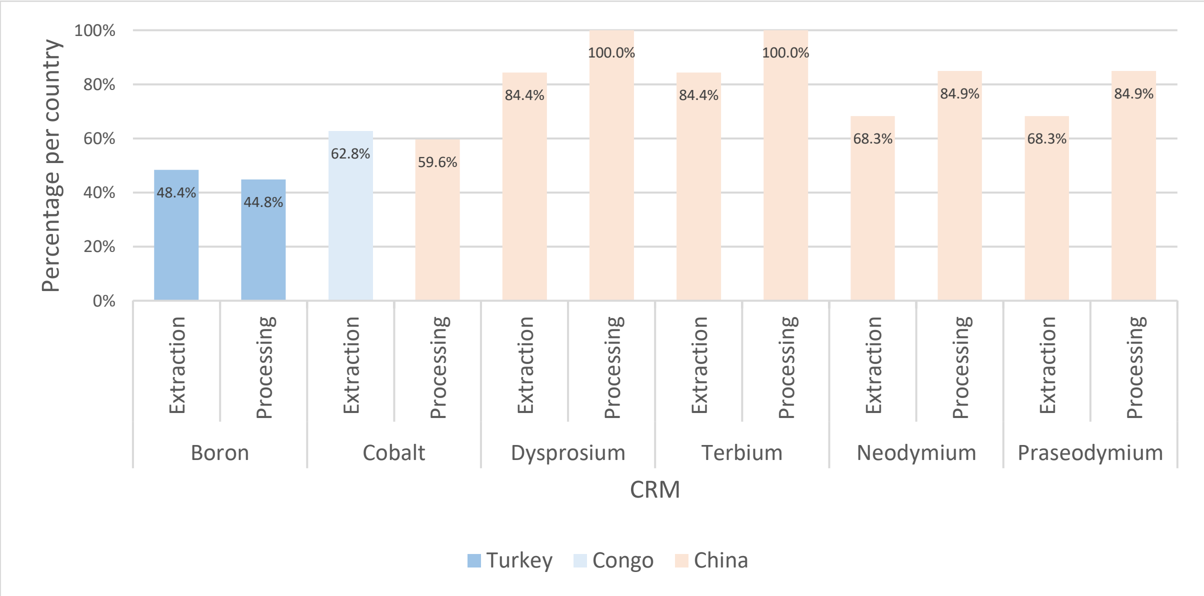

Figure 5 - Overview of extraction and processing per country per CRM included in NdFeB magnets

As seen in Figure 5, the countries with the highest share of extraction and processing per CRM are all located outside of the EU. The most dominant role is played by China which has been that way since 1990 (Du & Graedel, 2011). This dominance leads to conflicts between producers and users (Du & Graedel, 2011). In 2009, China announced export restrictions on Eu, Tb and Dy which spurred the EU, Japan and the US to question their dependence on a single supplier for these materials (McCallum et al., 2014). Also, the announcement of the export restriction of REE in 2010 caused troubles in the global economy since prices increased as much as 850 per cent (Mancheri, 2015). Such events should only be considered for China but for any dependence on a single supplier. So in this case, also for Boron and Cobalt, such events should be taken into consideration.

Next to the geopolitical considerations, it is also important to keep in mind the environmental and social challenges associated with the extraction and processing of CRMs needed for the production of NdFeB magnets. These issues related to CRMs are highlighted in Chapter 2.1.3.

03

Conceptual framework

3. Conceptual framework

The conceptual framework that forms a basis for this research will be elaborated upon in this Chapter. The framework will serve as a lens to collect, organise and analyse data during the research process. It will offer a theoretical grounding, which will allow one to navigate through complexity and ambiguity while maintaining coherence and rigour in the explanation.

In literature, there are many frameworks and concepts that promote the idea of the circular economy. One of these concepts is the 3R framework which encompasses strategies for Reduce, Reuse and Recycle. Another example to evaluate and measure circularity is the cradle-to-cradle approach which is based on the principle that resources should never be turned into waste but should be kept in the loop as long as possible minimising waste and maintaining quality (Pomponi & Moncaster, 2017). However, these concepts often do not capture the complete set of possibilities applicable to promote circularity to its fullest. This is also emphasised by Khaw-ngern et al. (2021) by highlighting that more nuanced hierarchies with shorter loop options enable the highest possible value retention of resources. This was established by combining the most common perspectives on R-imperatives into a single systematic typology (Khaw-ngern et al., 2021). Therefore the conceptual framework used in this study is based on the 9R framework of Potting et al. (2017). Which is also known as the 10R Strategy (Rahman et al., 2021).

This 9R framework consists of 10 possible strategies to handle materials circularly. These strategies are also called the hierarchy of resource value retention options which stem from circular economy literature and practice fundamental principles (Reike et al., 2022). There is disagreement in literature on the exact terminology and ranking of the R strategies. Reike et al. (2022) follows the strategies of Refuse, Reduce, Resell/Reuse, Repair, Refurbish, Remanufacture, Repurpose/Rethink, Recycle, Recover, Remine. They have added Remine while combining the terminology of Repurpose and Rethink, putting Rethink much lower than some other studies. In addition, some leave out steps such as Khaw-ngern et al. (2021), which did not acknowledge the strategy of Recovery as it was considered not substantially contributing to the circular economy.

In this research, the list presented in the research of Potting et al. (2017) will be used as a starting point. However, it is adjusted to fit the research of exploring circular strategies to reduce dependency on CRMs in NdFeB magnets. Therefore the definitions of strategies were redefined to fit this specific case. The definitions used in this research are presented in Figure 6.

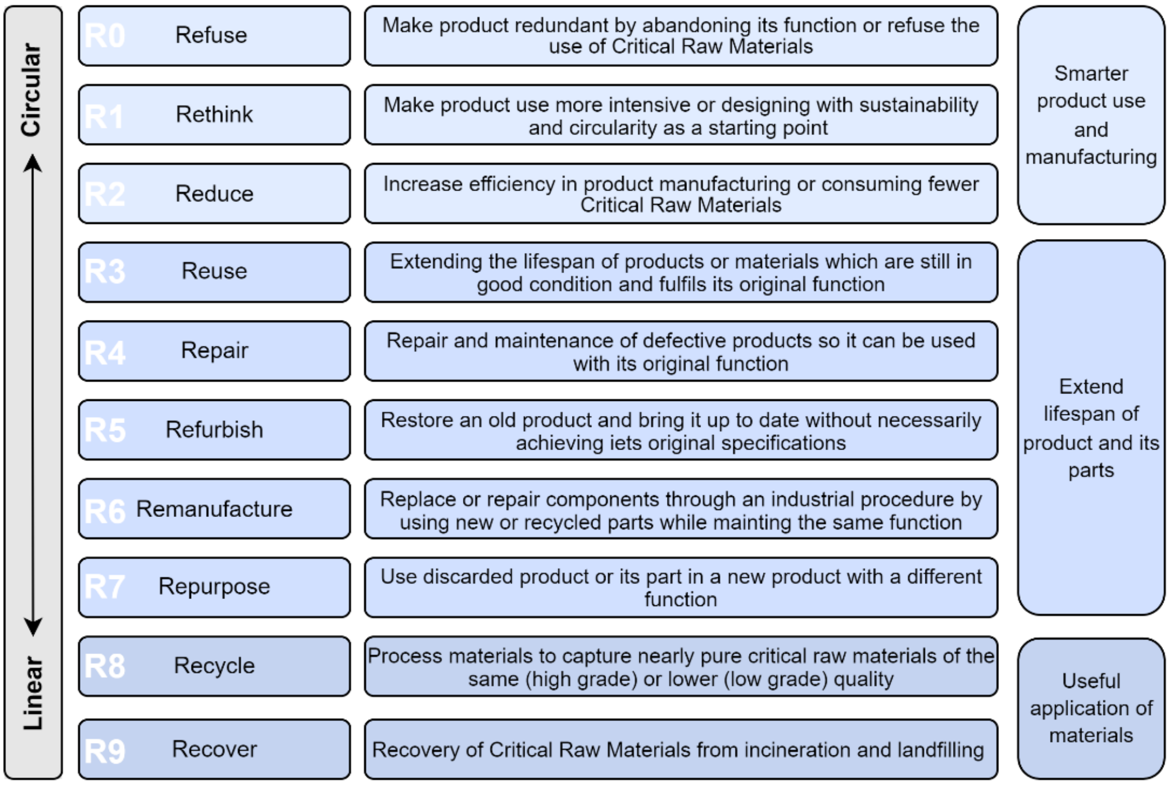

Figure 6 - 10R strategies for Circular Economy adjusted from Potting et al. (2017)

As seen in the Figure above the R strategies: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover can be divided into three categories. Namely, in smarter product use and manufacture (R0-R2), extend lifespan of product and its parts (R3-R7) and useful application of materials (R8-R9). Which can be assessed as most circular R0 to least circular and therefore more linear R9.

Smarter product use and manufacture starts with Refusing (R0) which is about making the product redundant by abandoning its function or by offering the same function with a radically different product (Potting et al., 2017). This is used in the context of the consumer and the producer (Reike et al., 2022). For consumers, this entails the choice to buy less or use less (Vermeulen et al., 2019). For producers, or more specifically, for designers, this implies that they can refuse specific hazardous materials or more broadly, any primary material (Reike et al., 2018). In this case, these primary materials relate to CRMs as these are deemed critical in supply in combination with negative environmental impacts. Rethink (R1) refers to both making the product use more intensive and reconceptualisation of ideas, dynamics, processes, concepts, uses and post-uses of a product (Morseletto, 2020). In other words, designing or redesigning a product or component with sustainability and circularity as a starting point (Jonker et al., 2022). This can be established by making the product use more intensive by for example sharing products (Potting et al., 2017). Similarly, it can propose new ideas and solutions to provide certain product functions by tracing back to the strategy of the product (Morseletto, 2020). The main goal of Reduce (R2) is to use fewer natural resources and therefore use fewer inputs of energy, raw materials and waste (Morseletto, 2020). Which in this research is especially focused on the lesser use of CRMs by efficient product manufacturing and consumption. This relates to consumers by purchasing less, using them longer and with more care and repairs (Reike et al., 2022). More commonly, it is linked to producers as they can include this strategy in the design of their products. They can ensure better use of materials during the design and manufacturing level as mentioned by Rahman et al. (2021). This definition can be extended to reducing the number of products and can thus be linked to Reuse (Morseletto, 2020).

The second category, the extension of the lifespan of the product and its parts begins with Reusing (R3). The practice of extending the lifespan of products or materials by using them again which are still in good condition and fulfils its original function is referred to as the strategy of Reuse (Potting et al., 2017). This helps to minimise waste generation and resource consumption by keeping products and materials in use for as long as possible. By consumers this is done via buying second-hand or finding a buyer for a product that was not or barely in use (Reike et al., 2022). At this step some minor alterations such as cleaning or minor adaptions for quality restoration by the consumer are applicable but no refurbishment or repair is involved here (Reike et al., 2022). Also by collectors and retailers this reuse can be applied. In this context quality inspections, cleaning and minor repairs are common (Reike et al., 2018). Repair (R4) refers to the refers to the maintenance of the defective product so it can be used within its original function to prolong the lifetime of the product (Morseletto, 2020; Potting et al., 2017; Reike et al., 2022). The reparation can be done by different actors with or without changing ownership (Reike et al., 2022). So the repair can take place in any location including repair companies. Refurbishment (R5) is about restoring an old product and bringing it up to date without necessarily disassembling it to its core components. It may not always achieve its original specifications but will regenerate its original functionality (Morseletto, 2020; Zink et al., 2014). Remanufacturing (R6) involves disassembling, inspecting, cleaning and if needed replacing or repairing every component through an industrial procedure (Reike et al., 2022). It maintains the original function of the product in the same application while containing new components and reprocessed parts (Gaustad et al., 2018). These new components can consist out of new parts and recycled parts (Reike et al., 2022). The quality of the remanufactured product should be equivalent to the quality of a new product (Morseletto, 2020). The use of a discarded product or its parts in a new product with a different function is defined as the strategy of Repurpose (R7) (Potting et al., 2017). It differs from the other strategies in this group as it requires a completely different function (Morseletto, 2020). The difficulty of the strategy lies within the creativity of the one to repurpose and the small scale at which this takes place (Morseletto, 2020).

Lastly, the useful application of materials applies to the strategies of Recycle and Recovery. These are also seen as long loops as they implicate more traditional ways of waste management activities (Reike et al., 2022). The processing of materials to obtain the same of lower quality is defined as Recycle (R8). It entails the processing of materials from mixed waste streams to capture nearly pure materials (Reike et al., 2022). These pure materials can either have the same or lower quality (Morseletto, 2020). Usually in this strategy, expensive technological equipment is used including shredding, melting and other processes (Vermeulen et al., 2019). As mentioned by Reike et al. (2018), these recycled materials have difficulty competing with primary materials as they can be collected from waste containing various quality levels which also coincides with low value for these materials. In the recycle process a high-energy input is typically required (Reike et al., 2018). Therefore, targets should be set to measure the potential environmental impact reduction from recycled vs primary materials (Morseletto, 2020). The last, most linear strategy is Recover (R9). This can be recovery of energy via incineration of material but is sometimes also described as collecting used products at the end of life or the extraction of elements or materials from end-of-life composites (Reike et al., 2022). Here only the recovery of CRMs will be examined. Which can be done both after incineration and landfilling. Landfill mining is generally defined as the strategy of Re-mine. However, since it also involves regaining something it is included in the strategy of Recovery as it is usually forgotten or ignored in literature (Reike et al., 2018).

To conclude, in this research, these R strategies will provide a structured approach to define possible circular strategies.

04

Methodology

4. Methodology

This Chapter is dedicated to elaborate on the different research methods used in every stage of the research to increase reproducibility. An overview is provided in Appendix 9.1.

This research is qualitative as it analyses data from real-world settings inductively to identify patterns and themes (Patton, 2005). Although this research could also perform some quantitative analyses, the choice was made to enter it with a qualitative view due to the lack of quantitative data relating to the secrecy of the defence sector. The research questions will be answered via the output of the three sub-questions mentioned in Chapter 1. The research flow diagram is presented below in Figure 7.

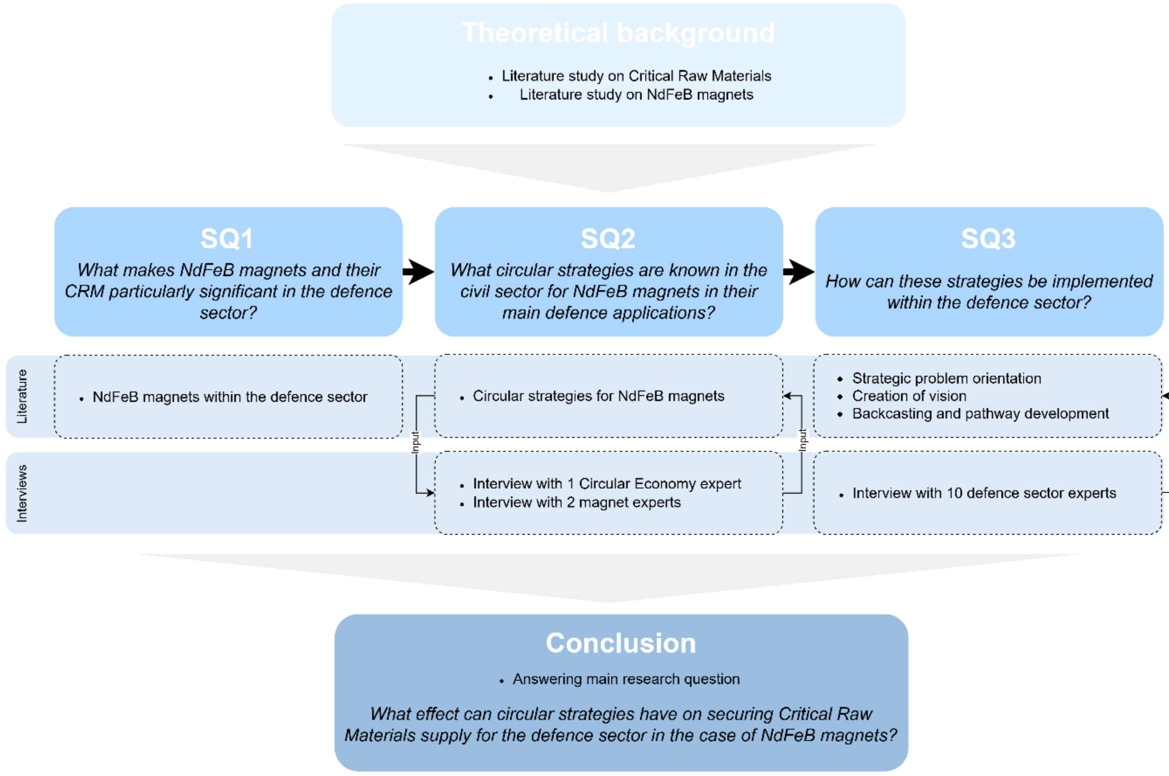

Figure 7 - Research Flow Diagram

4.1 Data collection methods

In this research, triangulation is used to counterbalance the deficiency of a single strategy and thereby better interpret findings (Thurmond, 2001). A combination of scientific literature, grey literature and interviews was used.

4.1.1 Secondary data collection

The secondary data of this research consists both of scientific literature and grey literature. For all sub-questions keywords were selected, which can be found in Table 1.

Table 1 - Literature review keywords

Sub question	Selection Questions	Keywords
SQ1 What makes NdFeB magnets and their CRMs particularly significant in the defence sector?	What are the properties and structure of NdFeB magnets?	*'Structure' 'Properties' 'Curie temperature' 'Magnetism' 'Characteristics' 'Coercivity' 'Composition' 'Remanence'*

	What are the applications in defence?*	*'Defence/ military /army applications' 'Defence/ military/ army equipment' 'Dual-use technologies'*
	What does the supply chain look like for NdFeB magnets?	*'Demand forecast/ analysis' 'Stock' 'Inventory levels' 'Processing' 'Extraction' 'Supply chain' 'Environmental implications' 'Social implications' 'Geopolitical considerations' 'Regulation'*
SQ2 What circular strategies are known in the civil sector for NdFeB magnets in their main defence applications?	What is known in literature on circular strategies?*	*'Refuse' 'Rethink' 'Reduce' 'Reuse' 'Repair' 'Refurbish' 'Remanufacture' 'Repurpose' 'Recycle' 'Recovery' 'Circular strategies' 'Circularity' 'Circular Economy'*
SQ3 How can these strategies be implemented in the defence sector?	What is the proposed vision and future scenarios?*	*'Critical raw materials act' 'objective EU' 'Mega trends' 'Geopolitics' 'Future regulation' '*
	What stakeholders are involved?*	*'Business' 'NdFeB magnet producers' 'Defence application manufacturer' 'Public sector' 'Industry organisation 'Long-term interest' 'Resources' 'Academia'*

**= questions for which information is both found in scientific and grey literature.*

As seen in Table 1, for all three sub-questions scientific literature was utilised. The literature search for scientific literature was mostly performed via Google Scholar in some cases there was searched directly on websites such as ScienceDirect. In addition, snowball sampling was used by evaluating reference lists of scientific literature to examine any other relevant sources. When selecting literature the geographical representativeness and data age were taken into account. The geographical representativeness was aimed to represent EU countries within NATO but also other geographies were examined to not exclude important information. Idem for the data age, the objective was to examine as much as possible the newest scientific literature available. However, in some cases, it was better to include examples from history hence why it ranges to 1928.

Grey literature was also used in all three sub-questions but to a lesser extent. It is consulted in cases where no information was available in the scientific literature. This was mostly the case with specific information about the defence. For example when looking for the applications within defence in which the NdFeB magnets are located. Sites used to find defence-related information are those of institutional, governmental and industrial websites such as those of the EDA, NATO, EIT, Department of Defence, defence application manufacturers etc.

4.1.2 Primary data collection

As some information was not available via secondary data and to get more in-depth knowledge, interviews with experts from multiple areas were held. In addition, literature might not capture the most recent situation of the matter. The interviews are particularly useful when detailed insights are required from individual participants (Gill et al., 2008). Which is required as some information was not available in literature due to many documents related to defence being confidential. Below, in Table 2, a list of interviewees based on their expertise can be found.

Table 2 - List of interviewees

Area of expertise	Applicable to sub-question:	Reference
Circular Economy	2 + 3	Circular Economy specialist [a]
Magnet	2 + 3	Assistant Professor in Materials Science and Engineering [b]
	2 + 3	Assistant Professor in Materials Science and Engineering [c]
Ministry of Defence	3	Senior Military Officer Maintenance & Logistics [d]
	3	Former Employee at Defence for Environment & Energy Resilience [e]
	3	Former Senior Military Officer Maintenance & Logistics [f]
	3	Senior Military Officer for Technical Documents [g]
Industry organisation	3	Advisor Sustainability, Environment and Safety [h]
	3	Senior Member of an international military organisation on Climate and Security [i]
Academia related to defence	3	Strategic Analyst at a not-for-profit research organisation [j]
	3	Strategic Analyst at a not-for-profit research organisation [k]
	3	Minerals and intelligence researcher [l]
Business related to defence	3	Former Employee at an aerospace manufacturer [m]

The participant selection was done on the basis of the expertise needed to fill gaps in the research. After establishing the expertise needed the network has been consulted by the researcher. The definition of expert entails the person having current or prior work experience within the field acquired. In case of no expert was available in the network Google, LinkedIn and the bibliography of this researches were checked and people were contacted. In addition, snowball sampling was used to ask the initial participants for recommended other contacts who fit the research criteria and who potentially might be willing to participate (Parker et al., 2019). In total 46 people were contacted, of which 13 were interviewed.

The interviews were conducted via a semi-structured approach to allow the interview or interviewee to diverge in order to pursue an idea or response in more detail (Gill et al., 2008). The list of questions per interview can be found in Appendix 9.2. At all interviews, a general introduction of the thesis was provided whereafter permission was asked to record it for transcription purposes. Interviewees were asked to what extent they wanted to take part in the research such as the level of anonymity in consensus with human research ethics (Nii & Ogbewe, 2023). In the end, they were asked for any final remarks and interviewees were thanked for their participation. The interviews lasted between 30 and 60 minutes.

4.2 Data analysis methods

4.2.1 Analysis of interviews

The interviews were transcribed and colour-coded. Colour coding was done by pre-defined categories such as for SQ2 the categories of *R0-R2, R2-7, R8-9, and Other*. And for SQ3 the categories of *Current state, Unique for defence, R0-R2, R2-7, R8-9, Stakeholders, Barriers general, Enablers and Other*. Relevant information was included in the report by referencing the interviewees by '*function [x]*', see Table 2. The interviews were also compared to each other to examine whether there was any contradictory information. This was not the case.

4.2.2 Analysis of results via backcasting method

To create the implementation plan for SQ3 the method of backcasting was applied with the basis of the research of Quist (2016). Backcasting is a planning methodology that is particularly helpful when problems at hand are complex and when present trends are part of the problems. This method generally consists of five steps of which three are included in this research, see Figure 8. The last steps were not performed due to time constraints. The data needed to complete the last step was collected from interviews.

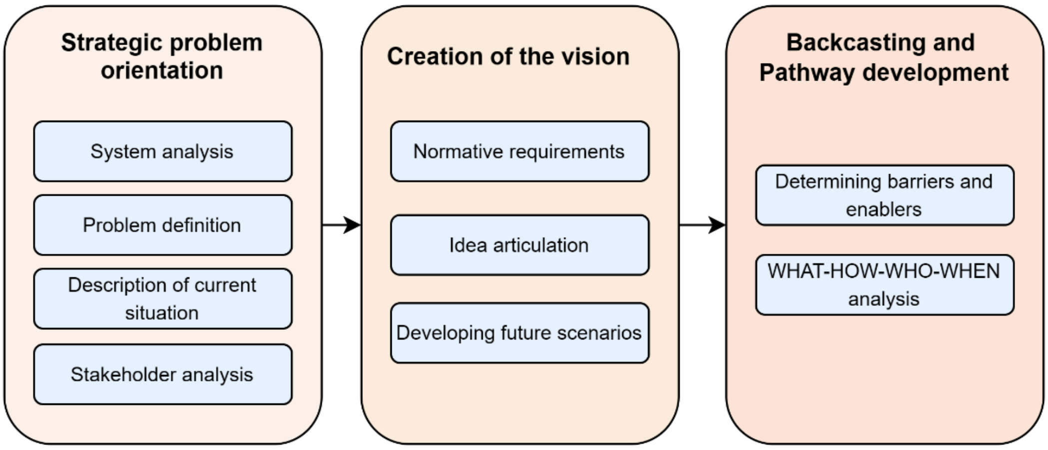

Figure 8 - Schematic overview of backcasting steps

4.3 Scope of study

The geographical scope of this study is the European Union countries that are members of NATO. This specific focus is due to the implications of NATO's collective defence mechanisms which influences individual countries. In addition, the focus of the EU has been added to simplify the consideration of which list to adhere to since the CRM lists differ per country/union. The temporal scope of this study is from February until the end of June, resulting in the defence of this research in early July. This scope has been pre-determined since the research is performed to complete the Master Industrial Ecology.

In addition, there are also other aspects determining the focus of this study. Firstly, although this study aims to reduce dependence on CRMs, it will only consider circular economy strategies. Meaning that strategies such as diversification or stockpiling will not be considered. In addition, the scope is dedicated to NdFeB magnets and the products they are located in. Lastly, the scope specifically involves steps in the value chain that involve manufacturing and usage phases, rather than mining.

4.4 Methodological limitations

During the research, some methodological limitations were encountered. Firstly, the research is limited to the geographical scope which is mentioned before. Therefore it may be limited in generalisability of the findings to other regions or sectors where conditions differ. In addition, throughout the research, it has been difficult to access detailed information due to the defence sector being characterised by a high level of secrecy.

The latter also relates to the limitations regarding the data collection method. Since it was difficult to obtain quantitative data it was chosen to perform interviews. During the selection of the respondents, it was difficult to figure out who has the specific niche knowledge needed and is also willing to share. While these interviews provide in-depth insights, they lack the generalisability that quantitative methods offer. In addition, also other methods such as focus groups were considered but due to the lack of time of respondents it was not possible to schedule this.

Overall, the study was done in a short time frame, which limited the number of respondents. This restriction may introduce subjective biases based on the perspectives of the few consulted experts. The short duration also constrains the ability to observe and measure the impact of implemented strategies over time. While in the meantime the landscape concerning CRMs is rapidly evolving which can outpace this research.

By acknowledging these methodological limitations, the findings can be interpreted accurately considering the scope within the conclusions are valid.

05

Results

5. Results

5.1 NdFeB magnets in the defence sector

NdFeB magnets play a significant role in motors and other devices, as mentioned in Chapter 2.2, making them crucial for both defence and civilian uses. This dual significance stems from NdFeB magnets being a key component in dual-use technologies. Dual-use technologies are technologies that can be used for both military and civilian purposes (Dunnicliff & Izewicz, 2015). The dual-use concept is advocated as the solution for maintaining a high-tech defence technology base and improving economic competitiveness through cooperation between civilian and military actors (Kulve & Smit, 2003). In the 20th century, this was the case for technologies in specific high-technology sectors such as the Internet and communication, aircraft, nuclear energy, semiconductors and earth observation systems as mentioned by Lee & Sohn (2017). Current examples of dual-use technologies include electric vehicles, drones and remotely piloted aircraft systems for which NdFeB magnets are key components (Gramatikov, 2017; Kumari & Sahu, 2023; C. C. Pavel & Tzimas, 2016). This highlights the important role of NdFeB magnets in civilian and military applications. Therefore, this chapter will address the sub-question: '*What makes NdFeB magnets and their CRMs particularly significant in the defence sector?*'.

Due to their exceptional strength and lightweight, NdFeB magnets are highly used in the defence sector (Grasso, 2013). The magnets are essential for defence applications as they require extremely compact designs which save weight and space (Mhango, 1989). For each defence application, a specially designed magnet on for example size, grades and performance characteristics is required (U.S. Department of Commerce, 2022). Therefore NdFeB magnets are a key component to specialised defence equipment such as military weapons systems (Tjaden, 2021). Other examples are aircraft, missiles and munitions which use the magnets in actuators that control the various surfaces during operation (U.S. Department of Commerce, 2022). An overview of the major applications and their subsystems in which NdFeB magnets are used in defence is provided in Table 3.

Table 3 - Products within defence containing NdFeB magnets

Type of product	Example product name	Sub-system	Relative weight	Dual use
Manned and unmanned aircraft	F-35 Joint Strike Fighter	Motors, generators and propulsion systems	High	Yes
	MQ-1 predator UAV			
	MQ-9 Reaper UAV			
	Drones			
Precision munition	Javelin missiles	Motors, guidance, control and propulsion systems	Moderate	No
	Excalibur Artillery Shell			
	Joint Direct Attack Munitions / Smart bombs / Guided Bomb Units			
	AMRAAM missiles			
Naval systems	Arleigh Burke Destroyer	Motors, propulsion systems and Radar and Sonar	High	Yes (partly)
	AEGIS Combat System			
Electronic devices	Portable computers	Receivers, motors and camera autofocus mechanisms	Low	Yes
	Speakers			
	HMMWV		High	Yes

Land-based vehicles	M1-A1 Abrams Tanks	Motors and navigation systems		

To provide more detail in Table 3, additional information is given for each type of product. For each product, the estimated weight is categorised as low, moderate, or high. As previously mentioned, NdFeB magnets are highly suitable for both military and civil applications (Sandurarajan et al., 2014). Therefore, it will also be indicated whether the technology is dual-use, allowing civil technologies to be considered if specific data for military applications is lacking.

Manned and unmanned aircraft

In both manned and unmanned aircraft, high efficiency and high rotational speed are required which can be delivered by an electric motor instead of an internal combustion engine (Sandurarajan et al., 2014). In this electric motor, the permanent magnets are located for which NdFeB magnets have the best performance over Sm-Co magnets as NdFeB magnets are smaller in size (Perrymam, 2006). For example, NdFeB magnets are part of the design of brushless DC motors as a very high output power-to-weight ratio and reasonably high efficiency are demanded (Mhango, 1989). The motor also must possess the capability to produce high torque even at low speeds to drive actuation systems such as movable flaps on aircraft wings and electric power generation systems as mentioned by Sandurarajan et al. (2014). In manned aircraft such as the F-22 fighter, miniaturised permanent magnet motors run its tail fins and rudder (Davey, 2012). For unmanned aircraft, they are used in electric engines for its electric propulsion (C. C. Pavel & Tzimas, 2016; Sandurarajan et al., 2014). But also smaller unmanned aircraft such as drones are now widely used in warfare such as the Ukraine-Russia war. Both military and commercial drones are used for their distinctive military effects such as an extension of air power or as ammunition (Kunertova, 2023). The weight of the NdFeB magnets in these applications depends on the weight of the application. A drone can weigh less than 10 kg whereas the weight limit of a specific aircraft can range from 10 886 kg to 360 000 kg (Bevilaqua, 2009; Kunertova, 2023; PilotInstitute, 2023). Although the exact weight of the NdFeB magnets in these applications is not publicly available, the amount of rare earth magnets in an F-35 Strike Fighter is said to be 420 kg (Fears, 2021). Since these magnets are used in fighter aircraft and commercial aeroplanes, this application can be examined as dual-use.

Precision munition

With precision munition, munition with the intent to precisely hit a specific target to minimise collateral damage and increase lethality against intended targets is meant. These guided missiles have for example been a major cause of aircraft destruction (Sonawane & Mahulikar, 2011). The types of missiles can vary a lot, examples of types are javelin missiles, artillery shells or smart bombs. In these precision munitions, NdFeB magnets are included in electric motors, guidance, control systems, actuators and amplifications (Y. Liu et al., 2019; C. C. Pavel & Tzimas, 2016). For example, in the actuators of BGM-109 Cruise missiles, the tail control is powered by NdFeB magnets (Sandurarajan et al., 2014). For smart bombs, also called precision-guided munition, the NdFeB magnet is used to control the drop direction and improve accuracy when dropped from an aircraft (Hedrick, 2004; Sandurarajan et al., 2014). To visualise the sub-systems in which the NdFeB magnets are located, Figure 9 is provided.

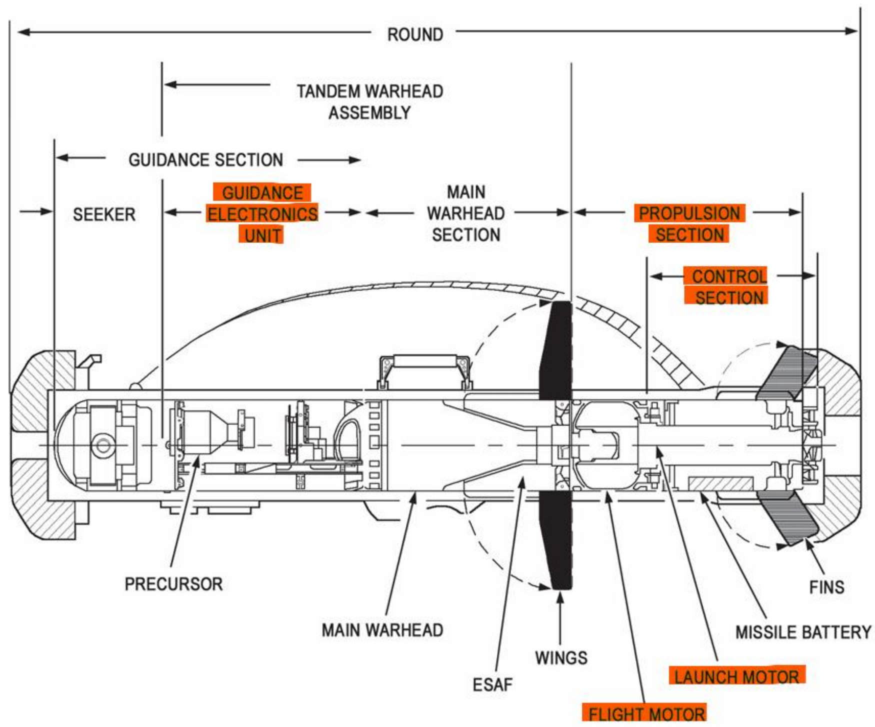

Figure 9 - Cutaway diagram of a javelin missile (U.S. Department of the Army, 2013)
The location of the NdFeB magnet is indicated in orange

The weight of NdFeB magnets used in this munition is heavily dependent on the size of the munition. As these precision munitions are much smaller than aircraft but much bigger than electronic devices, the weight is categorised as moderate. Since precision munitions are not used in the civil sector, this application is not considered dual-use.

Naval systems

In Naval systems, NdFeB magnets are used in various components of submarines. In the electric drive of the Arleigh Burke-class destroyers they are used to conserve fuel (Davey, 2012). To be more precise, the NdFeB magnet is located in the integrated motor-propeller which consists of a shrouded propeller around which the rotor of an electric motor is mounted (Gieras, 2008). But also in electromagnetic aircraft launch systems the magnets are essential due to the creation of a magnetic field (Gherman et al., 2018). Radar and sonar systems are used for collision prevention, surveillance and navigational assistance purposes, in which NdFeB magnets are also included (Kasinska, 2019). Using NdFeB magnets that provide a strong alternating magnetic field with low power consumption is ideal to analyse dynamic magnetometer data to provide object identification (Ezequelle, 2020). Also for this product, the relative weight is high due to the size of the application. Although radar and sonar systems are less popular in commercial ships, naval systems are considered to be partially dual-use as permanent magnets can bring significant space and weight savings in electric propulsion drives of ships (Rosu et al., 1998).

Electronic devices

NdFeB magnets are also key in the operations and research of the military due to their importance in advanced computer programs and disk drives (Tjaden, 2021). These computers which are used in many defence systems such as in aircraft, tanks, missile systems and command and control centres, are designed to withstand vibration, impact and g-forces (Hedrick, 2004). Their importance lies in the miniaturisation of these devices (Leich et al., 2020). Also in speakers and other sound system components NdFeB magnets are included which are important for psychological warfare (Hedrick, 2004). As mentioned by Hedrick (2004), they are used for decoy invasions for staging sounds of ships, tanks, helicopters and voices to distract attention from actual landing forces to come ashore miles away.

But also for helicopters, they are significant due to the creation of white noise that cancels or hides the sound of the rotor blades (Hedrick, 2004). The volume of the magnets within these applications is relatively low. The average weight of NdFeB magnets in hard disk drives in computers for data storage ranges between 2 and 20 grams (München et al., 2021). For mobile phones, this ranges from 0.4 to 1.3 grams (München et al., 2021). As electronic devices such as computers, speakers and phones are also used in the civil sector, this application is deemed dual-use.

Land-based vehicles

Within defence, hybrid electric vehicles are becoming more desirable due to features such as minimising fuel use while also meeting war demands in terms of mobility, survivability and lethality (Khalil, 2009). Therefore, NdFeB magnets can be utilised with high coercivity and thermal stability as they are suitable due to the low required volume, leading to high energy density and low moment of inertia (Sandurarajan et al., 2014). Also in other parts of these vehicles, they are included. For example, in the M1-A2 Abrams battle tank, the army relies on REE magnets for navigation systems (Davey, 2012). The weight of the magnets is relatively high as a typical EV carries between 2.5kg and 10kg of NdFeB magnet contingent upon its design. Whereas a tank is usually around 30 times as heavy as a regular electric vehicle. This application is examined to be dual-use due to the wide application of NdFeB magnets in commercial vehicles.

Not only in current applications NdFeB magnets are important but also in future development in defence technologies they will have an increasing importance. Without the magnets certain products would not have or not rapidly have been developed. They are seen as an enabler and drivers of technology (Croat & Ormerod, 2022). In addition, the demand for many raw materials for defence technologies is increasing while the defence sector works actively on making their militaries faster and more efficient with fewer fossil fuels (C. C. Pavel & Tzimas, 2016; Powell-Turner & Antill, 2017). Therefore, the use of neodymium will continue to grow in the coming decades due to its importance for electric drive systems (Powell-Turner & Antill, 2017).

A visualisation of the relation between defence applications, NdFeB magnets and CRMs, is provided in Figure 10.

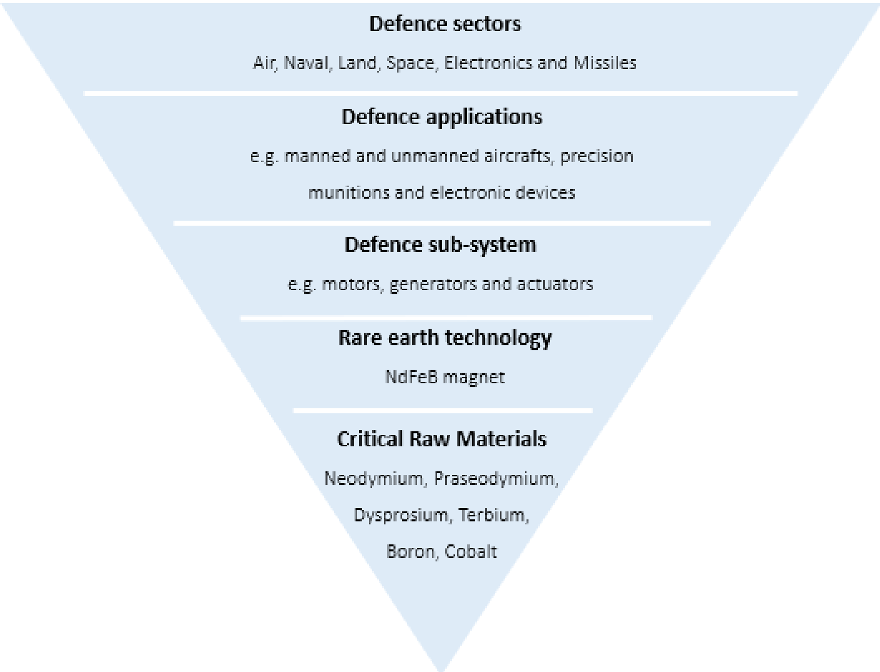

Figure 10 - Visualisation of the relation between defence applications, NdFeB magnets and Critical Raw Materials. Inspired by (C. C. Pavel & Tzimas, 2016).

5.2 Circular strategies for NdFeB magnets

As a reaction to supply uncertainties and growing markets for NdFeB magnets through 2050, producers and users of NdFeB magnets and components are making efforts to research substitution and reduction possibilities (Ormerod et al., 2023; Schulze & Buchert, 2016). McGuiness et al. (2015) also highlighted substitution options such as the development of permanent magnets with little or no rare-earth content but also mentioned options such as increased recycling of devices containing rare earths. Powell-Turner & Antill (2015) pointed out that defence equipment needs to be designed to be as adaptable as possible to enable future agility and ensure a more resilient outcome. This can be done via sustainable solutions for equipment throughout its entire life cycle (Powell-Turner & Antill, 2015). Whereas Gaustad et al. (2018) mitigated critical material demand by applying circular economy practices such as reuse, remanufacture and recycling. Therefore this chapter is dedicated to answering sub-question two: '*What circular strategies are known in the civil sector for NdFeB magnets in their main defence applications?*'.

The strategies will be discussed per value retention strategy based on the conceptual framework discussed in Chapter 3. For each of these strategies, specific examples will be provided of how they can be applied to NdFeB magnets and the products in which they are located. The examples given for each strategy will not be an exhaustive list but only an indication of if and how the strategy can be applied. The provided examples will largely come from the civil sector with a focus on the dual-use NdFeB magnet holding products defined in Table 3 in Chapter 5.1. These will be manned and unmanned aircraft, naval systems, electronic devices and electric vehicles. But in case relevant, also other examples will be elaborated upon.

To paint a picture of how the strategies affect the life cycle of a magnet, Figure 11 was created.

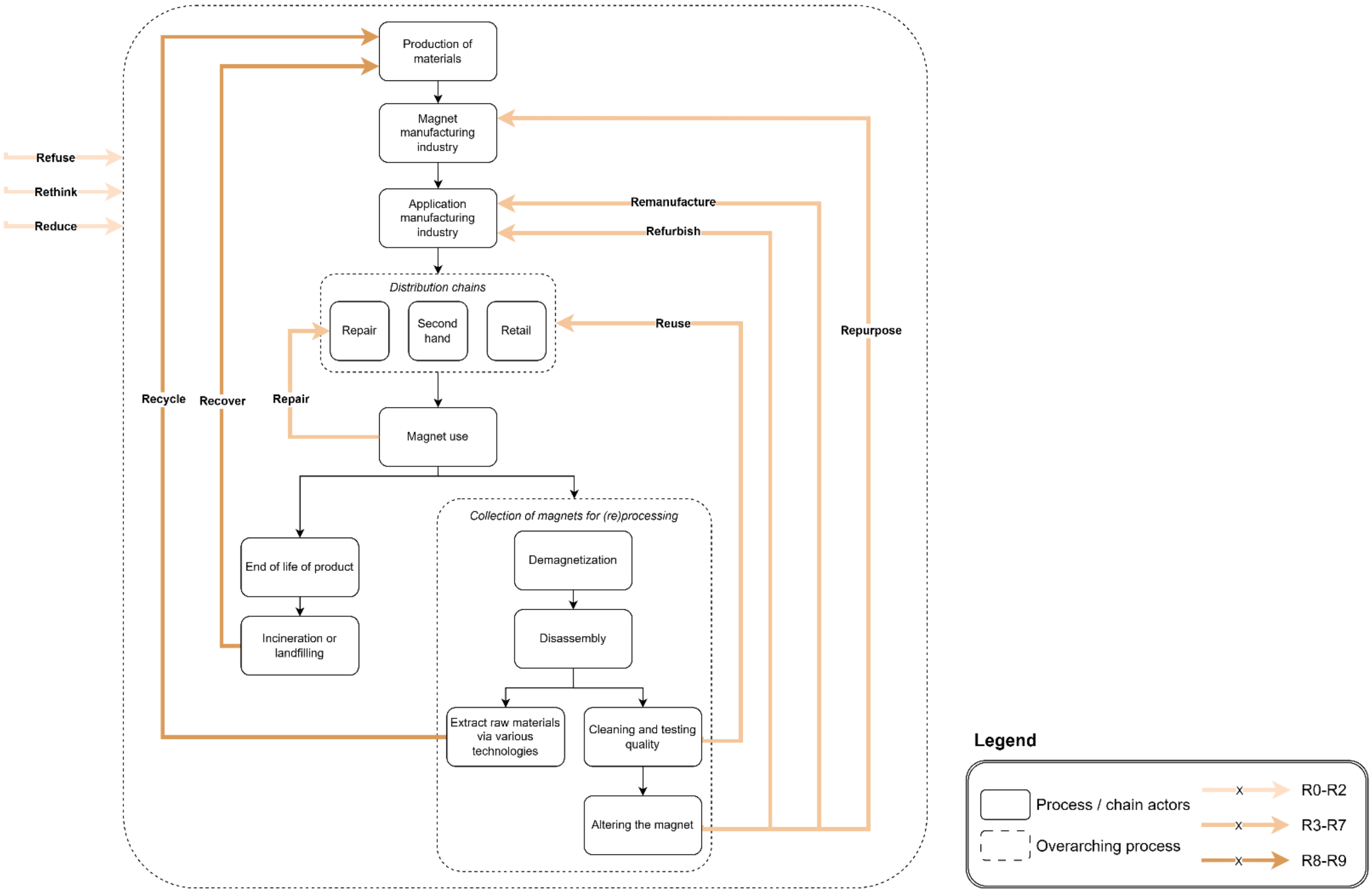

Figure 11 - Flow diagram of R strategies applied to the lifecycle of magnets

Before diving deeper into each strategy, it is important to address some challenges that may be encountered with each approach. Due to these challenges, the strategies are rarely implemented in practice, even though, in theory, all strategies could be applied to the magnet and its applications (Assistant Professor in Materials Science and Engineering [b], 2024). However, for all of these challenges solutions are available, see Table 4.

Table 4 - Challenges related to the extension of the lifespan

Challenge	Specific	Measures to overcome challenge
Identification	Presence and location unknown	Standardisation, Transparency
Deterioration	Hidden internal defects (microcracks, porosities, inclusions)	Ultrasonic testing
Disassembly and dismantling	Magnetism > safety Time Costs	Design for disassembly, modularity
Composition	Size, shape, impurities	Lego design
Pace of development	New design concepts	Standardisation

Firstly, it is difficult to identify which products contain NdFeB magnets (Assistant Professor in Materials Science and Engineering [b], 2024). After identification, other challenges come into play which are related to deterioration, disassembly and dismantling, composition and pace of development.

To determine whether any deterioration took place, the magnets need to be qualified as defect-free which is one of the biggest challenges in the reuse of magnets as mentioned by Ormerod et al. (2023). Even if materials seem flawless externally, hidden internal defects may exist which can cause magnets to fracture or perform an uneven surface magnetic flux leading to undesirable signals or motions in applications (Cui et al., 2023). To avoid this, the presence of internal defects such as microcracks, porosities and inclusions can be detected by ultrasonic testing (Cui et al., 2023). After testing, the products with no malfunctions can be returned for reuse purposes, and the products with minor functional issues due to some broken components can be sent back to the manufacturing step to be for example repaired or remanufactured (Habib, 2019).

Manual disassembly allows in principle for all magnetic material to be recovered (Sprecher et al., 2014). However, in the disassembly and dismantling process, some difficulties arise. The disassembly can make the process significantly longer and perhaps more costly (Li et al., 2019). The main difficulty lies in the magnets being magnetised which can cause dangerous situations when handling them. Handling these magnets is quite a specialist task and improper handling poses risks (Assistant Professor in Materials Science and Engineering [b], 2024). The disassembly of electrical motors and generator however is already state of the art as currently copper and steel are already extracted which makes the process already profitable without the recovery of magnets (Elwert et al., 2016). Also, other techniques are developed to make the process much quicker such as the dismantling technique developed by the Hitachi group (Baba et al., 2013). They developed a way to recover the magnets by loosening the screws through impact and vibrations after which they can reuse the NdFeB magnets hidden in Hard Disk Drives (Tanaka et al., 2013).

The composition of the magnet differs per application in size and grade. When you buy a magnet, you don't buy a specific composition but a grade of the magnet (Assistant Professor in Materials Science and Engineering [b], 2024). Therefore, the choices of manufacturers in the ratios of various elements could dictate what strategy you would use (Assistant Professor in Materials Science and Engineering [b], 2024). In addition, it is important to keep in mind the shape of the magnet, most strategies are more feasible for large, easily accessible magnets such as those from electric motors and generators (Högberg et al., 2017). However, electronic devices such as HDDs offer the benefit of being available in larger quantities than newer applications containing NdFeB magnets and could therefore also serve as a secondary source (Schulze & Buchert, 2016). As a result, NdFeB magnets can be reused in the next batch of similar types of products after meeting the performance criteria of the new products (Habib, 2019). Next to the size, the shape of the magnet can also act as a challenge as it might need additional machining steps to fit in the new design (Li et al., 2019). When extending the lifespan one would also have to deal with impurities such as glue residues (Li et al., 2019). The removal such as glue residues may act as a difficulty related to costs and not compromising the dimensions of the magnet (Elwert et al., 2016). For both the challenge of size and impurities, a 'Lego' design could be used which entails a solid-shaped magnet pole that can be continuously divided into smaller and standardised segments and is free from any glue for easy extraction (Li et al., 2019).

Lastly, the pace of development may also pose a barrier. Elwert et al. (2016) mentioned that the life extension of magnets in new generations of electric motors might not be realistic due to the progress of development of both the magnets and electric motors. After the life span of a certain product such as a wind turbine, which lasts 20, we need to consider if the same size and shape is required as the design might have changed (Assistant Professor in Materials Science and Engineering [c], 2024). Therefore, standardisation of modular designs should be considered at the stage of design thinking as it could have a huge potential to enable easy and cheap routes of reusing (Li et al., 2019).

An important enabler is that generally, the NdFeB magnet remains undamaged (Assistant Professor in Materials Science and Engineering [b], 2024). They may lose some properties if they are mechanically damaged or exposed to too high temperatures (Assistant Professor in Materials Science and Engineering [b], 2024). However, in most cases, NdFeB magnets are one of the components that remain in perfect condition when a product reaches its end of life.

5.2.1 Smarter product use and manufacture (R0-R2)

All three strategies, Refuse, Rethink and Reduce can influence multiple steps in the life cycle of the magnet. Therefore they act as three overarching strategies that can affect the whole, see Figure 11.

R0 – Refuse

In scientific literature, ongoing efforts have been made to develop permanent magnets without CRMs, especially without the use of rare earth elements (Chen et al., 2012; McGuiness et al., 2015; Molla et al., 2020). In addition, it is also a key topic in policymaking for which projects such as Replacement and Original Magnet Engineering Options are introduced (McGuiness et al., 2015). One of the goals of this project is to develop a rare-earth-free magnet to reduce Europe's dependence on Chinese imports (CORDIS, 2019). Also in practice, companies have been making efforts to not use these CRMs. One such example is Niron Magnetics, which is commercialising a high-performance rare earth-free permanent magnet called Iron Nitride, FeN. In collaboration with the University of Minnesota and funded by ARPA-E, this technology emerged as a substitute for several grades of NdFeB magnets (ARPA-E, n.d.; University of Minnesota, 2022). The magnet from Niron Magnetics does have lower coercivities but they have higher remanences, exhibit superior temperature stability up to operating temperatures of 200 °C and are less costly (Niron Magnetics, n.d.; U.S. Department of Commerce, 2022). This lower coercivity is also noted in scientific literature. Kumar et al. (2023) mention that the FeN magnets are more susceptible to demagnetisation at extreme temperatures compared to NdFeB magnets due to their lower coercivity and higher knee point of the BH curve. Therefore, the FeN magnet is said to substitute NdFeB magnets in applications that require large magnetic flux density but are not heavily loaded, specifically those that are exposed to demagnetisation fields greater than approximately half the remanence (U.S. Department of Commerce, 2022). Eventually, this leads to high-performance permanent magnets that are low-cost, minimise environmental impact and are secure in supply (Niron Magnetics, n.d.). Examples for which these FeN magnets are suitable are consumer, automotive and other commercial & industrial applications including electric vehicle drivetrains and e-mobility applications. Next to Niron Magnetics, the use of FeN magnets has also been investigated by Molla et al. (2020). They say FeN magnets can solve the problem of not using rare earths but still achieving high performance (Molla et al., 2020). In addition, the literature also mentions the applicability of FeN magnets for applications such as speaker magnets, hard disk drives, electrical motors, smartphone audio devices and other power generation machines (Wang, 2020).

Next to replacing the magnet with a rare-earth-free magnet, one can also alter the design in such a way that no magnet is needed at all. This is demonstrated by Turntide Technologies, which manufactures motors using switched reluctance motors that do not use NdFeB magnets (U.S. Department of Commerce, 2022). They allow for the simplest mechanical design to be free from permanent magnets (Turntide, 2022). Also for other applications, they investigate design without the need for magnets such as for Hard Disk Drives. These are currently being replaced by solid-state drives which do not use REE permanent magnets as they do not store data magnetically (Ormerod et al., 2023).

Many more examples exist for which effort goes out to options for designs without rare earths or magnets. An overview of motors is provided by Pavel et al. (2016) in which they discuss types free from rare earths and/or magnets. Next to the switched reluctance motor they also mention transversal flux motor, asynchronous motor, externally excited synchronous motor, asynchronous motor with high rpm and permanent synchronous motor with low-cost magnets to be free of rare earths (C. Pavel et al., 2017). Evidently, by refusing the technologies containing NdFeB magnets, the dependency on CRMs could be significantly lower.

More broadly, the concept of degrowth advocates a reduction in overall consumption and production levels which is also in line with the concept of refuse. Degrowth leads to reduced resource and energy use which arose in response to the increased metabolism of the society which causes more conflicts on resource extraction and waste disposal (Martínez-Alier, 2012). Therefore, some products or even industries can become redundant in a degrowth-oriented society such as the fashion and marketing industry (Nesterova, 2020). But also applications containing NdFeB magnets can be regarded as redundant and can thus be refused by society. For example the air transportation industry. Although this industry has been finding ways to make it more sustainable such as via biofuels, it will never lead to a strong core environmentally sustainable industry. Therefore, questions need to be asked on the purpose of the industry whether it justifies the social and environmental costs and how the benefits and costs are distributed geographically, temporally and socially (Köves & Bajmócy, 2022). This emerging way of thinking could accelerate the refusal of NdFeB magnets. Something to be kept strongly in mind when considering this perspective is that it deviates from the requirement of profit maximisation and therefore it is difficult to make degrowth compliant to profit-maximising firms (Nesterova, 2020).

R1 – Rethink

The way of reasoning in the concept of post-growth aligns with the strategy of Rethink. Here they argue the central idea of product design should become the principle of durability and related to this the principle of repairability (Nesterova, 2020). The inclusion of durability should replace the current practice of durability minimisation in pursuit of profit and should eventually minimise waste (Nesterova, 2020). In addition, prolonging a product its lifetime is an important tool to minimise negative environmental consequences (P. B. Jensen et al., 2021). This durability and longevity can argued to be just a technical fix but challenges lie in the uncertainty of new standards, lack of design frameworks and volatile consumer behaviour (P. B. Jensen et al., 2021). The idea is to shift away from the throwaway society and move to one that is centred around the longevity of products. But also rethinking the design in order to better recycle the product should be included in the rethinking process.

Take the case of mobile phones, Jensen et al. (2021) pointed out that the average lifetime of a mobile phone is around three years while the optimal lifetime is almost seven years. The display and battery are the most vulnerable parts of the phone and mostly limit the phone its lifetime while other parts are produced with a much higher environmental impact (Schischke et al., 2019). The enhancement of the longevity and recyclability of mobile phones, and thus the minimisation of environmental impacts, can therefore be achieved by durable or modular designs. The first improves the design of the lifetime-limiting components and the latter enables easy replacement of them (Schischke et al., 2019). Before, NdFeB magnets were mostly located in the speaker of the phones but now they have evolved from a phone containing only one magnet to containing 14 small NdFeB magnets (Stein et al., 2022). The main components they are in, next to speakers, are receivers, autofocus motors for smartphone cameras and vibration motors (Hochberger, 2018). As these components are mostly not perceived as lifetime-limiting components, this design for modularity would lead to a decrease in the demand for NdFeB magnets. But also in cars this can be beneficial as they contain around 40 magnets in small motors and actuators and 20 in sensors, each of these NdFeB magnets weighs around 250 g which is an annual use of 22 000 ton (Shaw, 2012).

Next to repairability, design for recyclability is also significantly important since the amount and quality of the REEs in the resulting material mixture are very low and their recovery may require a long sequence of separation processes (Zakotnik et al., 2016). Currently, these permanent magnets are not retrieved as the car is not pre-dismantled before shredding and are thus lost to ferrous or nonferrous scrap which is similar to the process of consumer electronics (Yang et al., 2017). Thus far, the willingness to dismantle the NdFeB magnet-containing components is subject to the market value (Yang et al., 2017). This challenge can be overcome by implementing design for recycling strategies to recover critical raw materials more easily (Buchert et al., 2012). In addition, it is often not known in what products NdFeB magnets are located, what the exact location is and the composition (Assistant Professor in Materials Science and Engineering [b], 2024; Assistant Professor in Materials Science and Engineering [c], 2024). Digital Product Passports could pose as a solution for this (Assistant Professor in Materials Science and Engineering [b], 2024). They provide full transparency along the value chain by allowing the identification of materials used and the potential for reusing existing materials (Adisorn et al., 2021). In addition, data can also be provided on for example usage, maintenance and environmental implications as mentioned by Jensen et al. (2023). This leads to a comprehensive overview of applications containing NdFeB magnets which simplifies the recycling process and enhances the recovery of high-quality metals to ensure good standards for input back into the market (Zakotnik et al., 2016).

Next to the design of the product being rethought, the ownership can be reconsidered. Such as by extended producer responsibility. This can take place in various forms. One of them is the individual take-back where each individual manufacturer is responsible for collecting its product after end-of-life and also maintains complete control of its product as it can decide upon a profit-maximising strategy such as remanufacturing which potentially eases the source for critical materials (Gaustad et al., 2018). In cases where the manufacturer remains the owner, designs are favoured in which repair, component reuse and material recycling are possible (Potting et al., 2017). A concrete example of this is a product service system (PSS). A PSS is defined by Manzini et al. (2001) as a business innovation strategy that adds value and reduces environmental impacts compared to current systems or products by offering a product as a service which is capable of fulfilling a client's needs and/or wants. A disadvantage to this kind of business model is for example the misbehaviour of consumers due to them not owning the product. However, when using a PSS, fewer products are needed due to product life extension which will result in a lower demand for NdFeB magnets.

R2 – Reduce

In practice, 75% of the industry executives acknowledged that CRMs should be handled by resource efficiency (Gaustad et al., 2018). Therefore, much effort needs to go into reducing CRMs in NdFeB magnets through efficient production. Currently, some producers use a higher grade and bigger size of magnets than required due to it being cost-effective at the time (Assistant Professor in Materials Science and Engineering [b], 2024). Therefore incentives should be set in place for companies to reduce their NdFeB magnet demand.

Much literature is dedicated to whether the composition of NdFeB magnets can be changed without compromising its performance such as on Dy. This element has been added to NdFeB magnets to improve coercivity and thermal stability (Z. Liu et al., 2012). Together with Tb, they are two of the most critical raw materials identified by the European Commission (McGuiness et al., 2015). Therefore, current research investigates whether they can be decreased or substituted by another material. A reduction in Dy can lead to a higher risk of demagnetisation as this element contributes to the remanence, coercivity and thermal stability of the magnet (Vaimann et al., 2013). However, if Dy is replaced by a similar material, no risk of demagnetisation should occur (Vaimann et al., 2013). Therefore, Dy can be partially substituted by Nd in the grain boundary diffusion process as mentioned by McGuiness et al. (2015). Next to Nd, Dy can also be replaced by Y (yttrium) which results in great remanence, energy product and thermal stability capabilities (Z. Liu et al., 2012; Vaimann et al., 2013). An alternative approach would be altering the main elements of the magnet. For example, using didymium as one of the main elements of the magnet leads to it being a didymium-iron-boron magnet. As didymium is a mixture of REE such as Nd, Pr, Dy and Tb this would also not lower dependency on CRMs. In addition, one could also choose to use another permanent magnet containing REEs such as a Sm-Co magnet (King & Eggert, 2022). This magnet usually contains, as the name suggests, the CRMs samarium and cobalt. To conclude, these efforts towards reducing the use of CRMs in NdFeB magnets while maintaining the same performance metrics, only shift the dependency from one CRM to another.

Next to the less use of materials, a producer could examine less waste. Producers could employ the target of less waste in the form of reducing scrap that arises from the production of NdFeB magnets (Morseletto, 2020). Scrap is said to be the automatic consequence of the economies of scale in material production by Allwood (2014). For the car industry, 30% of all materials are converted into scrap and for the manufacturing of an aeroplane in the aerospace industry this percentage is a booming 90-95% (Allwood, 2014). Also in the production of NdFeB magnets during the shaping and finishing alone, around 15-30% of the raw materials are wasted (Kumari et al., 2018). Many researchers already explored possibilities of extracting REEs from NdFeB magnet scrap (J. W. Lyman & G. R. Palmer, 1993; Xu et al., 2000). Although this scrap can be recycled, it is important to employ the reduction strategies firstly as such is more environmentally friendly than recycling. It would be beneficial if efforts were made to minimise the scrap that occurred during the production process. This can be done via two approaches. The first is the collaboration between designers of products and processes which will uncover substantial opportunities for material saving (Allwood, 2014). As producers have to grind and cut the magnet to fit into the size and shape criteria demanded by the end-use product manufacturers (Habib, 2019). Secondly, improvements in production techniques might facilitate more efficient use of materials which reduces the scrap generated in the production process (Allwood, 2014).

5.2.2 Extend lifespan of product and its parts (R3-R7)

For all strategies relating to the extension of the lifespan of the product and its parts, the challenges mentioned before should kept strongly into consideration. In addition, important to note are the possibilities on both component and product levels.

R3 – Reuse

After technical inspection, one can decide to directly reuse NdFeB magnets in a similar to the previous end-use product (Habib, 2019). This direct reuse entails the assembly and disassembly of magnets after the end of the life of the machine and the reuse of them in other applications (Upadhayay et al., 2018). An important advantage of this strategy, is the magnetic properties of the reused magnets are unchanged when directly reusing them in contrast to them being recycled where in some recycling technologies performance is lost (Högberg et al., 2017). Additionally, during the process of reusing the magnets such as the step of disassembly, no magnetic properties are compromised (Elwert et al., 2016). Over time it could be possible that the magnetic properties of NdFeB magnets gradually decrease with each cycle of reuse due to oxidation and contamination (Benke et al., 2017).

Some researchers have explored the direct reuse of NdFeB magnets, especially for motors in electric vehicles (Elwert et al., 2016; Upadhayay et al., 2018). In these cases, the NdFeB magnets are extracted before shredding the car by dismantling the motor to the rotor/stator or electric drive level (Elwert et al., 2016; Klier et al., 2013). However, it has been noted that reusing these NdFeB magnets in new generations of electric motors is unrealistic due to the rapid pace of technological development (Elwert et al., 2016). Furthermore, Klier et al. (2013) stated that the use of these magnets in secondary markets as second-life magnets needs further investigation. In smaller equipment, such as electric home appliances, it is proven to be a simple and cost-effective strategy (K. Lee et al., 2013). The process could be accomplished by demagnetising NdFeB magnets followed by re-magnetising them for direct reuse (K. Lee et al., 2013).

However, Ormerod et al. (2023) mentioned that extraction of the magnets from end-of-life products for reuse has not received enough attention due to it being labour-intensive and expensive. Generally, this strategy is said to be only applicable to large easily accessible magnets such as wind turbines, large electric motors and generations from hybrid and electric vehicles (Binnemans et al., 2013). Which are until this day not available in large quantities in scrap today (Binnemans et al., 2013). Despite these challenges, reusing has the potential to be economically and environmentally most beneficial compared to the other lifespan extension strategies, due to the low demand for energy and other operating materials and the lack of waste generation (Binnemans et al., 2013; Elwert et al., 2016).

An alternative way to stimulate the reuse of NdFeB magnets is the reuse of the entire application. One way to stimulate the reuse of products is via PSSs. Which entails an actor owning a subject that contracts them to different users (Morseletto, 2020). This strategy has already been elaborated upon in the strategy of Rethink. It will contribute to the strategy of reuse as it increases the longevity of a product. Therefore targets could be set which aim to increase the number of products falling into the PSS category (Morseletto, 2020).

R4 – Repair

Repair and maintenance are already applied to maximise efficiency and reduce waste in some industries (Ayeni et al., 2016). An example is the Maintenance Repair and Overhaul used in the aviation industry. For NdFeB magnets, this can also be applied. To improve the corrosion resistance of NdFeB magnets, protective coatings are added such as polymeric, metallic, including composite and conversion coatings (Maizelis & Bairachniy, 2019). Such a protective layer is also added in practice to other products. For electrodes, the lifetime could be increased by a factor of 5 when the coating is renewed in time (Shao et al., 2015). This could also be performed at NdFeB magnets by sending the magnets for repair, where their protective coating can be renewed (Habib, 2019). Habib (2019) also mentioned that the magnets can be re-magnetised by reparation to achieve satisfactory functional properties. Important to note is that the challenges for disassembly are also valid here since the application needs to be disassembled in order to repair the magnet.

Next to the reparation of the magnet, the application in which they are located can be repaired. This could be of significant value as the magnet itself usually does not damage or lose performance (Assistant Professor in Materials Science and Engineering [b], 2024). Therefore its lifetime could be extended via periodic repair to the NdFeB magnet holding application.

R5 – Refurbish

The literature does not mention how an NdFeB magnet can be refurbished. It is mentioned that refurbished magnets may not exhibit the same performance as that of a primary magnets (Kumari et al., 2018). Yang et al. (2017) state that reuse can take place after refurbishing. Chowdhury et al. (2024) elaborate upon the magnets in electric vehicles and turbines being suitable for refurbishment whereafter they can be repurposed. However, since NdFeB magnets either retain their performance or need to undergo an industrial process, refurbishment does not apply to the magnet.

It would be applicable at the product level. Currently, this is already done with, for example, cell phones and HDDs. For the latter, they can be refurbished by the manufacturer or a third party leading to them not having the same warranty as before (Simon et al., 2018). This could be expanded to other NdFeB magnet-holding applications.

R6 – Remanufacture

Since the magnet cannot be broken down into smaller components without compromising its performance. However, Habib (2019) argued that the melting of the magnets which are then made into new magnets followed by magnetisation can also be defined as remanufacturing. In this research, melting is included in the strategy of Recycle, based on the research of Vermeulen et al. (2019).

In addition, as mentioned before, the magnet is the component that generally remains undamaged (Assistant Professor in Materials Science and Engineering [b], 2024). Therefore, the remanufacturing strategy is, in practice, only relevant to the product level. This is demonstrated by Liu et al. (2017) where they maximise the use of resources and reduce energy consumption by remanufacturing electric motors. Also, here the before-mentioned challenges arise which relate to different designs. Increased manufacturing costs and reduced efficiency arise due to different designs of structures and iron cores which lead to different degrees of wear and different operating conditions (R. Liu et al., 2017).

R7 – Repurpose

In the case of magnet repurposing, this can be applied to DIY projects such as creating magnetic knife racks which it is said to extend the useful life and reduce waste (Crabb, 2023). Or they can be repurposed by going from a functional use in a product to experimental use. This is already done for used NdFeB magnets (Amazing Magnets, n.d.). A NdFeB magnet previously used in for example an electric vehicle and now used in consumer electronics with lower requirements is also defined as repurposing. This utilises the magnet in a role that it was not originally designed to perform (M. Schulz et al., 2020).

When deciding to repurpose, it is crucial to keep in mind what the new function of the product will be. If NdFeB magnets and thus CRMs would be integrated into products that might be deemed unnecessary, it can be questioned whether this is the appropriate use for the CRMs. Therefore it needs to be assessed whether another strategy would be more suitable.

5.2.3 Useful application of materials (R8-R9)

Also in these strategies, some challenges appear. These relate to the magnetic powers, impurities such as glue and corrosion and difficulty in access. Since more attention has gone to the strategy of recycling, this strategy will be highlighted in more detail.

R8 – Recycle

Recycling can be applied to NdFeB magnets in various ways such as via waste-to-alloy, hydro-metallurgical, pyro-metallurgical, melting, gas-phase extraction, and magnet-to-magnet approaches (M. Heim et al., 2023; Zakotnik et al., 2016). But also other processes exist such as selective precipitation, glass slag methods and solvent extraction, as mentioned by Hoogerstraete et al. (2014). However, currently, less than 1% of rare earths discarded undergo recycling (Du & Graedel, 2011).

Elaborating on some recycling processes, the hydrometallurgical process includes the extraction of specific elements from crushed and roasted NdFeB magnets using minimal acid, followed by purification through solvent extraction and precipitation into pure oxalate salts (Hoogerstraete et al., 2014). The extracted materials can also be used for the production of other applications outside of NdFeB magnets (Nlebedim & King, 2018). The process involves energy-intensive processing steps and large quantities of chemicals and waters (Burkhardt et al., 2023). An alternative to this approach is pyrometallurgy which requires less water, creates less waste but also has a high energy consumption (Burkhardt et al., 2023). A recycling approach which requires much less energy is magnet-to-magnet recycling which is also known as Hydrogen Processing of Magnetic Scrap (Burkhardt et al., 2023). When using Hydrogen Decrepitation in the recycling process, the magnets are converted to a powder due to the expansion of the material on hydrogen absorption (Zakotnik et al., 2006).

These recycling processes are more environmentally friendly compared to primary production, for example in the magnet-to-magnet recycling approach energy consumption is reduced by more than 45% (Zakotnik et al., 2016). Another research showed an emission saving of 11 tons of CO2 per ton of recycled magnet manufactured (Zakotnik et al., 2016). Recycling can also contribute to less toxicity for humans and freshwater ecosystems by 60-70% and less water use by 70% (Burkhardt et al., 2023). It also significantly minimises the dependency on raw materials. However, the dependency on raw materials is not entirely accounted for since for some recycling methods the recycled magnet production requires primary rare earth material, which is usually less than 5% of the starting material (Jin et al., 2018). Another important factor in recycling technologies is the performance of the recycled magnet. In literature, some disagreement revolves around the influence of the process on the performance. In the research of Elwert et al. (2016), they conducted experiments with production scrap which showed that 3% of remanence is lost in comparison to primary magnets. In magnet-to-magnet recycling, Jin et al. (2018) mention that recycled magnets offer stronger magnetic performance and better microstructure than primary magnets. This was also tested by Prosperi et al. (2018) by comparing recycled to conventionally NdFeB magnets in electric motors. The performance of the recycled magnet displayed improved magnetic and physical properties (Prosperi et al., 2018). Therefore it can be concluded that the performance of the recycled magnet is dependent on the recycle technology used.

Although it was argued by Elwert et al. (2016) that no industrial recycling for permanent magnets is present in Western countries and Hoogerstraete et al. (2014) mentioned that magnet producers mainly only recycle their production scrap, in practice the recycling of magnets is already performed. Currently, the recycling of NdFeB magnets is already done by companies such as Noveon which is located in the U.S. (Noveon, n.d.-a). Additionally, projects are set up by the European Union to develop a recycling supply chain for rare earth magnets within the EU (SUSMAGPRO, n.d.-a). In this project, they also employ magnet-to-magnet recycling for which they plan to establish four pilots (SUSMAGPRO, n.d.-b).

R9 – Recover

Currently, energy recovery is mostly done for organic waste such as municipal waste to substitute fossil fuels for power generation (Allwood, 2014). In this process, the waste is incinerated releasing heat which is used to produce electricity. However, the incineration of electronic devices, among which the NdFeB magnets are located, releases toxic pollutants, volatile organic compounds, poisonous gases and metallic emissions (Stewart & Lemieux, 2003). In addition, when incinerating the waste, the NdFeB magnets will lose their magnetic force and will become demagnetised permanently if it is heated above its Curie temperature (Haavisto, 2013). Since the average temperature of an incineration process is above 850°C and the Curie Temperature of NdFeB magnets is usually between 60-400 °C depending on the application, this will be detrimental for the magnets (Arkenbout, 2020; Haavisto, 2013). This is because the intense molecular heat movement destroys the regularity of the direction of the electronic motion which makes the magnetism of the magnet disappear (Reddy et al., 1999). Eventually, the magnet will melt and vaporise if the magnet is heated even more. This leads to the CRMs ending up in bottom ash, for which the concentration levels are considered too low to make their recovery economically feasible (Morf et al., 2013). This will lead to the loss of valuable materials which contributes to the depletion of natural resources.

Next to incineration, products holding NdFeB magnets also end up in landfilling. This is also shown by the recycling rates, which is less than 1% for REEs, showing poor circularity for CRMs (Gutiérrez-Gutiérrez et al., 2015). Therefore resource recovery from end-of-life products has become a subject exposed to more interest in recent years (Morf et al., 2013). In the EU in 2010 of the total 1230 tons of Nd flows used for NdFeB magnets, 597 tons have been reported into waste streams of which 207 tons went into landfill (Yang et al., 2017). Therefore, landfill mining where deposited materials are excavated, processed, treated and/or recycled may pose a possibility of recovering materials (Krook et al., 2012). However, also here disadvantages occur related to environmental and safety issues such as excessive leachate generation, accidental fire, air pollution, slope instability and respiratory problems for workers (Jain et al., 2023). Impact assessments should be held before landfill mining takes place to find out whether the advantages balance out the disadvantages.

To summarise all the strategies explained above, Table 5 was developed.

Table 5 - Summary of all circular strategies

Strategy	Possible Solution	Example
R0 – Refuse	Magnets without CRMs	REE free magnet: FeN
	Applications without magnets	SSD instead of HDD Switch reluctance motor
	Degrowth	Refusing entire industries
R1 – Rethink	Focus on durability and repairability	Modular design
	Design for recyclability	
	Adjusting ownership	Product Service System
R2 – Reduce	Efficient use	Closer regulation of size and grade used in product
	Diversion	Use of other permanent magnets with different supply countries
	Less waste	Collaboration between designers of products and processes Improvement in production techniques
R3 – Reuse	Direct reuse of magnet	-
	Reuse of product	-
R4 – Repair	Repair of magnet	Renew protective coating
	Repair product	Periodically repair
R5 – Refurbish	Refurbish product	Refurbished HDDs
R6 – Remanufacture	Remanufacture product	Remanufactured electric motors
R7 – Repurpose	Repurpose magnet	Experimental use Functional use
	Repurpose product	-
R8 – Recycle	Recycle to retrieve pure materials	Hydrometallurgy
	Recycle entire magnet	Magnet-to-magnet recycling
R9 – Recover	Landfill mining	Excavation of deposited materials

5.3 Implementation of Circular Strategies in Defence

This Chapter will elaborate upon how the circular strategies, defined in Chapter 5.2, can be incorporated into the defence sector. Grounded in the backcasting framework, this will be explained through a strategic problem orientation, the creation of a vision and the backcasting itself. To eventually figure out what is unique for the defence sector.

The sub-question that is dedicated to answering this is: '*How can these strategies be implemented in the defence sector?'.* To do this, a system analysis, problem definition and stakeholder analysis will be carried out in the strategic problem orientation. Whereafter the normative requirements, idea articulation and future scenarios will be defined. Lastly, the backcasting will exist out of the formulation of drivers and barriers and a what-how-who-when analysis.

5.3.1 Strategic problem orientation

The strategic problem orientation step includes a system analysis of relevant trends such as the moving geopolitical landscape and growing dependence on CRMs. This has already been touched upon in Chapters 2 and 5.1. This has led to a problem definition of CRMs being of high economic importance while being highly vulnerable to supply disruptions (European Commission, n.d.-c). The delineation of the system is that only the predetermined strategies would be considered with a geographic scope of EU countries in NATO.

To understand how these strategies can be implemented the current state of the system related to these strategies will be elaborated on. The emphasis and main priority within defence is operational effectiveness (Former Senior Military Officer Maintenance & Logistics [f], 2024; & Strategic Analyst at a not-for-profit research organisation [j], 2024). Therefore, defence is not yet very concerned with environmental sustainability alone but does however have an agenda to make defence more environmentally sustainable with specific steps (Senior Military Officer for Technical Documents [g], 2024; Advisor Sustainability, Environment and Safety [h], 2024). One of which is to move towards full circularity (Senior Member of an international military organisation on Climate and Security [i], 2024). This is partly because climate change is also leaving a mark on security and that mark is actually only going to get bigger and is going to become a determining factor, also in the work of military personnel (Senior Member of an international military organisation on Climate and Security [i], 2024). As the topic is fairly new and has not received attention for a very long time, there is still a lot of untapped potential in the field of sustainable technologies from which defence can benefit (Senior Member of an international military organisation on Climate and Security [i], 2024). But if they want to achieve their targets by 2050, there has to change something now for which they are trying to solve the puzzle of what to change (Senior Member of an international military organisation on Climate and Security [i], 2024). A similar, related problem is the one of strategic dependency. The defence has the desire to have guidelines in order to reduce strategic dependency, but these are currently far from sufficient (Advisor Sustainability, Environment and Safety [h], 2024).

The buying process is as follows. As the defence, you buy a product and in doing so you deliver a set of requirements in which specifications are stated (Senior Military Officer Maintenance & Logistics [d], 2024). In it, you can make all kinds of demands, including sustainability aspects or CRMs (Senior Military Officer Maintenance & Logistics [d], 2024). That is not done enough at the moment (Senior Member of an international military organisation on Climate and Security [i], 2024). You can also agree in the contract with the supplier that they have to keep producing spare parts for, say, 30 years or the whole lifespan (Senior Military Officer Maintenance & Logistics [d], 2024; Senior Member of an international military organisation on Climate and Security [i], 2024). The manufacturer then has contact with other manufacturers of the components inside. These manufacturers that supply materials for defence are 100% private (Former Senior Military Officer Maintenance & Logistics [f], 2024). As a result, some supply chain disruptions also affect defence very much. Examples are the blockage of the Suez Canal or COVID which caused longer delivery times and shortages of materials (Senior Military Officer Maintenance & Logistics [d], 2024; Senior Member of an international military organisation on Climate and Security [i], 2024). Therefore, it is important, also for manufacturers, to minimise dependency for which some manufacturers have rules about the origin of certain components they purchase (Former Employee at an aerospace manufacturer [m], 2024). But visibility of where all parts come from is still lacking (Strategic Analyst at a not-for-profit research organisation [j], 2024).

For the design of the product, they engineer a product in such a way that it lasts for a very long time and sometimes contains a modular kind of structure (Strategic Analyst at a not-for-profit research organisation [j], 2024). However, not enough consideration is being given to modularity (Former Employee at an aerospace manufacturer [m], 2024). Within defence, they already make many efforts to extend the lifespan of applications which is done because of budget considerations ((Senior Military Officer Maintenance & Logistics [d], 2024; & Former Senior Military Officer Maintenance & Logistics [f], 2024). They do this by servicing and repairing when something is not working properly (Senior Military Officer for Technical Documents [g], 2024). This also holds for applications taken to battlefields. During operation, everything is continuously maintained for strategic reasons whenever possible. After the battlefield, all materials go back to the country of origin after an operation where it is checked whether it is still according to specs, after which it is either reused or repaired if possible (Senior Military Officer for Technical Documents [g], 2024; Strategic Analyst at a not-for-profit research organisation [k], 2024). After the end of life, when it cannot be repaired by defence, the products are usually sent to a recycling company or sometimes back to the manufacturer (Senior Military Officer for Technical Documents [g], 2024; Former Senior Military Officer Maintenance & Logistics [f], 2024). After the end of life when the product is still functioning, sometimes they are divested to other countries such as with aircraft (Senior Member of an international military organisation on Climate and Security [i], 2024).

To establish which actors are part of this system, a stakeholder analysis has been made. These are stakeholders who have a stake in the system, can influence the system or can be influenced by the system (Quist, 2016). These stakeholders have been divided into four domains: business, public sector, academia and society. In the analysis, their interest and power will be looked at in detail as these could be able to steer possible solutions (Quist, 2016). The relative stable, long-term interest and what the stakeholder wants to achieve in this situation are provided in Table 13 in Appendix 9.3. That means they have to realise the objective, whether the resources can be replaced and if the resources are important for the problem resolution is elaborated upon in Table 14 in Appendix 9.3. This has led to the power-interest grid in Figure 12 to visualise interdependencies.

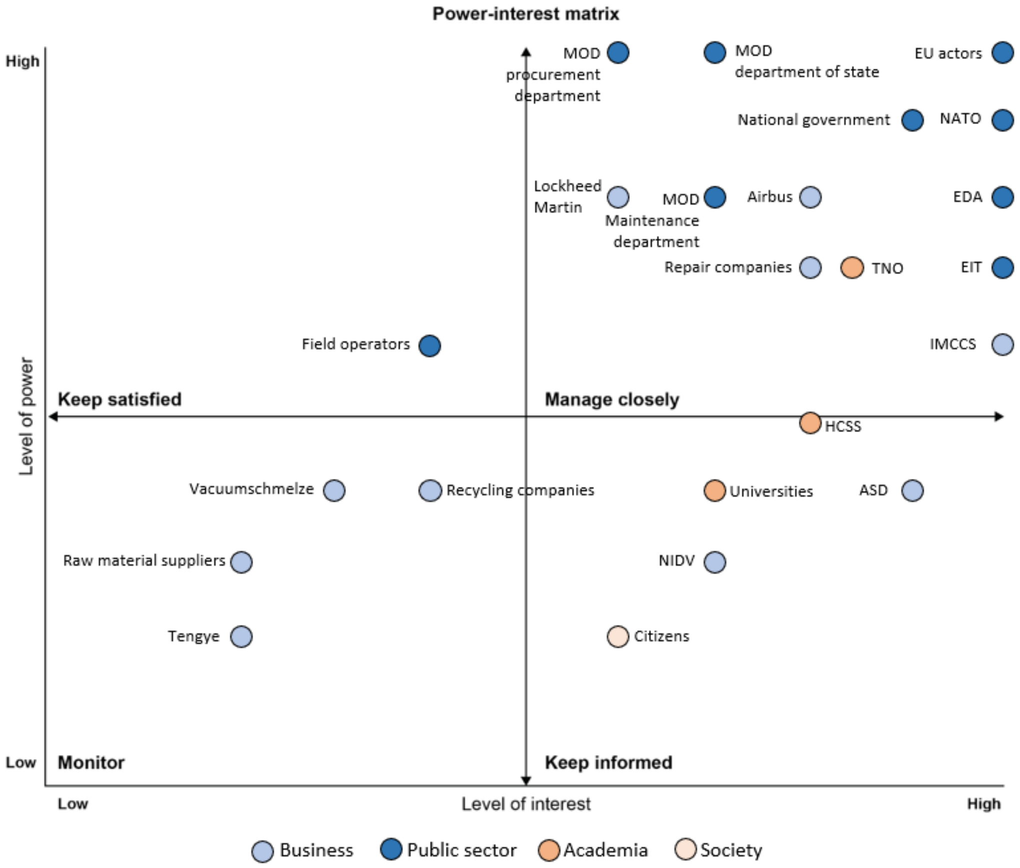

Figure 12 - Power Interest matrix

In the Figure above, it can be noted that the stakeholders are divided into four quadrants based on their influence over project outcomes and their interest in the project. On the top right, the most stakeholders are located which have a high power and high interest. They play a crucial role as they possess both the authority and motivation to drive and shape the project. Therefore, they need to be closely managed in order for the project to succeed. The stakeholders that need to be kept informed include society and some academia and industry associations. These are typically more concerned with the project's implications rather than its direct outcomes. Field operators should be kept satisfied, as these are fundamental as they can impact the project significantly as they are key players in the usage of the products. Lastly, the lower left quadrant should be monitored. Stakeholders require minimal engagement but their interest and influence should be monitored as it may change over time.

5.3.2 Creation of vision

The proposed vision is to ensure a secure and sustainable supply chain for critical raw materials, with a focus on NdFeB magnets, for the EU by 2050. More specifically, to reduce the EU's dependence on single third-country suppliers and to promote circularity and sustainable sourcing practices. This is in line with the objectives of the CRMA as with this regulation the EU intends to strengthen its global engagement to develop and diversify investment production and trade with reliable partners (European Commission, n.d.-c). The CRMA is also consistent with other EU policies such as the Green Deal Industrial Plan where they promote key carbon-neutral technologies for clean energy supply chains (European Commission, n.d.-c).

The elaboration of the idea to achieve this vision can be found in Chapter 5.2, which entails the incorporation of circular strategies. This is in line with the CRMA as it promotes sustainability and circularity of critical raw materials by for example investigating the potential for recovery and establishing rules for environmental footprints (European Commission, n.d.-c).

Although it is now known from where the backcasting should take place, the future scenarios are not yet known. Therefore two possible scenarios were developed to emphasise the continuously evolving landscape in which this idea, incorporating circular strategy, takes place. The future scenarios are based on megatrends on topics such as geopolitics, regulation, industry and culture.

Table 6 - Future scenarios

Future scenario	Level	Details
Business as usual	Geopolitical	Some structural shifts in the international system are taking place. China is on track to be the world's largest economy, reactions by status-quo powers to this shift in global power dynamics have been mixed which already resulted in a 'trade war' between the US and China (KPMG, 2021). Demand for CRMs is rapidly increasing but supply is geographically limited and highly politically sensitive (KPMG, 2021).
	Regulatory	Policies are in place which should improve access to CRMs (European Commission, n.d.-c). Dependency is increasing due to third-country suppliers introducing export restrictions (European Commission, 2024).
	Industrial	The industries are becoming more and more digitalised which increases the demand for electrical products. Therefore the demand for NdFeB magnets keeps increasing (Schulze & Buchert, 2016). Companies are somewhat implementing circularity in business but nothing radical. There is a focus on recycling instead of higher-value retention options.
	Societal	Society is becoming more aware of climate change due to extreme weather events (KPMG, 2021). They are pushing for more regulation for environmentally sustainable practices.
World War III	Geopolitical	China and Russia challenge the current order, West pushes back with arms for Ukraine and sanctions against China which escalates into a global war.
	Regulatory	An export ban is set in place for trading materials with opponents. More funds become available to stimulate industries to continue their activities.
	Industrial	The development of industries runs aground due to a lack of raw materials in the short term. Industries need to adjust to produce war-related products. Innovative ideas are put in place to continue with business activities.
	Societal	There is discontent and fear in society. Everything is focused on winning the war.

5.3.3 Backcasting and Pathway Development

Table 7 provides a comprehensive list of barriers across the different levels cultural, regulatory, market and technological which are adopted from the research of Kirchherr et al. (2018). These barriers impact the implementation of circular strategies to reduce dependency on CRMs.

The cultural norms and organisational priorities hinder the implementation of circular strategies. The cultural norms include a strict hierarchy which hinders grassroots initiatives (Senior Member of an international military organisation on Climate and Security [i], 2024; Senior Military Officer for Technical Documents [g], 2024). In addition, the organisational priorities are deemed the most important barrier as these ensure risk-averse behaviour towards anything that could affect operational effectiveness

(Strategic Analyst at a not-for-profit research organisation [j], 2024). This leads to scepticism towards implementing circular strategies. A lack of awareness is also present about the presence of NdFeB magnets and CRMs in products and about lifespan-extending practices. It is not known whether any equipment includes this kind of material and where employees can turn in the equipment for repair (Senior Military Officer Maintenance & Logistics [d], 2024); Senior Military Officer for Technical Documents [g], 2024). More broadly, public opinion also poses a challenge as it can lead to resistance which can delay implementation (Strategic Analyst at a not-for-profit research organisation [j], 2024).

Regulatory frameworks also present significant barriers. Most importantly, the current procurement processes fail to consider CRMs, the origins of products or circularity (Former Senior Military Officer Maintenance & Logistics [f], 2024; Senior Military Officer Maintenance & Logistics [d], 2024). This leaves crucial decisions to the discretion of companies. Political awareness and support for sustainability initiatives are limited (Senior Military Officer Maintenance & Logistics [d], 2024). Next to this, democratic decision-making slows down policy implementation and sustainability initiatives (Advisor Sustainability, Environment and Safety [h], 2024). Lastly, security constraints of the military equipment lead to challenges in handling and recovering materials (Minerals and intelligence researcher [l], 2024).

In the market domain, a major hurdle is the commercial pressure that drives lifecycle decisions, often leading to premature end-of-life for products (Former Senior Military Officer Maintenance & Logistics [f], 2024; Senior Military Officer Maintenance & Logistics [d], 2024). This is while there is also a high dependency on external suppliers which is a result of the low availability of alternative sources due to the niche knowledge needed to produce defence equipment (Former Senior Military Officer Maintenance & Logistics [f], 2024). Once products are purchased, there’s a "lock-in" effect where the users are tied to the original suppliers for components, which limits the flexibility to adopt circular practices such as repair or remanufacturing (Senior Military Officer Maintenance & Logistics [d], 2024). Meanwhile, there is a lack of including circularity and CRM requirements in the procurement process which limits control over sustainability and circularity within the supply chain (Senior Member of an international military organisation on Climate and Security [i], 2024). Economic considerations play a role in this as it is more expensive to include certain requirements (Senior Military Officer for Technical Documents [g], 2024).

Technological challenges include a lack of transparency in supply chains. Even if producers would want to track their components and materials, they don’t know exactly where their materials come from (Strategic Analyst at a not-for-profit research organisation [j], 2024). This makes it difficult for product developers to ensure sustainable sourcing. The development of new designs and technologies that meet stringent operational requirements, especially under extreme environmental conditions, is both time-consuming and complex (Strategic Analyst at a not-for-profit research organisation [j], 2024; Former Employee at an aerospace manufacturer [m], 2024). Throughout its lifecycle, the presence of unique parts complicates inventory management and maintenance (Former Senior Military Officer Maintenance & Logistics [f], 2024). Maintenance also struggles with a shortage of manpower and a limited timeframe due to battlefield implications (Senior Military Officer for Technical Documents [g], 2024; Former Employee at an aerospace manufacturer [m], 2024).

Table 7 - Identification of Barriers

Level	Barrier	Strategy
Cultural	Lack of awareness about the presence of NdFeB magnets and CRMs in products	R0-R9
	Hierarchical structure within defence, hindering grassroots initiatives	R0-R9
	Scepticism towards implementing circular strategies due to cultural norms and organisational priorities	R0-R9

	Insufficient awareness among employees in defence of lifespan-extending practices	R3-R7
	Public opinion and societal readiness for transitioning to sustainable practices, including resistance and unfamiliarity	R0-R9
Regulatory	Lack of industry-specific regulations and guidelines for implementing circular strategies, leaving implementation decisions to the discretion of companies	R0-R9
	Limited political awareness and support for sustainability initiatives, particularly in recognizing the potential impact of future conflicts and the importance of sustainable resource management	R0-R9
	Failure to track the origins of products and consider critical raw materials (CRMs) in procurement processes indicates a gap in regulatory frameworks for sustainable sourcing	R0-R9
	Democratic decision-making processes and regulatory constraints slow down policy implementation and hinder swift action	R0-R9
	Security constraints on material handling and recovery	R3, R7, R8 & R9
Market	Commercial considerations drive product lifecycle decisions, potentially leading to premature end-of-life for products	R1 & R3-R7
	High dependence on external suppliers due to low availability of other suppliers	R0-R2
	Limiting control over supply chain sustainability and circularity	R0-R9
	Insufficient emphasis on circularity requirements in procurement processes, leading to limited integration of sustainability criteria	R0-R9
	Lock in effect. Once a product is purchased, there's limited flexibility to replace or upgrade components, tying users to the original supplier and limiting circularity	R3-R7
	Economic considerations preventing investments in sustainable alternatives and favouring new purchases over repair or remanufacturing	R0-R7
	Lack of transparency in supply chains: Product specification developers may not have visibility into the origins of raw materials, complicating efforts to ensure sustainable sourcing	R0-R2
Technological	Long development times for new designs and technologies	R0-R2
	Stringent requirements for products to perform under various environmental conditions, including extreme climates, complicating design and maintenance	R0-R2
	High prevalence of unique parts and components, leading to inventory management challenges and difficulties in maintenance and repair	R4-R5
	The complexity of the applications and lack of tracking systems make it difficult to identify and manage materials through the life cycle	R0-R9
	Technical difficulties in redesigning products to meet circular economy requirements	R0-R2
	Maximum efficiency requirements	R0-R9
	Lack of maintenance due to a shortage of manpower or a limited timeframe	R3-R7

Next to the barriers, several enablers hold for implementing circular strategies to reduce dependence on CRMs in the defence sector. An overview of these enablers can be found in Appendix 9.4, Table 16.

Culturally, the recognition of sustainability as a boost to operational effectiveness is receiving more attention within the defence sector, stimulating initiatives across organisations (Senior Member of an international military organisation on Climate and Security [i], 2024; Advisor Sustainability, Environment and Safety [h], 2024; Former Senior Military Officer Maintenance & Logistics [f], 2024). This is complemented by the strategic perception that reducing dependence on CRMs enhances autonomy, an attractive proposition for defence and industries aiming for strategic independence (Advisor Sustainability, Environment and Safety [h], 2024). Tailoring communications to specific audiences further solidifies this support and fosters an environment where sustainability is seen as not just beneficial, but essential (Strategic Analyst at a not-for-profit research organisation [j], 2024). This can support small groups that can initiate a movement towards sustainability (Advisor Sustainability, Environment and Safety [h], 2024).

Regulatory frameworks also serve as crucial enablers, as political pressure can mandate specific requirements with legislation such as the Critical Raw Materials Act (Former Senior Military Officer Maintenance & Logistics [f], 2024). These regulations are also applicable to the defence sector while they are able to use regulatory priorities (Senior Military Officer Maintenance & Logistics [d], 2024). Contractual obligations can be deployed to ensure more life-extending practices (Senior Military Officer Maintenance & Logistics [d], 2024).

On the market front, the industry and EU are striving for strategic autonomy showing willingness to participate in the project (Senior Member of an international military organisation on Climate and Security [i], 2024; Former Senior Military Officer Maintenance & Logistics [f], 2024). Next to this, sufficient funds are available for defence whenever something is crucial to be implemented (Senior Member of an international military organisation on Climate and Security [i], 2024). Although, some initiatives can even boost the defence budget while being sustainable (Senior Military Officer Maintenance & Logistics [d], 2024).

Technologically, the drive towards minimising CRM use is facilitated by innovative design changes that make maintenance easier and reduce the need for rare materials (Former Employee at an aerospace manufacturer [m], 2024). Modular designs and standardisation across systems enable more straightforward upgrades and maintenance, extending the lifecycle of critical components as knowledge of maintenance is already present (Senior Member of an international military organisation on Climate and Security [i], 2024; Senior Military Officer for Technical Documents [g], 2024; Former Employee at an aerospace manufacturer [m], 2024). Furthermore, other innovative technologies can boost sustainability such as the ability to 3D print spare parts directly in the field represents a significant leap in operational efficiency and resource sustainability (Former Senior Military Officer Maintenance & Logistics [f], 2024). Lastly, the possibility of reusing or repurposing some equipment in the civil sector promotes circularity (Senior Military Officer Maintenance & Logistics [d], 2024).

From these barriers and enablers, it can be noted that the defence sector has some unique aspects compared to the civil sector. Firstly, relating to operational effectiveness, the performance requirements of products are more stringent and unique (Former Senior Military Officer Maintenance & Logistics [f], 2024; Senior Military Officer Maintenance & Logistics [d], 2024). Therefore, projects should be linked to mission requirements instead of sustainability (Former Employee at Defence for Environment & Energy Resilience [e], 2024). The need for the security and confidentiality of products is much higher (Strategic Analyst at a not-for-profit research organisation [j], 2024; Minerals and intelligence researcher [l], 2024). In addition, systems are often much more complex which leads to long development times but the products also last longer than in the civil sector (Strategic Analyst at a not-for-profit research organisation [j], 2024; Former Employee at an aerospace manufacturer [m], 2024). The defence sector is much more regulated but can enjoy certain exemption positions in critical scenarios (Senior Military Officer Maintenance & Logistics [d], 2024). This can also lead to more flexibility in terms of funding (Senior Member of an international military organisation on Climate and Security [i], 2024).

Now that it is clear what the barriers and enablers of implementing these circular strategies are defined together with what is unique for the defence sector, measures to overcome these barriers can be prepared. These can be found in Table 8.

Table 8 - What-How-Who-When analysis

Category	WHAT *Barrier*	HOW *Measure to overcome*	WHO *Stakeholder*	WHEN *Short/Medium /Long term*
Cultural	Lack of awareness about the presence of NdFeB magnets and CRMs in products	Communicate about including CRM requirements in the procurement process	Ministry of Defence	Short
	Scepticism towards implementing circular strategies due to cultural norms and organisational priorities	Integrate Climate Change into Professional Military Education whilst framing and presenting it in terms of the recipient	Academia, Ministry of Defence	Short
	Insufficient awareness among employees in defence of lifespan-extending practices	Communicate clearly about available practices	Ministry of Defence, specifically: maintenance department & field operators	Short
	Hierarchical structure within defence, hindering grassroots initiatives	Put it on the agenda of the top and give space to the bottom of the hierarchy	Ministry of Defence	Medium
	Public opinion and societal readiness for transitioning to sustainable practices, including resistance and unfamiliarity	Increase transparency of policies and educate society to lower resistance and unfamiliarity	National government, EU, society	Long
Regulatory	Lack of industry-specific regulations and guidelines for implementing circular strategies, leaving implementation decisions to the discretion of companies	Include CRMs and circularity requirements in the procurement process	NATO, EDA, Ministry of Defence	Short
	Security constraints on material handling and recovery	Review the requirements a product must meet to get a second life and limit by life span extending practices	Ministry of Defence	Medium
	Limited political awareness and support for sustainability initiatives, particularly in recognizing the potential impact of future conflicts and the importance of sustainable resource management	Create a specific agenda to make the defence strategic autonomous	EU actors, national government	Medium
	Failure to track the origins of products and consider CRMs in procurement processes indicates a gap in regulatory frameworks for sustainable sourcing	Monitor the origins of products and CRMs in defence	Ministry of Defence, department of procurement	Medium
	Democratic decision-making processes and regulatory constraints slow down policy implementation and hinder swift action	Establish special regulations for rapid responses and create a hub that is dedicated to continuously monitoring and adapting	EU actors, national government	Long

		regulation in response to technological advancement and sustainability goals		
Market	Commercial considerations drive product lifecycle decisions, potentially leading to premature end-of-life for products	Include design specifications on circular strategies to promote modular designs	Ministry of Defence, manufacturer of defence equipment	Short
	Insufficient emphasis on circularity and CRM requirements in procurement processes, leading to limited integration of sustainability criteria	Include design specifications on circular strategies to promote modular designs	Ministry of Defence, manufacturer of defence equipment	Short
	Lock in effect. Once a product is purchased, there's limited flexibility to replace or upgrade components, tying users to the original supplier and limiting circularity	Include design specifications on circular strategies to promote modular designs	Ministry of Defence, manufacturer of defence equipment	Short
	Economic considerations preventing investments in sustainable alternatives and favouring new purchases over repair or remanufacturing	Include design specifications on circular strategies to promote modular designs	Ministry of Defence, manufacturer of defence equipment	Short
	High dependence on external suppliers due to low availability of other suppliers	Enhance relationships with suppliers and plan collaboratively to ensure reliability	Ministry of Defence, manufacturer of defence equipment	Long
	Limiting control over supply chain sustainability and circularity	Introduce digital product passports to track materials	EU, NATO, EDA, Ministry of Defence, manufacturer of defence equipment	Long
	Lack of transparency in supply chains: Product specification developers may not have visibility into the origins of raw materials, complicating efforts to ensure sustainable sourcing	Introduce digital product passports to track materials	EU, NATO, EDA, Ministry of Defence, manufacturer of defence equipment	Long
Technological	High prevalence of unique parts and components, leading to inventory management challenges and difficulties in maintenance and repair	Plead for more standardisation of products in product specifications to reduce the number of unique parts	Ministry of Defence, manufacturer of defence equipment	Short
	Long development times for new designs and technologies	Include design specifications on circular strategies to promote modular designs	Ministry of Defence, manufacturer of defence equipment	Short
	Technical difficulties in redesigning products to meet circular economy requirements	Help with research funding to help identify how something that currently is not in the defence supply chain but could potentially meet defence qualifications	EU, Academia, defence application manufacturers	Short

	Maximum efficiency requirements	Explore other areas of usage when a product does not provide maximum efficiency such as divestment to the civil sector	EU, national government, society, Ministry of Defence	Short
	Lack of maintenance due to a shortage of manpower or a limited timeframe	Hire more people to maintain products	Ministry of Defence	Short
	Stringent requirements for products to perform under various environmental conditions, including extreme climates, complicating design and maintenance	Engage in partnerships with universities, research institutions, and industry to leverage science and technology that can help overcome environmental requirements	Academia, Ministry of Defence, manufacturer of defence equipment	Medium
	The complexity of the applications and lack of tracking systems make it difficult to identify and manage materials through the life cycle	Introduce digital product passports to track materials	EU, NATO, EDA, Ministry of Defence, manufacturer of defence equipment	Long

In the table above, actionable measures to overcome the barriers are indicated. In addition, it is stated what stakeholders are involved with the measure and an indication is provided on what time frame this needs to be implemented.

In the short term, a strong foundation needs to be laid for a wider adoption of circularity principles. Increasing awareness and education of people within defence about circularity and CRMs must be started. This involves communicating the significance of including CRMs in procurement processes and integrating circularity topics into professional military education. Stakeholders such as the Ministry of Defence and academic institutions are pivotal in spreading this knowledge. Simultaneously, NATO, EDA and national ministries of defence need to revise procurement guidelines to enforce the inclusion of CRMs and circularity requirements. This ensures that new purchases and designs immediately begin to reflect these principles, setting a standard for future acquisitions and developments. Funding in terms of knowledge and money should be of service to manufacturers to help facilitate this. This is in line with measures needed on a technological level as it encourages defence manufacturers to adopt design changes that promote modularity and adaptability which will contribute to lifespan-extending practices. To make sure these practices can be carried out, more people should be allocated to the maintenance of products.

In the medium term, once awareness is created it should be explicitly put on the agenda of the people on top of the hierarchy whilst giving room to the bottom for grassroots initiatives. Politically speaking there should now be an agenda created to increase the strategic autonomy of the defence and the origins of products and CRMs embedded in the products should be able to be monitored. Engagement should also be increased with universities, research institutions and industry to leverage science and technology to help actually implement procurement requirements.

Finally, in the long term, more complex issues need to be addressed. Public opinion and societal readiness need to be created by improvements in transparency to prevent any delays. Special regulation needs to be developed to make sustainable initiatives easier to implement. In addition, digital product passports need to be established to make it possible to track materials. Whilst empowering relationships with suppliers and planning collaboratively to reach strategic autonomy.

With these measures, the defence sector is creating a suitable environment to implement circular strategies to lower dependence on CRM. It is notable that in order to implement these strategies, a high level of collaboration is required. Which asks for a cohesive approach that spans regulatory compliance, market incentives, cultural shifts, and technological innovations.

As the geopolitical landscape is very important for the defence sector, which is currently very turbulent, it was also examined what the need for and the role of circular strategies in lowering dependence on CRMs would be in the scenario of a world war. Currently, the EU faces a huge problem as it is not in a position to be able to supply the products we need for a long time to be able to continue to support such a war (Advisor Sustainability, Environment and Safety [h], 2024; Strategic Analyst at a not-for-profit research organisation [j], 2024). In addition, if in such a scenario supply from CRMs would stop, the defence does not have actions in place to fill these gaps (Senior Military Officer for Technical Documents [g], 2024; Senior Member of an international military organisation on Climate and Security [i], 2024).

In this scenario, there would be a major shift in prioritisation. On the one side, if a world war would take place then circularity becomes a complete sideshow and receives no more attention (Strategic Analyst at a not-for-profit research organisation [k], 2024). But if a circularity strategy would bring advantages in terms of efficiency or finances, it would be on the front seat (Minerals and intelligence researcher [l], 2024). In that way, they would be forced to look into circularity strategies such as lifespan extension and useful application of materials (Strategic Analyst at a not-for-profit research organisation [j], 2024).

06

Discussion

6. Discussion

In examining the implementation of circular economy strategies within the defence sector for NdFeB magnets, this discussion addresses a comprehensive examination of the validity, interpretation of results, limitations and implications.

6.1 Validity

This research was performed to examine what effect circular strategies have in lowering the dependence of CRMs for the defence sector, focusing on NdFeB magnets. The methodology was carefully designed to align with this objective, employing qualitative analyses such as literature reviews and interviews with stakeholders to gather insights specific to the defence sector's unique conditions. The measures taken were appropriate for addressing the research questions posed, ensuring that the study directly examined the impact of circular strategies within the intended context.

The generalisability of the findings to other geographical areas or technologies is somewhat limited. The conclusions drawn from the study are context-specific and primarily applicable to the defence sectors within the EU. While the findings provide valuable insights into the potential benefits of circular strategies in enhancing CRM security for defence applications, their generalisability to other sectors or geographic regions may be limited. This is due to differences in regulatory environments, market dynamics, and the strategic importance of NdFeB magnets in various defence technologies.

The reliability of this research is supported by the comprehensive methodological approach, which includes multiple forms of data collection such as literature reviews and expert interviews. These diverse sources help to mitigate biases and provide a robust base for the conclusions.

6.2 Interpretation of results

The findings from this study correspond with the initial expectations that circular strategies can have a positive effect on securing critical raw materials supply for the defence sector in the case of NdFeB magnets. What was surprising is that some strategies did not apply to NdFeB magnets and therefore a more holistic approach was taken using the product in which the NdFeB magnet is located. For smarter product use and manufacturing the potential of applying the circular strategies is very high for both the magnet and the product. For the extension of lifespan, more challenges are present. Where it was mainly applicable for the product instead of the magnet due to its exceptional robustness. Lastly, it was remarkable that highly efficient technologies exist for the recovery of the materials within the magnet. Making it a very good option to retrieve the materials but as it is the most resource-intensive it should be considered as last available option. What was apparent throughout the research is that the terminology of circular strategies is mixed up tremendously in scientific literature. For example, the term Recycling was used many times when what was meant was Reuse (Elwert et al., 2016). The same holds for Refurbish, which was both in literature and in interviews misused as the right term should have been Repair or Remanufacture (Yang et al., 2017). In addition, the emphasis in scientific literature lies on the strategy of recycling. This was surprising as it is one of the least value-preserving strategies.

These results presented in this research do integrate cohesively with the theoretical framework. In addition, Chapter 5.2 is structured based on the framework after which Chapter 5.3 indicates what strategies correspond with the identified barriers.

Several new insights were generated during the research. Starting off with the current state of the defence sector which was not yet defined in terms of these 10 circular strategies. In addition, it was surprising how little knowledge was present about CRMs in the defence sector. This also acted as one of the main barriers found. Therefore, the identification of specific challenges and enablers for implementing circular strategies within the defence sector provides highly important insights. The most distinct barriers compared to the civil sector were the requirements for operational effectiveness, the hierarchical structure, security constraints on material handling and recovery, high dependence on external suppliers, lock-in effect and long development times. The unique enablers for defence are the need for strategic autonomy concerning safety, possible policy priorities, sufficient available funds, overarching organisations such as NATO and in times of war priority on other industries. These insights are instrumental in proposing practical steps for policy and strategy formulation aimed at integrating circular strategies into the defence sector.

Compared to other research in this area, this study adds to existing knowledge by specifically focusing on the defence sector, a less explored area in circular economy research. In addition, it shows how different technologies can be applied to the 9R framework. Previous studies have predominantly concentrated on civilian applications without delving into the unique constraints and opportunities presented by the defence sector. For example, research by Ormerod et al. (2023) on the recycling of NdFeB magnets primarily addresses technical and economic aspects without considering the strategic and security dimensions crucial to the defence sector. In addition, much literature was focused on recycling strategies while this research provided an extensive list of all possibilities to lower the use of CRMs (Kumari & Sahu, 2023).

6.3 Limitations of the study

The lack of interviews with people having knowledge of both the NdFeB magnet and defence might affect the validity negatively. This is because it is very specific niche knowledge that only very few people possess. Therefore, it is hard to figure out who has that knowledge and is also willing to share this. This also touches upon the secretive nature of the defence sector. As a lot of the information relating to CRMs is strategically sensitive, this poses challenges to absolute transparency and completeness of the data, which could to some extent affect reliability. An example is the data in Chapter 5.1 such as the precise amounts and location of NdFeB magnets in defence applications. To address this in the future, this research should be continued by people within the defence sector which will make more data available and allow better consultation of the network.

Next to this, this research was carried out from the geographical location of The Netherlands by a researcher with Dutch nationality. This may lead to a bias in both the interpretation of results and collection of data due to the interviewees being selected from a specific network which might not comprehensively represent all viewpoints within the sector. Related to this is that the insights of the interviewees are bound by their personal experiences and may not cover all facets of the defence sector. Another factor here is that only ten people were interviewed. In future research, this could be addressed by extending the time frame of the research to have a larger set of respondents and collaboration with organisations with a broader, perhaps global, perspective such as the EU and NATO. This approach would help mitigate the current geographic and scope limitations and enhance the depth and breadth of the gathered insights.

6.4 Implication of the Study

The study contributes to scientific literature and fills a significant gap by tailoring circular economy strategies to meet the specific needs and challenges of the defence sector. This provides a nuanced understanding that complements and expands the existing literature, especially in the field of Industrial Ecology. The principles of Industrial Ecology traditionally are not often associated with the defence sector. This approach not only demonstrates the flexibility of Industrial Ecology principles. It also contributes to the field of circular economy. It highlights the importance of using the highest possible value retention option of the 9R framework, even within sectors with stringent performance and security requirements. It also shows a lack of standardised terminology for value retention strategies in literature which makes investigating possible strategies very difficult.

From a societal perspective, this work addresses critical vulnerabilities in national security linked to the supply risks of CRMs. By developing strategies to reduce these risks within the defence sector, this research has direct implications for enhancing resilience. Furthermore, this research aligns with broader global objectives of sustainable development. Advocating for the adoption of circular strategies in the defence sector contributes to reducing environmental impacts. The extraction and processing of CRMs which are related to high environmental impacts will be reduced and resources will be used more efficiently.

07

Conclusion & recommendations

7. Conclusion & recommendations

7.1 Conclusion

This research investigated what effect circular strategies have on securing CRM supply for the defence sector for the defence sector in the case of NdFeB magnets. In this Chapter, the conclusions of this analysis are provided answering the three sub-questions stated in Chapter 1 and answering the main research question.

1. What makes NdFeB magnets and their CRMs particularly significant in the defence sector?

The significance of NdFeB magnets and their CRMs in the defence sector is marked by their indispensable role in enhancing military technology through improved efficiency and compact, lightweight designs. NdFeB magnets, possessing exceptional magnetic properties such as high coercivity, remanence, and energy product, make them integral to various military applications such as manned and unmanned aircraft, precision munitions, naval systems, electronic devices and land-based military vehicles. Not only are they indispensable in military technologies but they also serve applications in the civil sector of which some are dual-use.

Moreover, the reliance on NdFeB magnets for their superior performance in critical applications stresses the strategic vulnerability associated with their supply chain. The raw materials needed for producing these magnets are mostly sourced from geopolitically sensitive regions, leading to potential supply disruptions. This vulnerability is compounded by the high concentration of production and processing capabilities in these countries, which hold a dominant position in the global supply of these CRMs. The strategic importance of NdFeB magnets thus extends beyond their technical capabilities to encompass important geopolitical and economic dimensions, giving them a key role in defence resilience.

2. What circular strategies are known in the civil sector for NdFeB magnets in their main defence applications?

In addressing the sub-question concerning what circular strategies for NdFeB magnets would be applicable in the defence sector, it was imperative to explore what strategies from dual-use applications in the civil sector already existed. The civil sector has pioneered several circular strategies that could be effectively translated into defence applications. These strategies were divided into three categories: smarter product use and manufacturing, lifespan extension of the product and its parts and useful application of materials.

The category of smarter product use and manufacturing encompasses various strategies that optimise the use of NdFeB magnets from refusing the magnet of the component in which they are located, rethinking the magnet or product with sustainability as a starting point or reducing the use of CRMs, the magnet or the product in which it is located. Design for disassembly and modular designs can be particularly useful as they facilitate lifespan extension practices and material recovery.

For the lifespan extension of products, some strategies were found to be more effective than others. Reuse, Repair and Repurpose could be applied to the magnet as the product. The strategy of Reuse is very important as it involves the direct reuse of these magnets in other applications after their initial life cycle without the need for extensive processing. Additionally, regular Maintenance and Repair of equipment containing NdFeB magnets not only prolongs the operational life of the technologies but also ensures their optimal performance over extended periods. Repurpose is important as it then can be used for a different goal. Refurbish and Remanufacture can only be applied to the product as a whole and not to the magnet itself. But are still important strategies to consider when aiming to lower dependency on CRMs. Overall it is significant to note that the NdFeB magnet typically remains undamaged and is often one of the components in perfect condition when a product reaches the end of its lifecycle. Therefore, lifespan extension practices should be more focused on the product rather than the magnet itself.

In the category of smarter product use and manufacturing, both Recycle and Recover can be implemented to recover CRMs from spent NdFeB magnets or products. This is important as technologies exist that can recycle an NdFeB magnet without losing any performance mitigating dependency on supply. However, the emphasis should be on the strategies before these.

In conclusion, by adopting practices that promote smarter product use and manufacturing, extend the lifespan of products and their components, and facilitate the useful application of materials, the defence sector can achieve significant advancements in sustainability. These strategies not only enhance the operational efficiency of military technologies but also align with broader environmental and strategic objectives, ensuring the sector's resilience and adaptability in facing future challenges.

3. How can these strategies be implemented within the defence sector?

Implementing circular strategies within the defence sector is very complex and requires a structured approach. Therefore backcasting was used which started from the vision: *Ensure a secure and sustainable supply chain for critical raw materials, with a focus on NdFeB magnets, for the EU by 2050*.

The most important barriers to overcome when implementing this are cultural and organisational norms prioritising operational effectiveness and fuelling scepticism towards sustainability initiatives. Next to this, the lack of consideration for circularity practices and CRM requirements in procurement processes is one of the most significant barriers. Next to this, the commercial considerations and lack of transparency in the supply chain are bottlenecks for implementing the strategies.

Also, enablers were found which can accelerate the implementation. These were used to define measures to overcome the barriers. In the short term, it is important to increase awareness and integrate circularity and CRM principles into military education and procurement practices. This will lead to manufacturers adopting design changes that promote modularity and adaptability. Resources such as funds and people should be allocated as well. In the medium term regulatory adjustments and technological innovations will facilitate more sustainable product designs and maintenance practices. Over the long term, comprehensive changes in regulatory frameworks and stakeholder engagement across government, industry, academia, and the public are essential to implement the strategies within the defence sector.

What effect can circular strategies have on securing critical raw materials supply for the defence sector in the case of NdFeB magnets?

Circular strategies through NdFeB magnets and its products, such as reuse, recycling, and lifecycle extension, play a critical role in securing the supply of CRMs for the defence sector. These magnets are vital in military technologies due to their high magnetic strength but rely heavily on materials like neodymium, dysprosium, and praseodymium, which are susceptible to supply chain disruptions due to geopolitical tensions. By implementing circular strategies, the defence sector can significantly mitigate these risks. Smarter product use and manufacturing, extension of lifespan of product and its parts and useful application of materials help to use these valuable materials more efficiently. Most important are investing in technologies which use no CRMs and optimise Repair and Remanufacture processes for which modularity and design for disassembly play a key role. Adopting these strategies requires an integrated approach that includes changes in cultural, regulatory, market and technological aspects. The need for a collaborative approach with multiple stakeholders is of significant importance. A visualisation of this conclusion can be found in Figure 13.

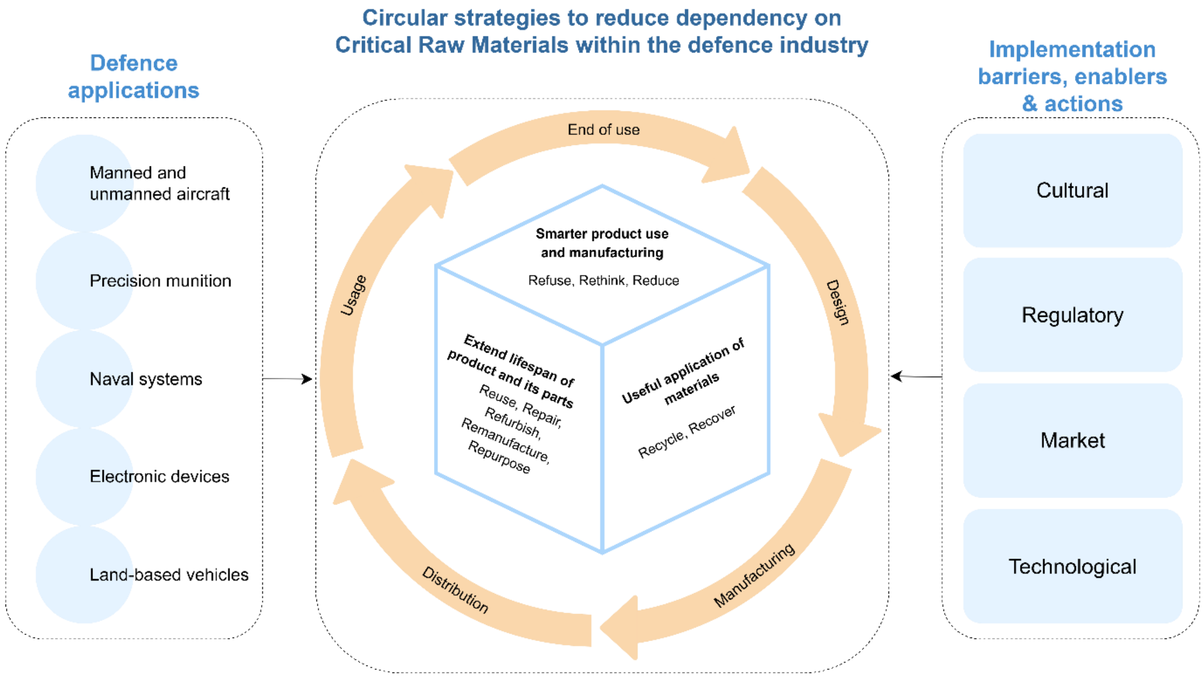

Figure 13 - Research Framework

The implementation of circular strategies will not only strengthen the resilience of the defence sector against CRM supply uncertainties but also align with broader sustainability objectives, ensuring the sector remains technologically advanced and operationally effective.

7.2 Recommendations

Based on the results and the limitations of the research, recommendations can be made for both practice and future research. Firstly, the results will encourage the incorporation of circular principles to reduce dependency on CRMs into the procurement guidelines of governments and defence agencies. In addition, it promotes collaboration between various stakeholders within the defence sector such as the product manufacturers, the Ministry of Defence and academia. Such collaborations could address specific technical challenges to incorporate circular strategies. Both the guidelines and collaboration will then promote design changes such as an increase in modularity and an increase in investments in technologies needed to implement circular strategies.

This research is above all also very accurate as it is in line with the CRMA, which was developed during the writing of this research. In April 2024 the Critical Raw Materials Act was signed, after which it was published in May 2024. As of May 23 2024, it was entered into force, meaning that every business should adhere to this act. The act mentions that permanent magnets should be a priority product for increasing circularity. More specifically, it requires manufacturers to include labels indicating the presence of permanent magnets such as NdFeB magnets but also information about the weight, location, chemical composition and presence of coatings glues and other additives. Efforts should also go out to monitor the CRMs used in the NdFeB magnets. The CRMA Act is going to be a driver of the industry. As this research is in accordance with the recommendations of the CRMA, but provides an even more specific implementation plan, this research is of the utmost importance.

For future research, it is recommended to quantify the impacts of the circular strategies within the defence sector over an extended time. Generalisability can also be increased when more subcomponents are researched for possible circular strategies. In this way, it can be examined to what extent all strategies can be implemented in the entire defence sector. To increase the success rate of implementation, it is important to make a more detailed implementation plan in which smaller actions are provided. This can be achieved by performing research with a bigger scope and cross-sector collaboration. Future studies should also focus on the development of innovative technologies aimed at decreasing dependency on CRMs in an environmentally sustainable way.

These recommendations aim to guide practical implementations and future research directions, to promote a more sustainable and resilient defence sector in alignment with circular economy principles.

08

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09

Appendix

9. Appendix

9.1 Methodology matrix

Table 9 - Methodology matrix of the research

Sub questions	Selection Questions	Data collection methods			Data analyses	Validity & reliability
		Literature review	*Grey literature review*	*Interview expert*		
SQ1. What makes NdFeB magnets and their CRMs particularly significant in the defence sector?	What are the properties and structure of NdFeB magnets?	X			*Literature:* Collect relevant data to elaborate on the properties and structure of NdFeB magnets	Cross-verifying properties and structures from multiple scientific sources
	What are the applications in defence?	X	X		*Literature & grey literature:* Create a list of the most important applications in which NdFeB magnets are located	Triangulation using both literature and grey literature
	What does the supply chain look like for NdFeB magnets?	X			*Literature:* Mapping of the supply chain of NdFeB magnets from raw material sourcing to end-use in defence technologies	Using recent sources
SQ2. What circular strategies are known in the civil sector for NdFeB magnets in their main defence applications?	What is known in literature on circular strategies?	X			*Literature*: Systematically categorise findings from literature into the 9R framework to assess their applicability	Using recent sources and compare interviews and literature findings
	What is known in grey literature on circular strategies?		X		*Grey literature:* analyse any relevant data that could not be found in scientific literature and categorise findings	Using recent sources and compare interviews and literature findings

	What are experts opinions on different strategies?			X	*Interviews*: Code and cluster all relevant information from expert interviews and categorise findings	Interview 2 experts, compare interviews and literature findings
SQ3. How can these strategies be implemented in the defence sector?	What is the proposed vision and future scenarios?	X	X		*Literature & grey literature:* Determine a proposed vision and future scenarios in which the implementation will take place	Using recent sources
	What stakeholders are involved?	X	X	X	*Literature, grey literature & interviews:* Identify key stakeholders involved and their roles in the implementation from data gathered	Using recent sources and compare different sources
	What drivers and barriers exist for the circular strategies in defence?			X	*Interviews:* Identifying barriers and drivers from expert interviews	Compare results of 11 respondents
	How can drivers and barriers be overcome in defence?			X	*Interviews:* Develop measures for overcoming identified barriers	Compare results of 11 respondents

9.2 Interview questions

Table 10 - Interview questions Circularity Expert

Introduction

- Short introduction was provided to thesis
- It was asked whether it could be recorded

9R framework

- Do these definitions seem right to you? Do you have any recommendations for improvement?

Related to reuse/repurpose

- Would you consider the magnet going from an electric vehicle to a portable device (so having the same function bit in a different application) as repurposing or reusing?
- Does the product need to be a different function or does the magnet need to have a different function?

Flow diagram

- Does this flow diagram seem right to you? Do you have any recommendations?

Barriers

Broadly

- What do you notice so far for barriers in implementing circular strategies in the EU?
- Do you have solutions to address these?

Specific

- Can you think of any barriers which are directly related to reducing dependency on Critical Raw Materials?
    - How do you think policy will evolve around this topic?

- Who is involved in these barriers?
    - How would you motivate certain stakeholders?

- Do you have solutions to address these barriers?

Implementation

- Have you ever implemented circular solutions on the EU scale?
    - did you have a pilot?
    - where did you bump into?
        - what are the key takeaways from this?

- Are there any other case studies which tried to implement solutions to multi-stakeholder problems (perhaps in other industries) that we could look at?

Closing

- Do you have any recommendations where we can look for barriers and solutions?
- Do you know anyone in your field who would be a valuable contribution to our research?
- Thank you for your time

Table 11 - Interview questions Magnet Experts

Introduction
- Short introduction was provided to thesis
- It was asked whether it could be recorded

9R framework

0 Refuse
- To what extent are companies also looking into not using the magnets so using different technologies that don't include them?

1 Rethink
- Do you see in practice that designer/manufacturers are changing design in order to retrieve magnets or other components?

2 Reduce
- Do you think applications have magnets where it is not necessary? Do you think applications have magnets bigger than needed?

3 Reuse
- Does reuse already happen in practice?
- In which application can these magnets be reused?
- Is the magnet used in the same kind of application or in an application with a totally different function?
- Would you argue that NdFeB magnets mostly do not get damaged in a product and can therefore be mostly reused when recovery is possible?

4 Repair
- Does it ever happen that a magnet needs repair? If so, can the consumer do it himself? Can a repair shop do it?
- An example would be to replace the coating, do you have any other possibilities what can be repaired if it does not go back to a remanufacturer?

5 Refurbish
- Can a magnet be refurbished?
- Or doesn't it lose any of its performance?

6 Remanufacture
- Can a magnet be broken down into components and remanufactured? Would it compromise its performance?

7 Repurpose
- Do the magnets go from high-quality products to low-quality products?
- Would it be possible?

8 Recycle
- Which recycling process is most popular in practice? Magnet to magnet approach?
- Is there a limited number of which you can recycle the magnets?

9 Recover
- To what extent can critical raw materials be recovered after incineration? What happens to the magnets if they do end up in incineration?
- Is there any company that already recovers CRMs from bottom ash?

Flow diagram

- Does this flow diagram seem right to you? Do you have any recommendations?

Barriers

- What do you think the biggest barriers to implementing these strategies would be?

Closing

- Any questions for me?
- Thank you for your time

Table 12 - Interview questions Defence Experts

Introduction

- Short introduction was provided to thesis
- It was asked whether it could be recorded

Barriers

Organisation

- What does your organisation do?
- Is your organisation familiar with CRMs?

Current state

- What is the defence already doing in terms of circularity?
    - *a.* Where could they improve*?*

General

- What barriers would play a role when implementing circular strategies in the defence sector?
- What would be different from civil compared to the defence sector?
    - a. Is the defence sector less restricted to money?
    - b. How would this be in case of war?
- What measures could be used to overcome these barriers?
    - o Which stakeholders are most important for this?
- Which stakeholders hold the highest powers in including circular strategies in defence equipment?

Policy related

- How does defence policy typically get compiled?
- How does it differ in wartime?
    - o What restrictions are not in place for defence which are present for civil?
- If there were World War III, would policy be possible to restrict primary raw materials to defence? Meaning that the civil sector would mostly only use secondary raw materials (recycled)
- After you advice on defence policy, what happens after the advice?

Manufacture Related

- Do designers look at components which are vulnerable in supply to replace these?
- Is defence equipment designed for disassembly? To retrieve certain parts or make repair more accessible?
- Can recycled materials be included in defence equipment?
- To what extent does the government (Ministry of Defence) influence what equipment is produced, and how it is produced?

- To what extent are the defence manufacturer companies privatised?

Maintenance Related

- Does defence equipment come back after the battlefield?
- How many times does equipment get used?
  - How do you test these and are they repaired if necessary?
- If a tank malfunctions on the battlefield, does it get repaired at the location?
  - How does this work for smaller equipment?
- Does this depend on the size and value of the product?

Logistics

- How do CRMs affect the procurement of materials for defence?
- Have you experienced difficulties due to export restrictions from third-country suppliers?
- What supply disruptions could appear specifically for defence?

Final

- Do any other barriers or enablers come to mind in the meantime?
  - Which would be unique for defence?

Scenarios

- How would these barriers and measures differ or would there be extra barriers or measures in the case of a large-scale war (world-war three)?

Closing

- Any questions for me?
- Thank you for your time

9.3 Stakeholder analysis

Table 13 - Stakeholder analysis interest for lowering dependence on CRMs by circular strategies for defence

<table>
<tr><th colspan="3">Actors</th><th colspan="2">Interest</th><th>Score</th></tr>
<tr><th colspan="3">Actor-level</th><th>Interest
'Relatively stable abstract, long term'</th><th>Objectives
'Specific and shorter-term'</th><th>1-5</th></tr>
<tr><td rowspan="9">Business</td><td rowspan="2">Manufacturers of defence equipment</td><td>Lockheed Martin (USA)</td><td>Solve complex challenges, advance scientific discovery and deliver innovative solutions to help our customers to keep safe (Lockheed Martin, n.d.-a)</td><td>Establishing a sustainable supply chain and incorporating aspects of environmental sustainability (Lockheed Martin, n.d.-b).</td><td>3</td></tr>
<tr><td>Airbus (EU)</td><td>Continually push the boundaries on what is possible to safeguard our world for future generations (Airbus, 2021a).</td><td>Design, manufacture and deliver products, services and solutions whilst including sustainability aspects (Airbus, 2021b)</td><td>4</td></tr>
<tr><td rowspan="2">Manufacturers of NdFeB magnets</td><td>Tengye (China)</td><td>Supplying neodymium magnets to the global industry and addressing magnet-related challenges (Tengye, 2021a).</td><td>Provide guidance, expertise, and resources to ensure effective integration of magnets into the design, manufacturing, and functionality of your products (Tengye, 2021a).</td><td>1</td></tr>
<tr><td>Vacuumschmelze (EU)</td><td>Produce and supply NdFeB magnets</td><td>Have a stable supply chain and look into innovative ways to secure the production of NdFeB magnets</td><td>1.5</td></tr>
<tr><td colspan="2">Raw material suppliers</td><td>Ensure extraction, production and supply of natural resources to meet demand of industries.</td><td>Ensure supply of CRMs and managing prices to remain competitive.</td><td>1</td></tr>
<tr><td colspan="2">Recycling companies</td><td>Recovering and repurposing valuable materials from waste streams.</td><td>Invest in technologies to for example enhance recyclability of CRMs.</td><td>2</td></tr>
<tr><td colspan="2">Repair companies</td><td>Extend lifespan of products and equipment.</td><td>Improve product longevity while being economically effective.</td><td>4</td></tr>
<tr><td>Industry organisation</td><td>NIDV: Netherlands Industries for Defence & Security</td><td>Ensures sustainable positioning of the Defence and Security sector in the Netherlands (NIDV, n.d.).</td><td>Cooperate with government on procurement, conservation and disposal of equipment (NIDV, n.d.).</td><td>3.5</td></tr>
</table>

		ASD: Aerospace, Security and Defence Industries	Support competitive development of the industry at both European and global levels (ASD, n.d.-b).	Follow and support EU initiatives on securing supply of CRMs and promote exchange of best practices and development of solutions (ASD, n.d.-a).	4.5
		IMCCS: International military council for climate and safety	Anticipate, analyse and address the security risks of a changing climate (IMCCS, 2019).	Sharing experiences doing research and ensuring it is implemented in policy (Senior Member of an international military organisation on Climate and Security [i], 2024).	5
Public sector	EU actors		Improve economic, social and territorial cohesion and solidarity among EU countries and contribute to global peace security and sustainable development of the earth (EU, n.d.).	Meeting objectives of agreements such as The Paris Agreement, the Critical Raw Material Act and the Circular Economy Action Plan (European Commission, n.d.-a, n.d.-c; European Council, n.d.).	5
	National government		Safeguarding the sovereignty, security, and prosperity of its country.	Address risks of new dependencies and use products and raw materials more economically and smartly through circular strategies (Ministry of Economic Affairs and Climate Policy, 2023; Ministry of Infrastructure and Water Management, 2022).	4.5
	Ministry of Defence	Department of state	Provide defence, security and resilience to its country.	Executing a large array of tasks and tackle as many threats where the best systems and most advanced material are available.	3.5
		Procurement department	Acquire various goods, services or works needed to perform duties.	Meeting immediate operational requirements and being budget efficient.	3
		Maintenance department	Ensure operational readiness and longevity of military equipment.	Maintaining reliability and safety for military equipment including vehicles, aircraft, weapons systems, and facilities by routine and corrective maintenance.	3.5
		Field operators (end-users)	Effectively execute their missions and safeguard national security.	Accomplish assigned tasks, ensure safety of personnel and equipment. Remain adaptable to unpredictable environments and optimise resource allocation.	2

	EDA	IFCEED	Improving defence capabilities through European cooperation by spending better, working better together, train together, form priority projects and anticipate needs (EDA, n.d.-a).	Extend the Circular Economy concept and policies, already present in the civil sector, also to the defence domain (EDA, n.d.-c).	5
	NATO		Safeguard the freedom and security of all its members by political and military means (NATO, 2023a).	Solve critical defence and security challenges from operating in denied environments to tackle threats to our collective resilience (NATO, n.d.). And accelerate efforts in environmental security and environmental protection (NATO, 2024).	5
	EIT	EIT Raw Materials	Advance Europe's transition into a sustainable economy (EIT RawMaterials, n.d.).	Support securing the supply of critical raw materials to the European industry by driving innovation along the raw materials value chain (EIT RawMaterials, n.d.).	5
Academia	HCSS		Inform public discourse, public and private decision making and contribute to international and national security by conducting independent research (HCSS, 2024).	Researching how CRMs can be secured for critical sectors for example by examining policy options and determining strategic raw materials for defence (HCSS, 2020, 2023).	4
	Universities	TU Delft	Generate new knowledge by investigation of problems and try to provide possible solutions to those problems.	Developing knowledge on the topic of sustainable critical raw materials (TU Delft, n.d.).	3.5
	TNO		Use knowledge and technology to create innovations for people who are committed to our peace and security (TNO, n.d.-c).	Find answers to geopolitical challenges throughout the volatile supply chain by creating business intelligence about scarcely available critical raw materials (TNO, n.d.-b).	4.2
Society	Citizens		The pursuit of collective well-being, progress and harmony.	Ensuring safety needs such as personal security in any future scenario.	3

Table 14 - Stakeholder analysis power for lowering dependence on CRMs by circular strategies for defence

Actors			Power			Score
Actor-level			Important resources *'Means to realise objective and exert influence'*	Replaceable? *'Can resources be replaced easily or unique?'*	Dependency? *'Are resources important for problem resolution?'*	1-5
Business	Manufacturers of defence equipment	Lockheed Martin (USA)	Knowledge and expertise to incorporate circularity.	Yes, but not easily as expertise is very specific.	Yes, dependent on their design of the product.	4
		Airbus (EU)	Knowledge and expertise to incorporate circularity.	Yes, but not easily as expertise is very specific.	Yes, dependent on their design of the product.	4
	Manufacturers of NdFeB magnets	Tengye (China)	No important resources.	Yes, but not easily.	No, does not relate to circular strategies.	1
		Vacuumschmelze (EU)	Providing magnets from an EU country.	Yes, but not easily.	No, does not relate to circular strategies.	2
	Raw material suppliers		The delivery of primary CRMs.	Partly, mostly country dependent but within country they are replaceable.	No, reliability on primary CRMs would be much less.	1.5
	Recycling companies		Expertise in recovering CRMs.	Yes, could be replaced by other recycling companies.	Yes, important that CRMs are recovered.	2
	Repair companies		Knowledge and skills to improve life extension.	Yes, could be replaced but as it requires very specific knowledge this is difficult.	Yes, important to improve longevity.	3.5
	Industry organisations	Netherlands Industries for Defence & Security	Network.	Yes, but not easily.	Somewhat, network could be useful.	1.5
		Aerospace, Security and Defence Industries	Providing expertise to institutions and member companies.	Yes, but not easily.	Somewhat, network could be useful.	2
		International military council for climate and safety	Network expertise and knowledge.	Yes, by other organisations.	Yes, network and knowledge would be useful.	3

Public sector	EU actors		EU regulation, networking power, provide subsidies.	No, cannot be replaced.	Yes, resources such as funding and regulation are very important.	5
	National government		National regulation, networking power.	No, cannot be replaced.	Yes, can perform pressure by regulation.	4.5
	Ministry of Defence	Department of state	Influence regulation.	No, cannot be replaced.	Yes, have to include guidelines on circularity and CRMs.	5
		Procurement department	Power to adjust requirements set at purchase.	No, cannot be replaced.	Yes, have to monitor on CRMs and set demands.	5
		Maintenance department	Power to extend lifespan.	No, cannot be replaced.	Yes, have to carry out important lifespan extending practices	4
		Field operators (end-users)	Responsible for handling the products.	No, cannot be replaced as a whole, only individuals.	Partly, have to adjust to some new practices	3
	EDA	IFCEED	Network, facilitates collaborative defence projects, research and innovation (EDA, n.d.-b)	No, cannot be replaced	Yes, can foster collaborative defence projects between countries	4
	NATO		Developing guidelines for the defence sector, fostering greater industrial and technological cooperation, generates economies of scale, reduces costs and delivers interoperability by design (NATO, 2022)	No, cannot be replaced	Yes, abilities to set guidelines and multinational cooperation on both procuring and technological	4.5
	EIT	EIT Raw Materials	Collaborative environment with over 300 partners from industry, academia,	Yes, could be replaced by other networks but not easily	Yes, networks and collaboration are important to foster	3.5

			research, and investment (EIT RawMaterials, n.d.)		disruptive and breakthrough innovations	
Academia / research institutes	HCSS		Knowledge from research	Yes, could be replaced by other research institutes	Yes, as they investigate the role of CRMs in defence (Girardi et al., 2023)	2.5
	Universities	TU Delft	Knowledge from research	Yes, could be replaced by other universities as others also investigate CRMs	Potentially, their knowledge could be important	2
	TNO		Knowledge from research and Council for Defence Research determining policy regarding defence research (TNO, n.d.-a)	Partly, only when other members of the Council for Defence Research are appointed	Partly, due to them steering where research is focused and their research itself	3.5
Society	Citizens		Protesting/lobbying	No, cannot be replaced as it involves the entire society	Resources are not necessary for implementing circular strategies	1

9.4 Backcasting and pathway development

Table 15 - Identification of barriers and quotes

Level	Barrier	Quote	Strategy
Cultural	Lack of awareness about the presence of NdFeB magnets and CRMs in products	*'Ik heb geen idee of wij überhaupt een systeem hebben waar dit soort materialen in toegepast worden. Ongetwijfeld wel, maar dat ben ik me absoluut niet bewust' – Senior Military Officer Maintenance & Logistics [d], 2024*	R0-R9
	Hierarchical structure within defence, hindering grassroot initiatives	*'Ik kan wel iets schrijven. Alleen ja, de hiërarchie binnen defensie is zo groot' – Senior Military Officer for Technical Documents [g], 2024*	R0-R9
	Scepticism towards implementing circular strategies due to cultural norms and organisational priorities	*'A lot of the barriers are more cultural Because in defence, you have to be very careful and very risk averse and you don't want to take any sort of risks that would have*	R0-R9

		anything to do with your own operational effectiveness or your mission' – Strategic Analyst at a not-for-profit research organisation [j], 2024	
	Insufficient awareness among employees in defence about lifespan extending practices	*'Medewerkers weten niet dat ze sommige materialen kunnen inleveren ter reparatie' – Senior Military Officer for Technical Documents [g], 2024*	R3-R7
	Public opinion and societal readiness for transitioning to sustainable practices, including resistance and unfamiliarity	*'Public opinion in Europe, struggling enough, prices aren't as low as we would like, would be possible that things will even further delay when implementing some strategies' – Strategic Analyst at a not-for-profit research organisation [j], 2024*	R0-R9
Regulatory	Lack of industry-specific regulations and guidelines for implementing circular strategies, leaving implementation decisions to the discretion of companies	*'Er wordt onvoldoende rekening gehouden met CRMs in het selectieproces' – Former Senior Military Officer Maintenance & Logistics [f], 2024*	R0-R9
	Limited political awareness and support for sustainability initiatives, particularly in recognizing the potential impact of future conflicts and the importance of sustainable resource management	*'Politiek Nederland is nog niet volledig bewust van dat we binnen een voorzienbare tijd een grootschalig conflict kunnen hebben waarbij NL betrokken is'* – Senior Military Officer Maintenance & Logistics [d], 2024	R0-R9
	Failure to track the origins of products and consider critical raw materials (CRMs) in procurement processes indicating a gap in regulatory frameworks for sustainable sourcing	*'Defence does have knowledge of system level but not of the supply chain: who's in charge of the various sub components et cetera, then then it gets a bit blurry '- Strategic Analyst at a not-for-profit research organisation [j], 2024*	R0-R9
	Democratic decision-making processes and regulatory constraints slowing down policy implementation and hinder swift action for sustainability initiatives	*'Regelgeving beweegt niet snel genoeg mee met sommige ontwikkelingen' – Advisor Sustainability, Environment and Safety [h], 2024*	R0-R9
	Security constraints on material handling and recovery	*'Dan zijn er absoluut ook wel systemen geweest die zwaar onder vuur zijn gekomen, komen te liggen en die je op dat moment gewoon ook niet meer kon bergen. Ja dan gebeurt het wel dat die dingen daar ter plekke vernietigd worden. En, dat betekent een of twee granaten erin opblazen, zodat de vijand er niks meer aan heeft' - Senior Military Officer Maintenance & Logistics [d], 2024*	R3, R7, R8 & R9

Market	Commercial considerations driving product lifecycle decisions, potentially leading to premature end-of-life for products	*'De industrie heeft er belang bij om dingen niet open te laten maken' – Former Senior Military Officer Maintenance & Logistics [f], 2024* *'Hoe dichter wij bij de civiele markt producten kopen, hoe lastiger dat wordt Omdat de omloopsnelheid van bepaalde producten en levenscycli van die producten veel sneller gaat dan dat het bij ons gaat'* – Senior Military Officer Maintenance & Logistics [d], 2024	R1 & R3-R7
	High dependence on external suppliers due to low availability of other suppliers	*'The defence spending budget is only a fraction of total GDP and thus a small fraction of the customer base of manufacturers' – Minerals and intelligence researcher [l], 2024* *'Er zijn zeker een aantal producten waarvan de markt zegt van, hé maar luister, ja dit is het. En dat Defensie, willen ze het hebben, dan zullen ze dus akkoord moeten gaan met datgene wat er te leveren is' – Advisor Sustainability, Environment and Safety [h], 2024*	R0-R2
	Limited control over supply chain sustainability and circularity	*'Producers don't know exactly where their materials come from, especially as they often don't manufacture a lot of components, they just build them together. Sometimes they know where their components come from but don't know those secondary suppliers from which they got materials and their subcomponents' – Strategic Analyst at a not-for-profit research organisation [j], 2024*	R0-R9
	Insufficient emphasis on circularity and CRMs requirements in procurement processes, leading to limited integration of sustainability criteria	*'We zijn niet dwingend genoeg over de eisen in het eisenpakket bij de werving. Circulariteitseisen zijn eigenlijk nog niet of nauwelijks ingebed In de verwerving' – Senior Member of an international military organisation on Climate and Security [i], 2024*	R0-R9
	Lock in effect. Once a product is purchased, there's limited flexibility to replace or upgrade components, tying users to the original supplier and limiting circularity	*'Als je iets hebt gekocht, zit je voor de levensduur van dat wapensysteem vast aan alles wat daarin' – Senior Military Officer Maintenance & Logistics [d], 2024*	R3-R7

	Economic considerations preventing investments in sustainable alternatives and favouring new purchases over repair or remanufacturing	*'Het is duur om bepaalde specificaties te verplichten waardoor NSN nummers niet altijd hetzelfde blijven' – Senior Military Officer for Technical Documents [g], 2024*	R0-R7
	Lack of transparency in supply chains: Product specification developers may not have visibility into the origins of raw materials, complicating efforts to ensure sustainable sourcing	*'Ik denk dat we niet eens kennis hebben van waar grondstoffen vandaan komen' – Senior Military Officer Maintenance & Logistics [d], 2024*	R0-R2
Technological	Long development times for new designs and technologies	*'You don't have a lot of time in terms to implement circular design as the window of opportunity is already shortening to reach goals for even 2050 as the products last 20-30 sometimes 40 years' – Strategic Analyst at a not-for-profit research organisation [j], 2024* *'Het duurt ongeveer 30 jaar om een vliegtuig te ontwerpen. Soms kan je dan toekomst ontwikkelingen niet inschatten' – Former Employee at an aerospace manufacturer [m], 2024*	R0-R2
	Stringent requirements for products to perform under various environmental conditions, including extreme climates, complicating design and maintenance	*'Producten moeten voldoen aan alle soorten omstandigheden zoals klimaat. - tussen de min 30 tot en met de plus 50 nou. Dat is nogal een klimaat range' – Senior Military Officer Maintenance & Logistics [d], 2024*	R0-R2
	High prevalence of unique parts and components, leading to inventory management challenges and difficulties in maintenance and repair	*'Er zijn veel unieke onderdelen: We hadden In de SAP 450.000 unieke Partnummers waarvan 260 000 daadwerkelijk op voorraad liggen, dat maakt onderhoud moeilijk' – Former Senior Military Officer Maintenance & Logistics [f], 2024*	R4-R5
	Complexity of the applications and lack of tracking systems making it difficult to identify and manage materials through the life cycle	*'Producers don't know exactly where their materials come from, especially as they often don't manufacture a lot of components, they just build them together. Sometimes they know where their components come from but don't know those secondary suppliers from which they got materials and their subcomponents' – Strategic Analyst at a not-for-profit research organisation [j], 2024*	R0-R9

	Technical difficulties in redesigning products to meet circular economy requirements	*'Maar de barrières, als die er zijn, zouden vooreerst op technisch niveau liggen' – Strategic Analyst at a not-for-profit research organisation [k], 2024*	R0-R2
	Maximum efficiency requirements	*'If a system loses 3 or 5% of efficiency, in civil it would not be an issue and could even be used as new. However for defence it has to have a maximum efficiency' – Strategic Analyst at a not-for-profit research organisation [j], 2024*	R0-R9
	Lack of maintenance due to a shortage of manpower or a limited timeframe	*'Onderhoud voor batterijen moet eigenlijk elke 3 maanden, door mankracht te kort is dat iedere 6 maanden of zelfs niet' – Senior Military Officer for Technical Documents [g], 2024* *'Op het moment dat hij gelijk de lucht zien moet, dan zou je wat minder onderhoud doen' – Former Employee at an aerospace manufacturer [m], 2024*	R3-R7

Table 16 - Identification of enablers and quotes

Level	Enablers	Quote	Strategy
Cultural	Growing recognition of sustainability initiatives contributing to the operational effectiveness	*'Wij zijn gaan kijken hoe dat wij een kamp in Afghanistan minder afhankelijk kunnen maken van energie. Daar was een operationele reden voor, want alles van aggregaten en airco's en alles wat op het elektriciteit draait' – Former Senior Military Officer Maintenance & Logistics [f], 2024*	R0-R9
	Only a small group of people can initiate a movement such as a shift towards sustainability	*'Je hebt maar een kleine groep mensen nodig om een beweging te starten die vervolgens wordt overgenomen door de rest van de groep' – Advisor Sustainability, Environment and Safety [h], 2024*	R0-R9
	The perception that saving on CRMs can contribute to strategic autonomy	*'als jij ervoor kunt zorgen dat er minder van die zeldzame mineralen in apparaten zitten of dat je die minder nodig hebt, dan ben je dus aan het werken aan je strategische autonomie' – Advisor Sustainability, Environment and Safety [h], 2024*	R0-R9

	Speaking in the same 'language' and frame the problem in terms of the recipient	*' it is a matter of knowing how we frame and present certain things' – Strategic Analyst at a not-for-profit research organisation [j], 2024*	R0-R9
	Cross-fertilisation of different agencies such as academia can increase awareness and help it include into the education of soldiers	*'In een living lab ontstaat ook kruisbestuiving. Doen experimenten, afstuderen, kost bijna niks alleen ruimte en krijgt er veel nieuwe ideeën uit waar je nieuw beleid uit kan halen' – Senior Member of an international military organisation on Climate and Security [i], 2024*	R0-R9
	Putting it on the agenda on the top of the hierarchy and provide room to the bottom	*'Ook de commandanten, de leiding, de leidinggevende moeten dit op hun agenda hebben staan. Er zit aan de onderkant heel veel creativiteit' – Senior Member of an international military organisation on Climate and Security [i], 2024*	R0-R9
Regulatory	Obligation of the industry including defence to comply with legislation including sustainability laws	*'In het kader van duurzaamheid hebben wij natuurlijk als overheidsorganisatie te maken met de Nederlandse regelgeving daarop' – Senior Military Officer Maintenance & Logistics [d], 2024*	R0-R9
	Political pressure mandating specific requirements for products such as the Critical Raw Materials Act	*'D.m.v. politieke druk kan je eisen stellen aan producten' – Former Senior Military Officer Maintenance & Logistics [f], 2024* *'Then you can financially support recycling by creating certain law incentives' - Circular Economy specialist [a], 2024*	R0-R9
	Possible regulatory priorities in Europe that could dictate differences of policy for civilian sector compared to defence	*'Als er extra transportcapaciteit nodig is, kan er bij transportfirma's in Nederland worden gezegd van: het is leuk dat je commerciële baan hebt, maar nu claimen wij deze voertuigen en wij gaan dingen mee doen' - Senior Military Officer Maintenance & Logistics [d], 2024*	R0-R9
	Contractual agreements with suppliers such as an extended supply of spare parts	*'Meer contracten invoeren waarbij defensie aan leveranciers eisen stelt voor leveren van reservedelen'- Senior Military Officer Maintenance & Logistics [d], 2024*	R2-R7
Market	Selling off materials at the end of their life cycle to boost the defence budget and drive sustainability	*'Het verkopen van materiaal aan het einde van hun levensduur geeft een impuls aan het budget van defensie en*	R2-R7

		is dus een drijfveer' – Senior Military Officer Maintenance & Logistics [d], 2024	
	The industry and EU striving for strategic autonomy	*'Ook bedrijven willen geen kwetsbaarheid hebben en zo min mogelijk afhankelijk zijn van landen' – Senior Member of an international military organisation on Climate and Security [i], 2024* *'Producenten hebben er ook belang bij dat er zo weinig mogelijk spullen in hun producten zitten waar ze moeilijk aan kunnen komen' – Former Senior Military Officer Maintenance & Logistics [f], 2024*	R0-R9
	Sufficient funds available for defence	*'Geld is geen probleem: wij hebben de macht van het geld' – Senior Member of an international military organisation on Climate and Security [i], 2024*	R0-R9
Technological	Design changes that eliminate the need for NdFeB magnets or CRMs and make maintenance easier	*'Design kan er voor zorgen dat het makkelijker te onderhouden is en misschien ook makkelijker om te produceren' – Former Employee at an aerospace manufacturer [m], 2024*	R0-R9
	Modular designs to continuous upgrade equipment	*'Modulair werken kan ruimte bieden aan continue upgrading' – Senior Member of an international military organisation on Climate and Security [i], 2024*	R3-R7
	More standardisation leading to more exchangeable parts facilitated by NATO by NSN numbers and easier maintenance	*'Door NSN nummers kunnen delen worden uitgewisseld met andere mogendheden, als deze nummers hetzelfde zijn' – Senior Military Officer for Technical Documents [g], 2024*	R3-R7
	Presence of technical knowledge by the presence of experts at military bases	*'Er gaan nu al soms mensen van Lockheed mee naar een legerbasis in een ander land om onderhoud te plegen, kennis is er dus' – Former Employee at an aerospace manufacturer [m], 2024*	R3-R7
	Possibility to 3D print spare parts	*'met een 3D printer kunnen we reservedelen printen in het inzetgebied' – Former Senior Military Officer Maintenance & Logistics [f], 2024*	R3-R7
	Possibility to reuse/repurpose some equipment or materials in civil sector	*'Materiaal (zoals vrachtwagens) wordt na hun levensduur afgestoten en vaak krijgen ze dan nog een tweede leven bij tactische materiaal aan andere landen of bij duaal*	R3 & R7

		materiaal naar de civiele sector' – Senior Military Officer Maintenance & Logistics [d], 2024	