Circular Economy Strategies' Impact on Critical Raw Materials in Servers:

A Case Study from the Perspective of a Dutch Telecommunications Company

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Abstract

Critical Raw Materials (CRMs), materials with high economic importance and supply risk, are the key components of strategic sectors, including Information and Communications Technology (ICT). With foreseeable growth in CRMs demand, principles such as Circular Economy (CE) strategies are gaining attention as means to mitigate risks associated with CRMs. This study examines the effect each CE strategy has on CRMs in servers, via case study of a Dutch telecommunications company. The study was conducted via collecting industry insights from 16 industry experts and performing literature review.

Results show that out of 47 types of CRMs, at least 20 CRMs are contained in 4 sub-assemblies and 2 extension tools of a rack server. Among the sub-assemblies, the motherboard is found to contain the most diverse types of CRMs, while the HDD contains the largest amount of CRMs.

CE strategies were investigated in two ways, first by studying current strategies implemented by the company and its value chain partners, and by investigating advanced practices and strategies discussed in literature. Results indicate that each CE strategy impacts the CRMs in sub-assemblies in different ways, while also having varied limitations in their potential. The result also shows that current implementation of CE strategies do not always lead to enhanced circularity of CRMs, as indicated in most of CRMs being lost in current recycling practices. The degree of effect also differs depending on the strategy and sub-assembly. In the case of the motherboard, substantial potential to improve circularity was identified in the substitution method and advanced recycling strategy, with more CE strategy in need for Ba and P containing components. For HDDs significant potential was observed in the functional substitution by SSDs and advanced HDD recycling technology. In addition, the strategies’ potential in mitigating the supply risk and environmental impact associated with CRMs was explored. While each strategy is seen to have potential in reducing risk, its effectiveness depends on multiple factors and further case studies will be necessary to quantify it.

The results imply that enhancing the circularity of CRMs is a complex challenge where diverse interest from actors in the value chain is involved. For this reason, the study stresses the need for an active collaboration among value chain partners and system-level support, to be able to design each CE strategy tailored for intended improvement in CRMs circularity. For the advancement of the topic, further studies are recommended, including the four goals of inventing secure ways for CRMs data sharing across the value chain, design for lifetime extension and CRMs recycling via collaboration between suppliers and downstream partners, finding economically viable business models for CRMs circularity, and assessing each CE strategy’s risk mitigation potential via specific case studies.

Acknowledgement

About exactly one year ago, with many uncertainties regarding the covid situation, I was wondering if I should come back to the Netherlands for the last academic year of my study. After encountering an opportunity to write about this topic - 'critical raw materials and circularity' at KPN, I made up my mind to come back and make the last academic year most valuable. From time to time I found it challenging working from home during the lockdown. Still, the past year has been a journey of immense learning and growth both in academic and professional aspects, and I never had a single doubt on the decision I made.

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Abbreviations

CPU	Central processing unit
CRMs	Critical Raw Materials
DIMM	Dual in-line memory module
HDD	Hard disk drive
ICT	Information and Communications Technology
IT	Information technology
NIB	Neodymium-Iron-Boron
NIC	Network interface controller
PCB	Printed circuit board
PCBA[1]	Printed circuit board assembly
PGMs	Platinum group metals
PMs	Precious metals
REEs	Rare earth elements
SmCo	Samarium-cobalt
SSD	Solid state drive
TI	Telecom infrastructure
VRP	Value Recovery Partner
ZB	Zettabyte

Chemical element

Al	Aluminum
Bi	Bismuth
Ce	Cerium
Co	Cobalt
Dy	Dysprosium
Er	Erbium
Fe	Iron
Ga	Gallium
Ge	Germanium
In	Indium
Li	Lithium
Mg	Magnesium
Nd	Neodymium
Pd	Palladium
Pr	Praseodymium
Pt	Platinum
Sb	Antimony
Tb	Terbium

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[1] PCBA is used to describe the motherboard among suppliers, while PCB is widely used for recycling practices. Therefore, both terms are adopted to describe the motherboard in this study.

1. Introduction

1.1. Critical Raw Materials and circularity

1.1.1. Significance of CRMs

Raw materials are crucial for products and technologies used in our everyday lives. With advances in technology and economic growth, the global annual demand for natural resources including minerals and ores is expected to increase threefold reaching 140 billion tons by 2050 if the current trend continues (UNEP, 2011). As securing materials with high demand becomes strategically important, the European Union (EU) has identified critical raw materials (CRMs) since 2011 and has updated the list every three years (European Commission, 2020a). The most recent version of the list, as seen in Table 1, was published in 2020.

Defined as raw materials with high economic importance and high supply risk, CRMs are seen as key components of emerging technologies and innovations which will allow for an enhanced quality of life and an energy transition tackling the major societal challenge of the era: climate change (Hofmann et al., 2018). They are expected to play an especially essential role in the strategic sectors of digital technologies, renewable energy, electric mobility, defense, and aerospace (European Commission, 2020b).

Antimony	Hafnium	Phosphorous
Baryte	Heavy Rare Earth Elements (HREEs)	Scandium
Beryllium	Light Rare Earth Elements (LREEs)	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	Bauxite
Fluorspar	Niobium	Lithium
Gallium	Platinum Group Metals (PGMs)	Titanium
Germanium	Phosphate Rock	Strontium

Table 1. List of CRMs (European Commission, 2020a)

Among the sectors, the use of CRMs in Information and Communications Technology (ICT) is seen as fundamental. ICT not only supports the majority of our daily business and communication, but also enables digital technologies required for all other strategic sectors (European Commission, 2020b).

Diverse types of CRMs frequently appear in ICT devices. According to Kleinmagd (2020), 29 types of CRMs were identified from the study on four example ICT devices, as seen in Table 2.

Si	4	**B**	2	**He**	1
P	4	**Ge**	2	**Be**	1
Ga	4	**Ru**	2	**V**	1
Ba	4	**Pt**	2	**Y**	1
Mg	3	**Bi**	2	**Nb**	1
Co	3	**La**	2	**Hf**	1
Rh	3	**Ce**	2	**Pr**	1
Pd	3	**Nd**	2	**Sm**	1
In	3	**Dy**	2	**Gd**	1
Sb	3			**Er**	1

Table 2. CRMs occurrence in four ICT devices (Adjusted from Kleinmagd, 2020)

With the trend of digitalization and digital transformation, the demand of CRMs for the ICT industry is expected to increase exponentially in the coming years (European Commission, 2020b). One main result of the trend will be the exponential growth in the amount of data produced and stored in data centers or other data endpoints. According to The International Data Corporation, the global datasphere – the gross sum of all the data produced – will reach 175 Zettabytes (ZB) by 2025 compared to 33 ZB in 2018 (Reinsel, Gantz, & Rydning, 2018). This will increase demand for CRMs required to produce memory units that process and store the data. In the case of Nd, the material used for the permanent magnet within hard disk drives (HDD), up to 80 kilotonnes of Nd is expected to be in demand to meet the growth of the datasphere by 2025, which amounts to about 120 times of the current EU demand (Ku, 2018a).

At the same time, CRMs are key constituent materials for low-carbon technologies. Rare earth elements (REEs) such as Dy, Nd, Pr and Tb are used for permanent magnets of wind turbines. Ga, Ge, In, Ga are necessary for solar cell production. Dy, Nd, Pr are again required for high-performing magnets in electric vehicle motors. CRMs such as Co, Li, and natural graphite are used in Li-ion batteries for energy storage, while platinum group metals (PGMs) are essential for fuel cells that convert hydrogen into electricity (Carrara et al., 2020; Charles et al., 2020; European Commission, 2020a).

With the worldwide acceleration of energy transition, the demand of the CRMs required for low carbon technologies are facing a tremendous increase. For example, in the 'most demanding scenario for EU countries,' the annual demand for the REEs contained in wind turbines is expected to grow 15 times by 2050 compared to 2018. The growth in CRMs demand is expected for all materials related to photovoltaics (PV) deployment in its 'high demand scenario.' In and Ga demand for instance are expected to increase 40 times by 2050 (Carrara et al., 2020).

1.1.2. Concerns regarding CRMs supply risks

As the demand for CRMs are ever-increasing, concerns grow regarding the supply risk of the materials. Supply chain risk, one of the two main factors considered for the criticality assessment by the EU, refers to factors influencing the procurement of necessary materials incurred by suppliers, manufacturers, and distributors (Griffin et al., 2019). The main concern of potential supply disruption is due to the fact that globally the extraction of CRMs is highly concentrated in only a few countries. For example, as seen in Figure 1, China is the major supplier for Sb, Bi, Mg, and REEs while South Africa and Russia are the largest supplier for PGMs. Not only the initial extraction but additional processing such as smelting and refining also take place in a limited number of countries (European Commission, 2020a).

Adding to the fact that the supply and processing of CRMs are concentrated in a few countries, multiple factors can cause supply disruption of the materials, such as scarcity, natural disasters, political conflicts, and demand volatility. Geopolitical risks are often highlighted as primary in affecting the supply of CRMs, as the producing countries can restrict the availability of materials by imposing controls or limits on the export of the materials. Such measures can have immense consequences with regard to the price volatility and supply chain in the economies relying on the import of the materials (Griffin et al., 2019).

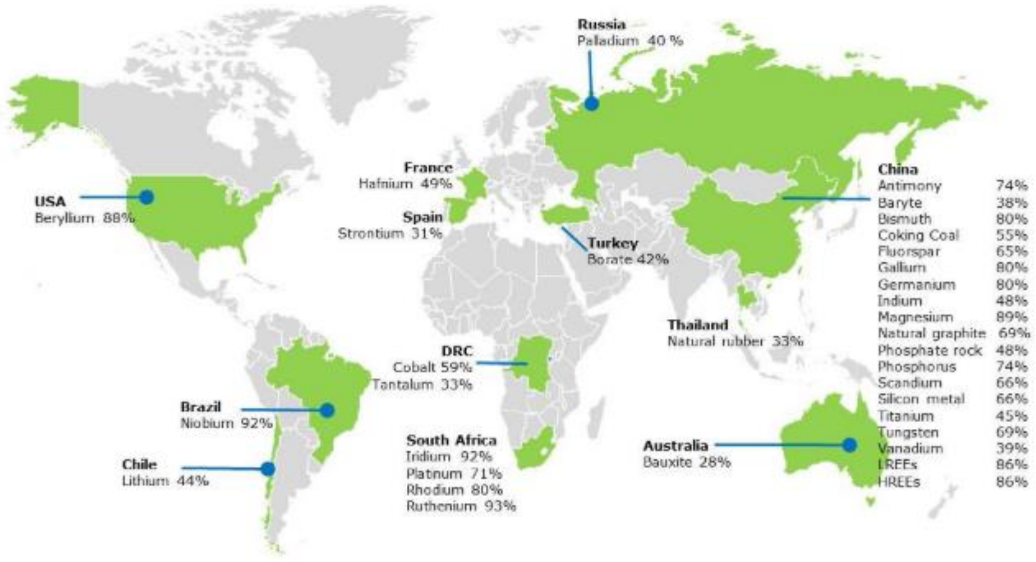


Figure 1. Countries accounting for largest share of global supply of CRMs (from European Commission, 2020a)

The supply risk is especially concerning to the economy of the EU, as the upstream - the production and harvesting - of many CRMs does not exist in the EU. Its economy is mainly saturated with the manufacturing and refining industries, whose processes take place after the extraction of raw materials or at the end-of-life stage of a final product (European Commission, 2018). Mobilizing the materials present within European region can be one mitigation plan, however they cannot provide timely supply to meet the region's domestic demand. Establishing new mining sites usually requires long-term and large-scale investment and is therefore not an adequate solution to respond to short-term changes in the supply chain. Therefore, the EU does not have other options but to rely on the import of the materials which comes with high supply risk. Mitigating the supply risk is crucial to the survival of the economy, as the potential disruption can greatly impact the availability of final products and the competitiveness of involved industries (European Commission, 2020a).

Kolotzek et al. (2018) describes that the three dimensions of sustainability need to be considered when assessing the criticality of materials in the corporate context. Likewise, the environmental and social impact of CRMs are considered as an additional dimension of risk along with supply risk in the study, as seen in Table 3.

Sustainability dimensions for criticality assessment (Kolotzek et al., 2018)	Indicator category
Supply risk dimension	Concentration risk
	Demand increase risk
	Political risk
	Supply reduction risk
Environmental dimension	Impact on ecosystem quality
	Impact on human health
Social dimension	Impact on local community
	Societal factors
	Working conditions

Table 3. Description of risks considered for criticality assessment of materials
(Adjusted from Kolotzek et al. 2018)

From a corporate perspective, negative impacts of supply chain disruption are proven to be substantial and long-term (Gaustad et al., 2018; Griffin et al., 2019). Supply disruptions were found to result in 13.5% higher share price volatility, 107% drop in operating income, and 114% drop in sales return (Henricks and Singhal, 2005a; 2005b). It is estimated to take two or more years for firms to recover their business to the level before the disruption, while some end up failing to return to the same level of performance (Henricks and Singhal, 2005a & Sheffi and Rice Jr, 2005).

Despite the risks, the demand for CRMs continues to rise and is expected to multiply in the near future in strategic sectors. To realize a low-carbon economy and reduce the impact of climate change, the demand for low-carbon technologies needs to be met with a secure supply of required CRMs. At the same time, the supply of CRMs for digital technologies remains crucial as they form the basis of an overarching range of technologies, also enabling a smarter deployment of low-carbon technologies, as seen in the operation of smart grids. The European Commission (2020b) foresees that the high growth rate of future strategic sectors will not directly transform into supply bottlenecks; however, it will depend on the balance of supply and demand between sectors. Therefore, sustaining that balance will be the key factor determining the successful transition into a smarter and low-carbon future.

Concerning the high-risk factors CRMs bring to the supply chain of businesses, there need to be risk mitigation strategies which can be deployed at a firm level. As proven by Henricks and Singhal (2005), firms are main bodies whose business heavily rely on the supply of the materials and at the same time experience firsthand the consequence of the supply disruptions. Moreover, they hold little control over external factors that affect the risks (Griffin et al., 2019). Simultaneously, they constantly face growing pressure from customers and competitors to incorporate environmental and social considerations into their supply chains (Kolotzek et al., 2018). For this reason, alternative strategies that can help firms prevent and alleviate the supply, environmental, and social risks associated with CRMs are highly sought after.

1.1.3. Circularity as a possible mitigation strategy

Among the strategies in discussion for the mitigation of the risks associated with CRMs, application of Circular Economy (CE) principles has gained attention in both policy and academic arena as potential strategy that can stabilize the supply chain by reducing the demand of new primary resources (Gaustad et al., 2018). The EU announced 'circular use of resources' as one of its action plans for secure and sustainable supply of CRMs. The announcement states that the secondary use of the materials is expected to bring advantages in both supply security and reduction in energy and water use (European Commission, 2018b).

Rising as an alternative to the dominant linear economic system of 'take, make, and dispose,' CE aims to keep products, components, and materials at their highest utility and value at all times (Webster, 2017). Thereby the CE aims to slow, close, and narrow resource loops in the economic system (Bocken et al., 2016). With the aspect of closing the resource loop, two additional aspects are often added to describe the concept: firstly, that CE is restorative and regenerative by intention and design (EMF, 2013 & Webster, 2017), and secondly it enables economic prosperity while maintaining the quality of the environment (Sihvonen & Ritola, 2015). Considering the restorative characteristic of the concept, other environmental aspects such as the use of renewable energy (EMF, 2013), and minimizing the emissions and energy leakage are stressed together with closing the resource loops (Geissdoerfer et al., 2017).

Variety of CE principles have been discussed as pathways to achieve CE. The 3R framework of 'reduce, reuse, and recycle' principles are most frequently used to describe the circular economy. The framework at the same time expands to broader frameworks, from 4R with 'recovery,' to 9R (Kirchherr et al., 2017) as described in Figure 4.

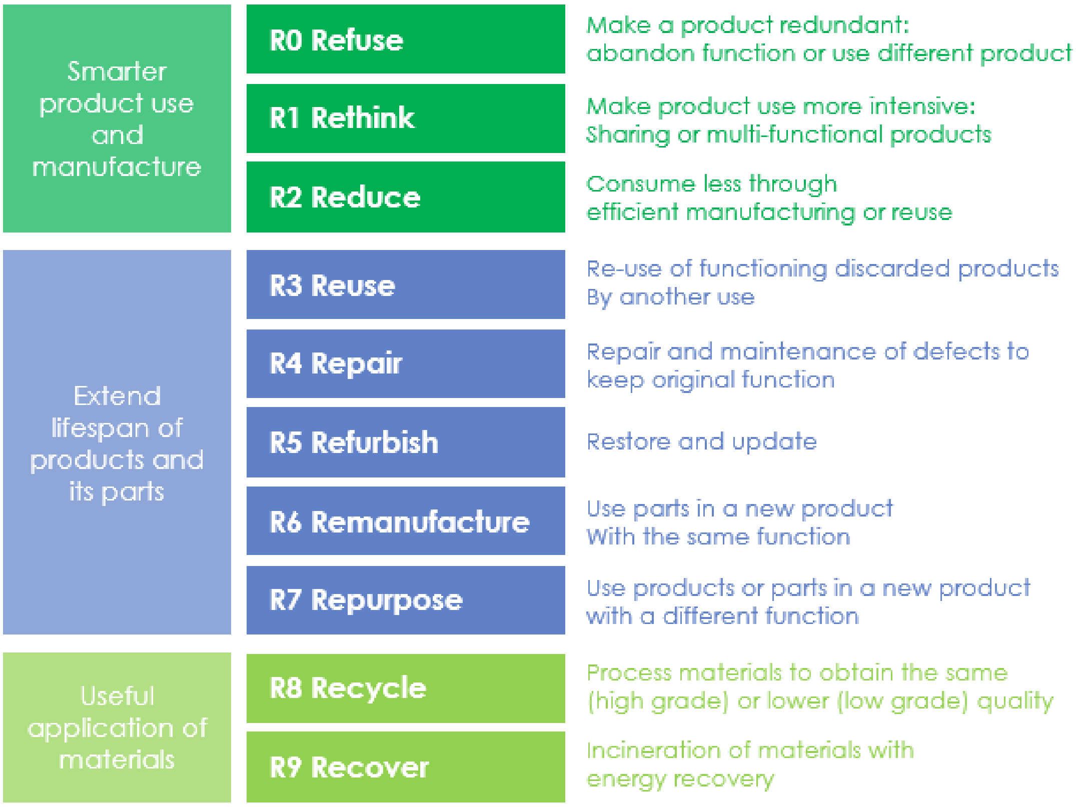


Figure 4. Description of CE principles based on (Potting et al., 2017) (from PRé Sustainability, 2020)

Applying CE principles to points of leverage under a firm's scope is seen as an effective strategy to make its CRMs supply chain resilient. According to Gaustad et al (2018), diverse types of CE strategies, such as recycling, reuse, and extensively dematerialization and diversification of supply chain bring substantial potential in tackling the supply chain vulnerability. For example, recycling of CRMs can provide a part of in-house source or a domestic source. A representative example was shown in the case of China where the recycling of In was found to have potential in meeting up to 24% of domestic demand by 2020 (Duan et al., 2016).

In addition, the use of secondary CRMs is expected to bring significant environmental benefits. The energy and water consumption found to be much lower when producing metals from scraps, compared to the case of ores. The circular use of CRMs has potential in bringing other environmental advantages, for example lower impacts to biosphere and reduced waste per ton of extracted material (European Commission, 2018).

While diverse CE strategies are gaining attention as potential risk mitigation strategies for CRMs, they come with limitations. The recycling rate of many CRMs stays at a negligible level due to multiple economic and technical barriers (Gaustad et al., 2018). A few types of CRMs show substantial recycling rates; however, the amount of recycled materials is not sufficient to meet the growing demand and therefore takes up a limited part of raw material supply. For example, the recycling rate of PGMs reaches up to 95%, however the secondary PGMs covers only 14% of raw material supply. Additionally, CRMs locked in assets with long lifetime can be another factor delaying the CRMs supply for the recycling input (European Commission, 2018).

Potting et al. (Potting et al., 2017) points out that promoting more circularity can lead to causing less circularity or more environmental burdens. The study mentions that advanced recycling technology for the recovery of certain materials can lead to more resource use, such as fossil fuels. Also worth noting is that the circularity of CRMs is largely affected by the sector they are used in. The demand, length of use, and the recyclability for CRMs rely on the nature of the product they are contained in (European Commission, 2018). The benefits circularity brings in terms of reduced primary material production and less environmental impact are widely regarded as a rule of thumb (Ganzevles et al., 2016). However, the above examples indicate that a thorough review needs to be conducted on a business level to fully identify how CE strategies can influence the CRMs used in a specific product and business area.

1.2. Research gap

The significance of CRMs in strategic sectors such as the ICT industry remains high, and therefore the need for CE strategies to mitigate associated risks are greatly recognized. However, there seldom was a case study on what influence CE strategies can potentially bring to CRMs in the industry or corporate-specific context. A few studies looked into the CRMs treatment in the automobile industry at the product's end of lifetime (Cucchiella et al., 2016) and clean energy technologies (Mocker et al., 2015; Schmidt et al., 2019), however, the study was limited to the value, demand, or criticality assessment of CRMs and did not examine the potential set of circular strategies applicable for CRMs that corporates can incorporate into their businesses.

Some research has been conducted with a focus on CRMs contained in ICT equipment with a general scope. However, none were relevant to the concept of circularity or focused on the ICT industry. Studies conducted by Chancerel et al. (2013; 2015) provide quantity estimation of CRMs in ICT equipment, however it does not investigate relevant CE strategies. Some studies investigate CRMs recovery options of frequently used electronic devices or components including a few ICT equipment, but the scope of selected products was spread over multiple industries (Jo et al., 2019; Işıldar et al., 2019).

Among ICT devices, a few studies were conducted on enterprise servers, from the perspective of circularity, material efficiency, and eco-design (Commission, 2015; Fulvio & Peiró, 2015; Talens Peiró et al., 2020; Weloop, 2020). However, the studies either lacked specific focus on CRMs, or did not cover diverse types of CE strategies but focused on a few materials or a limited number of strategies such as recycling.

A criticality assessment and mitigation strategies applied by General Electric (Gaustad et al., 2018)) provide useful insight for manufacturing companies. However, the cases come with a limitation that they are mainly useful for manufacturers and the manufacturing process. It is rare to find a cast study that speaks for the business actors that are located in later tiers in the supply chain, who are often customers of original equipment manufacturers (OEM). A case study from the perspective of these non-manufacturing, service provider companies would bring new insight to various firms providing services in similar tiers of the value chain.

Likewise, the lack of studies on CE strategies' potential impact on CRMs on a firm level fails to provide scientific support necessary for businesses to translate the goal of CRMs supply resilience into action. At the same time, existing criticality studies conducted on a firm level show limitations in covering the perspective of non-manufacturers, such as a service provider. Considering the growing need for circular strategies for CRMs and the fundamental role ICT serves for other strategic sectors, there is a strong need to investigate CE strategies for CRMs used in the ICT industry, especially from the perspective of a service provider.

1.3. Research approach

For this reason, a case study of a Dutch telecommunications (telecom) and ICT service provider will be conducted, to identify the effect CE strategies have on CRMs used in the ICT industry. KPN, a major telecommunications and ICT service provider in the Netherlands has set a goal to achieve material circularity in its business operation by 2025 (KPN, 2017). Starting with applying the goal to mass materials, the company recently started investigating the circularity potential to the extent of CRMs. The criticality assessment of CRMs frequently used in its ICT equipment has been conducted as an initial study regarding CRMs at KPN last year (Kleinmagd, 2020). With the findings, KPN wants to understand how existing and possible CE strategies can influence the usage of CRMs and associated risks.

Considering that the usage of CRMs differs between ICT devices, one reference device, the server, has been chosen for the study. The study will therefore focus on the CE strategies applicable to servers, especially on the two sub-assemblies chosen as the focus of the study which are further explained in chapter 3.1.3. Thus, the CRMs discussed in the paper will also focus on those identified to be contained in the focus sub-assemblies.

In specific, the goal of the research is to investigate how CE strategies influence CRMs in servers and risks associated with them, via a case study of a Dutch Telecom and ICT service provider. It will first identify the CRMs contained in servers, and CE strategies applicable to servers, and lastly discuss the strategies' impact on contained CRMs. Accordingly, the research questions will correspond with the mentioned goals, as described in Figure 5.

1.4. Report structure

The paper follows the structure in Figure 5. to answer the main and sub research questions. After the introduction, a methodology will be described including a clarification on the scope of the study. The result will follow, where the initial answers to the three sub-questions are given. The first chapter of the result will begin with explaining the server's role at the telecom service provider. Later the paper will identify CRMs contained in servers, and with the result of gathered data the sub-assemblies of focus will be decided. The second chapter of the result will discuss CE strategies applicable to servers. First it will give an overall description on downstream processes of servers in place at the company. Then it will explain CE strategies applied to the chosen sub-assemblies of servers in practice, among current partners of KPN. Later, it will further investigate advanced strategies that are found to be possible in practice or in theory. In the last chapter of the result the effect CE strategies has on CRMs will be examined. First it looks into what kind of effect each strategy brings to each sub-assembly, and to what extent such effect is taking place in practice or can potentially happen. Secondly it checks to what types of CRMs each strategy has an impact on, and thereby identifies CRMs under substantial effect, or little effect therefore need further attention. Lastly, the section explores what effect the strategies can have on supply risk and environmental risk associated with CRMs. In the discussion section, the reason behind the gap between practices and possibilities are analyzed. The second part of discussion identifies points of leverage found throughout the research, that can be exerted along the product value chain and from a system level. In the end, conclusions and recommendations for future research are provided.

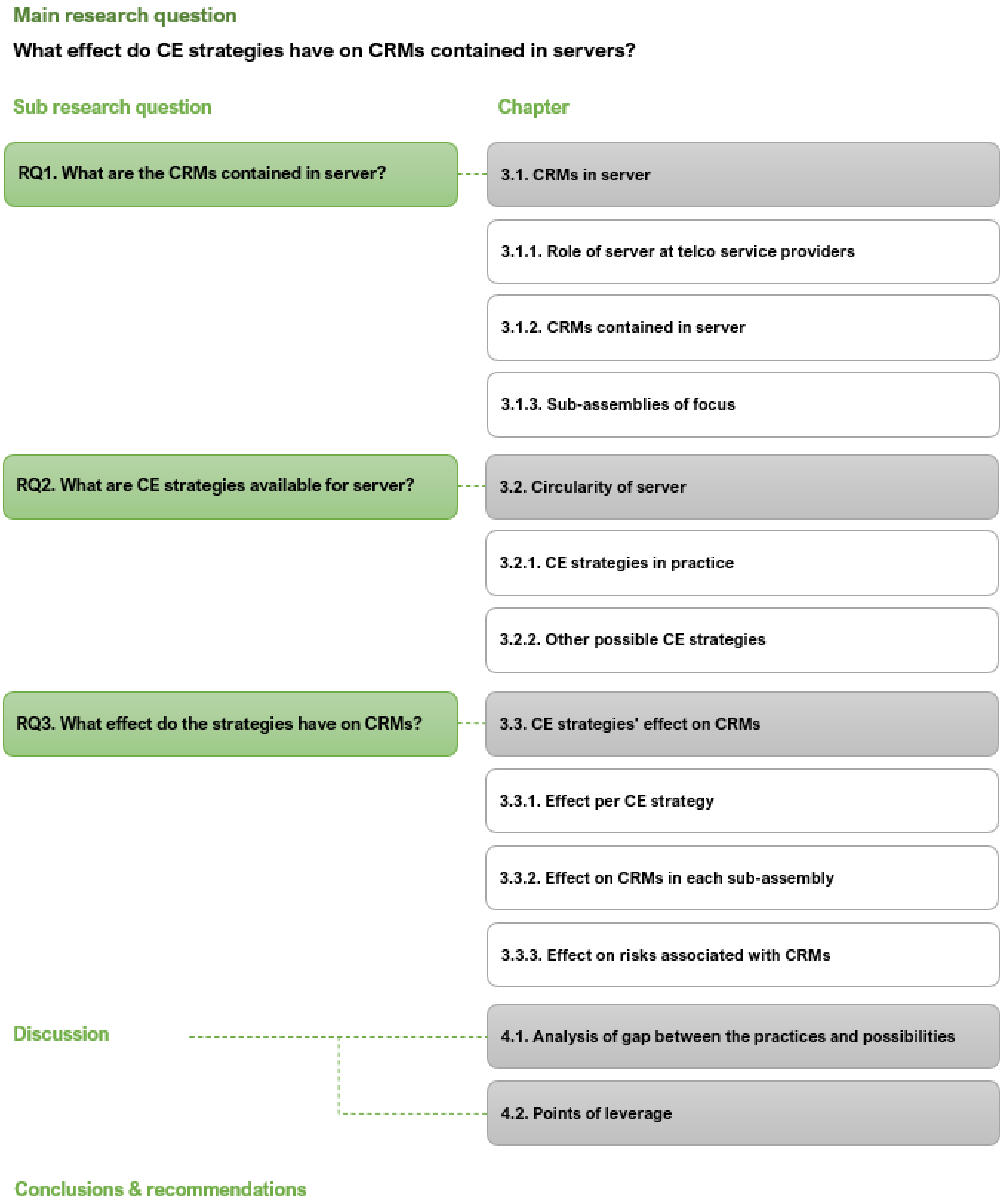


Figure 5. Research questions and report structure

2. Methodology

2.1. Applied methodology

As the study looks into an existing business case, empirical data gathering methods such as interviews, surveys, and field research were used in combination with desk research as the main research methodologies. Especially multiple interviews and personal communications were conducted with internal experts within KPN and relevant parties, with details of interviewees described in below Table 4.

Party	Type of business	Title
Supplier A	Original equipment manufacturer, large multinational IT company	Sustainability Team
VRP A	Value recovery service partner, small to medium IT company	Director
		Senior Accountmanager
VRP B	Value recovery service partner, small to medium IT company	Sales Director
Pre-processor A	Pre-processor, small to medium recycling company	Manager
		Senior Accountmanager
Pre-processor B	Pre-processor, small to medium recycling company	International Trader
End-processor A	End-processor, medium to large multinational materials technology company	Project & Supply Manager
Telecom service provider A	Telecom service provider, large multinational telecom company	Life Cycle and Circular Economy Analyst
KPN	Telecom service provider	Advisor Sustainability and Circular Economy ACN Sustainability & Support
		Contract and Service Manager ACN Sustainability & Support
		Architect Telco Cloud & Datacenter Services
		Datacenter Specialist and Senior Server and Cloud Consultant
		Strategic Lead Energy & Environment
Leiden University	Academic institute	Institute of Environmental Sciences (CML)

Table 4. List of experts participated in interviews

As seen in Figure 6, internal interviews and literature review were conducted to understand the role of servers in telecom and ICT business. Core data on CRMs contained in servers was collected via interviewing and requesting data to manufacturing partners and was complemented by additional data found in literature. Investigation of CE strategies involved multiple empirical methodologies. Internal and external semi-structured interviews were conducted to understand the downstream process of servers, detailed refurbishment processes at value recovery partners (VRPs), and details of the recycling processes. In the case of the disassembly and pre-treatment processes of the current recycling practice of KPN, a field visit was conducted to provide detailed understanding and context.

Possible CE strategies were investigated mainly via literature review and interviews. In the case of substitution data, a survey was shared with motherboard and HDD suppliers for a cross-checking of the data. Information gathered in the first two chapters of the result was reviewed in detail with other literature to identify CE strategies' effect on CRMs and the associated risks. In the discussion, the analysis of the gap between current practices and possible strategies was performed with opinions from industry experts and information found in literature and online data search. Lastly, the leverage points were gathered and discussed by incorporating the findings and insights gained throughout researching current and potential CE strategies.

Figure 6. Research and analysis methodology applied for each chapter

2.2. Scope definition

Sub-assemblies and CRMs of focus

Not every CRM is a common constituent of ICT devices, and contained CRMs differ between each ICT device. Therefore, the study focuses on the CRMs contained in the reference device of study, especially on the CRMs contained in the sub-assemblies of focus defined in chapter 3.1.3. Likewise, usages of the term 'CRMs' that appear after the chapter can be understood as indicating the 'CRMs contained in the selected sub-assemblies of the server.'

CRMs data

CRMs data gathered from suppliers is used as the basis of study. However, additional data gathered during the research (for e.g., PCB of the HDD, and the SSD) has been included in chapter 3.1.3. and Appendix A.1.

Definition of circularity

The study mainly focuses on the aspect of 'material' throughput of the economy among diverse aspects associated with the concept of circular economy. Therefore, the discussion mainly consists of ways to slow, close, and narrow down the CRMs 'resource loop' via CE strategies. However, considering the regenerative and prosperity-driven characteristic of the CE concept, the paper tries to incorporate the other aspects by taking into account the environmental impact and business perspective while interpreting the result.

Circular economy (CE) strategy

Among the CE principles introduced in chapter 1.1.3., strategies of high relevance to servers are mainly discussed in the paper. The 3R principle of 'reduce, reuse, recycle' is used as the overarching framework to introduce and categorize CE strategies. However, the paper refers to specific strategy names as indicated in 9R principle (e.g. direct reuse, repair, refurbish, remanufacturing) when explaining the details of each strategy under the umbrella of 3R principle (e.g. reuse).

Types of risks associated with CRMs

Diverse types of risks associated with CRMs under the dimension of supply, social, and environmental aspect are explained in chapter 1.1.2. However, when the CE strategies' impact on risks associated with CRMs is discussed in chapter 3.3.3., the section mainly focuses on the discussion of supply risk and environmental risk of CRMs.

3. Results

3.1. CRMs in servers

3.1.1. Server and telecommunications service

Server's role at telecom service provider

A server is defined as a computer designed to process requests, store data, and deliver the data to other computers over the internet and local network. At a telco service provider, the device delivers a distinct role for multiple service platforms and therefore requires different specifications.

In the telco environment, the server can be seen as a compute platform where multiple processing units are built in to process instructions of code in order to provide a direct function. Software applications and programs needed for telecom services are installed and run on the physical device to provide intended functions. Some components of servers are especially crucial for the provision of the functions. First, the processing of instructions is executed by a physical processor that retrieves, interprets and executes instructions for which it retrieves additional data from memory (RAM). In case instructions or data are not yet loaded in RAM, an Operating System is used to load the digital information from a storage medium such as a hard disk integrated directly in the server or connected by a storage network. Telecom applications in general require many cores (typically 20-24) per processor and a lot of RAM (typically 384GB) in order to provide the required performance as per Telecom protocol specification, as obtaining the code from other storage sub-assemblies such as HDD or the SSD requires longer retrieval time than RAM. The last distinct functionality of the server relies on the network interface card (NIC). The card provides the connectivity to the local network that connects the server with other servers in its vicinity, and to other networks and the internet. Therefore, adding to other default sub-assemblies of the server, the four components: processor, RAM, storage disk drive such as HDD or SSD, and NIC are seen to be crucial for the telco service operation (Internal Expert #3, personal communication, April 9, 2021).

As seen in Figure 7, servers deliver specific functions for each platform at KPN. Among different platforms, IMS (a telecom standards-based platform for delivering real-time voice telephony and messaging communications services) and OMC (a telecom standards-based platform for delivering real-time session and mobility management for mobile 2G, 3G, 4G and 5G terminals) platforms can be seen as the platforms where the servers deliver a telco-specific function distinct from other cloud service providers. In the two platforms in charge of voice and mobile data service, servers in each platform are grouped into either general or specific purpose servers where they are used for designated functions.

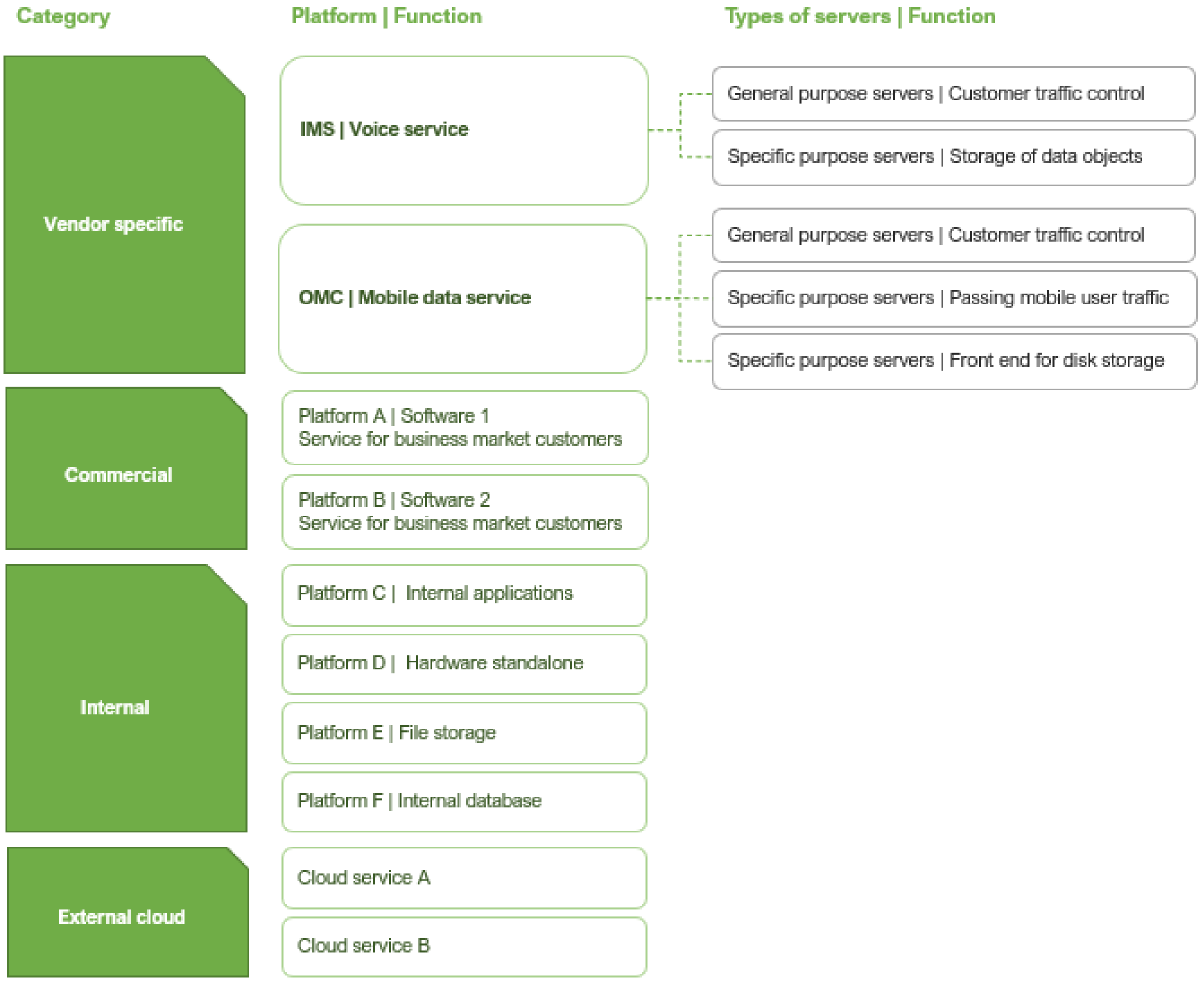


Figure 7. The role of servers in service platforms of KPN

As part of fixed network devices, a potential disruption in the supply of servers is found to bring a potential in impacting every service provided by KPN (Kleinmagd, 2020). While such a scenario seems unlikely as a company would generally monitor the situation, this still shows the importance of developing risk mitigation strategies for the CRMs contained in the server.

3.1.2. CRMs in servers

Data on CRMs contained in the server was collected via interview with and request of data to partner suppliers and industry experts. Gathering a complete collection of CRMs data was however found to be highly challenging, as the investigation and collection of CRMs data is a new endeavor for suppliers themselves while often suppliers higher up the supply chain are hesitant to share the data as it is regarded proprietary (Supplier A, personal communication, March 2, 2021). High complexity of the value chain with numerous tiers of suppliers involved also adds difficulty to the collection of the data (Kleinmagd, 2020).

Figure 8. summarizes the CRMs data gathered in multiple sub-assemblies and extension parts of a rack server. The figure briefly shows compiled data on types of CRMs and their contained mass, with detailed data provided in Appendix A.1.

Among the ten sub-assemblies of a server: motherboard, hard disk drive (HDD), solid state drive (SDD), dual in-line memory module (DIMM, RAM stick), central processing unit (CPU), smart network interface controller (NIC), disk array (RAID) controller, peripheral component interconnect (PCI) bus, power supply unit, smart battery, CRMs data concerning the four sub-assemblies of motherboard, HDD, smart battery, and power supply unit were obtained with the help of suppliers. CRMs data on SFF (small form factor) transceiver and external fiber optic cables was also gathered, which are extension tools essential for connecting the server to external networks.

Motherboard had a heterogeneous feature in its CRMs composition, as it contains diverse types of CRMs usually in a very low amount except for the silicon substances, as shown in Table 5. A detailed CRMs composition of HDD is provided in Table 6. The supplier information clearly identified a noticeable amount of CRMs, especially of REEs as Nd and Dy in its neodymium-iron-boron (NIB) magnet parts (Erust et al., 2021). In literature further CRMs data on small printed circuit board (PCB) contained in HDDs is identified, therefore added with the first gathered data in the table.

Smart batteries also contained a substantial amount of Co and Li, in the form of cobalt lithium dioxide. In the case of DIMM, a supplier answered that no CRM is used for DIMM production other than Ce. However, the cerium dioxide is not contained in the final DIMM product itself but used in the manufacturing process, in specific in the chemical mechanical polishing process to make the wafer surface flatter (Supplier A, personal communication, April 21, 2021). A recycler also shared that a substantial amount of Pd and Pt are recovered from DIMM and therefore are a good source of profit for recyclers (Pre-processor B, personal communication, April 29, 2021). In the case of SSDs, a study identified that the sub-assembly contains Si and Ta content (Ku, 2018). Tantalum is recognized to be contained in the capacitors of some SSDs (Telecom service provider A, personal communication, April 12, 2021). From the inquiry to SSD suppliers, it was additionally found that the cerium oxide is used for the SSD production, as a hardening agent for one of the slurries used in its frontend manufacturing process (Supplier A, personal communication, May 6, 2021). The SFF transceiver contains a very low amount of Ga, while the Er contained in the fiber optic cable is identified to be 'trace amount' – average concentration less than 100 parts per million (ppm).

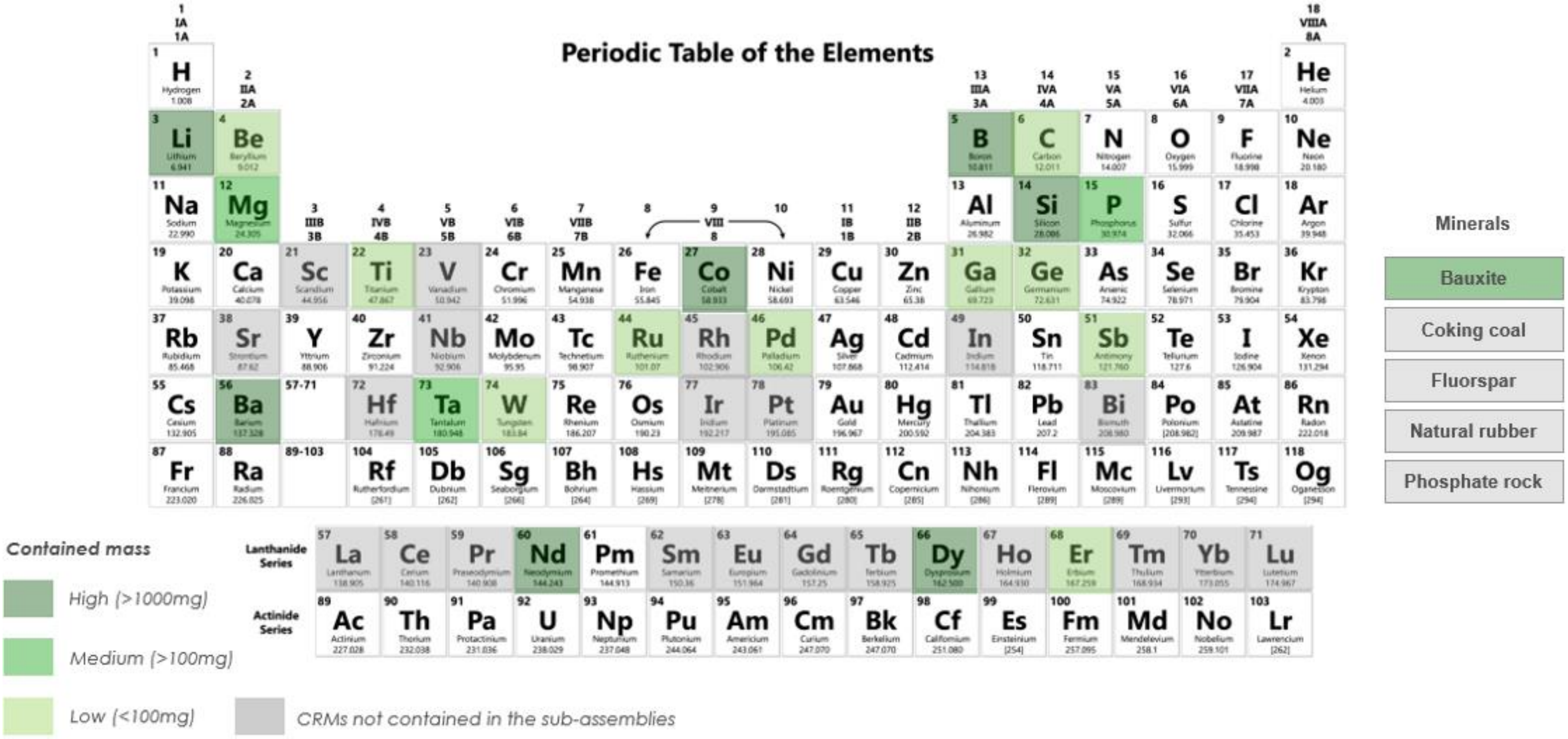


Figure 8. Types and total weight of CRMs contained in sub-assemblies and extensions of a rack server (case of motherboard, hard disk drive, power supply unit, battery, SFF transceiver & fiber optical cable)

Motherboard

CRM	Substance	use within the sub-assembly	Weight*
Sb	Sb_2O_3	Integrated circuit encapsulant flame retardant synergist	Low
Ba	$BaTiO_3$	Multilayer capacitors (SMT)	High
Bo	Boron	Semiconductor dopant	Low
	B_2O_3	Passive component glass/ceramics	High
Co	Iron-Ni-cobalt alloy	Iron-Cobalt alloy for Hermetic sealed parts: crystals; oscillators	Medium
Ge	Germanium	Transistor die	Low
Mg	MgO	Flame retardant & Filler in PCB fabs & integrated circuit encapsulants	Medium
	Mg alloy	Integrated circuit lead frame	Low
	$Mg_3Si_4O_{10}(OH)_2$ Talc	Low Halogen flame retardant and filler integrated circuit encapsulants	Low
Pd	Pd metal thin film	Plating layers in ceramic multilayer capacitors and thick film resistors	Low
P	Phosphorus Bronze alloy (Cu-P-Zn)	Connector terminals; leadframes in ICs	Medium
Ru	Ruthenium oxide (RuO_2)	Resistive element in thick film resistors (SMT)	Low
Si	Silicon	Diodes, transistors, crystals, integrated circuit wafer materials	Medium
	Si_2O_3	Capacitors and resistors; diodes, transistors, crystals, Integrated circuits	High
Ta	Ta metal +Ta_2O_5	Tantalum capacitors	Medium
W	Tungsten metal	Semiconductor die metallization	Low

** Contained amount: High: higher than 1000mg, Medium: higher than 100mg, Low: lower than 100mg*

Table 5. CRMs contained in the motherboard of a rack server

HDD
(Large Form Factor)

Substance	use within the sub-assembly	Weight*
Sb	Printed circuit board**	0.1% of the weight
Ce	Printed circuit board**	0.5% of the weight
Co	Base Motor Assembly, VCM Assembly, Magnet Circuit, Magnet Raw Material	Medium
Dy	Base Motor Assembly, VCM Assembly, Magnet Circuit, Magnet Raw Material	High
Nd	Base Motor Assembly, VCM Assembly, Magnet Circuit, Magnet Raw Material	High
	Printed circuit board**	0.2% of the weight
Ta	Printed circuit board **	0.8% of the weight

** Contained amount: High: higher than 1000mg, Medium: higher than 100mg, Low: lower than 100mg*
***(Ueberschaar & Rotter, 2015)*

Table 6. CRMs contained in the HDD of a rack server

3.1.3. Sub-assemblies of focus

With the gathered insight and data, the sub-assemblies of focus for the study were chosen. Data reliability and the amount of contained CRMs were regarded as two most important criteria among multiple factors considered as shown in Table 7. For this reason, the motherboard and HDD were chosen as the sub-assemblies of focus. The fact that the potential environmental benefits related to reusable parts (reusability benefit index) were investigated with a focus on four components of motherboard, HDD, DIMM, and CPU in previous study (Fulvio & Peiró, 2015) also played a role in the selection.

Sub-assemblies	**Data availability**	**Data reliability**	**Amount of CRMs**	**Relevance to telco service**	**Reusability benefit index***
Motherboard	Yes	High	Substantial	Not mentioned	2.2%
HDD	Yes	High	Substantial	High	1.9%
SSD	Limited	Low	No data	High	Not included
DIMM	Limited	Medium	Limited data	High	3.3%
CPU	No	Low	No data	High	2.2%
SFF transceiver	Yes	High	Low	Not mentioned	Not included
Fiber optic cables	Yes	High	Trace	Not mentioned	Not included

*Reusability benefit index rate referred to data from Fulvio & Peiró (2015), of Global Warming Potential (GWP) impact category

Table 7. Criteria considered for focus sub-assemblies selection

3.2. Circularity of servers

3.2.1. CE strategies in practice

In this section, CE strategies deployed by KPN for its own IT (information technology) device downstream process are explained. Keeping the 100% material circularity goal in mind, KPN lies specific condition to partners involved in the downstream processes as described in Table 8. The preference of KPN's CE strategies correspond with the hierarchy featured in the R framework of CE: KPN prefers reuse over recycling, and recycling over energy recovery or landfill. Recycling of the devices or parts need to be conducted only by WEELABEX certified operator. Additionally, the partners need to provide information on how the device sent to the reuse and recycling party have been processed.

Order of preference	1. Re-use/Re-marketing of the equipment as a whole
	2. Re-use/Re-marketing of components
	3. Recycling of materials
	4. Incineration (preferably with energy recovery)
	5. Landfill
Example conditions	Buyer's effort in following the hierarchy of CE strategy preference
	Process of received device within certain amount period
	Recycling done by WEELABEX certified companies according to relevant environmental laws

	Report on the device sent to downstream partners: 1. Product information 2. Reuse: identification of a re-marketing or recycling third party where the device is sent to 3. Recycling: material breakdown and recycling rate per material fraction

Table 8. Example requirements for downstream partners of KPN (KPN, 2018)

3.2.1.1. Downstream process of servers

Servers at KPN data centers are chosen as the major focus of study as the servers sold to end-customers belong to the customers and therefore their end-of-life treatment is decided by the customers themselves, with no influence exerted by KPN.

There are two bodies that engage in the downstream treatment of servers at KPN: the procurement team, and the sustainability team at the core network department. The procurement team participates in the process when the replacement of large amounts of high-value devices need to be deployed (Internal Expert #1, personal communication, March 1, 2021).

Most of the used networking devices go through the fixed set of downstream processes set up by the network sustainability team depicted in Figure 9. While the process slightly differs between the IT and TI (telecom infrastructure) device, the processes for servers are depicted in Figure 9.

Servers at KPN data centers can be distinguished into two types: 1) servers owned by KPN and 2) servers owned by end-customers. The second type of ownership is often called 'collocation,' where the end-customers run servers for their own service operation, by renting a space at the data centers of a telecom company. They usually go through different processes compared to KPN-owned devices, which will be described at the end of the section.

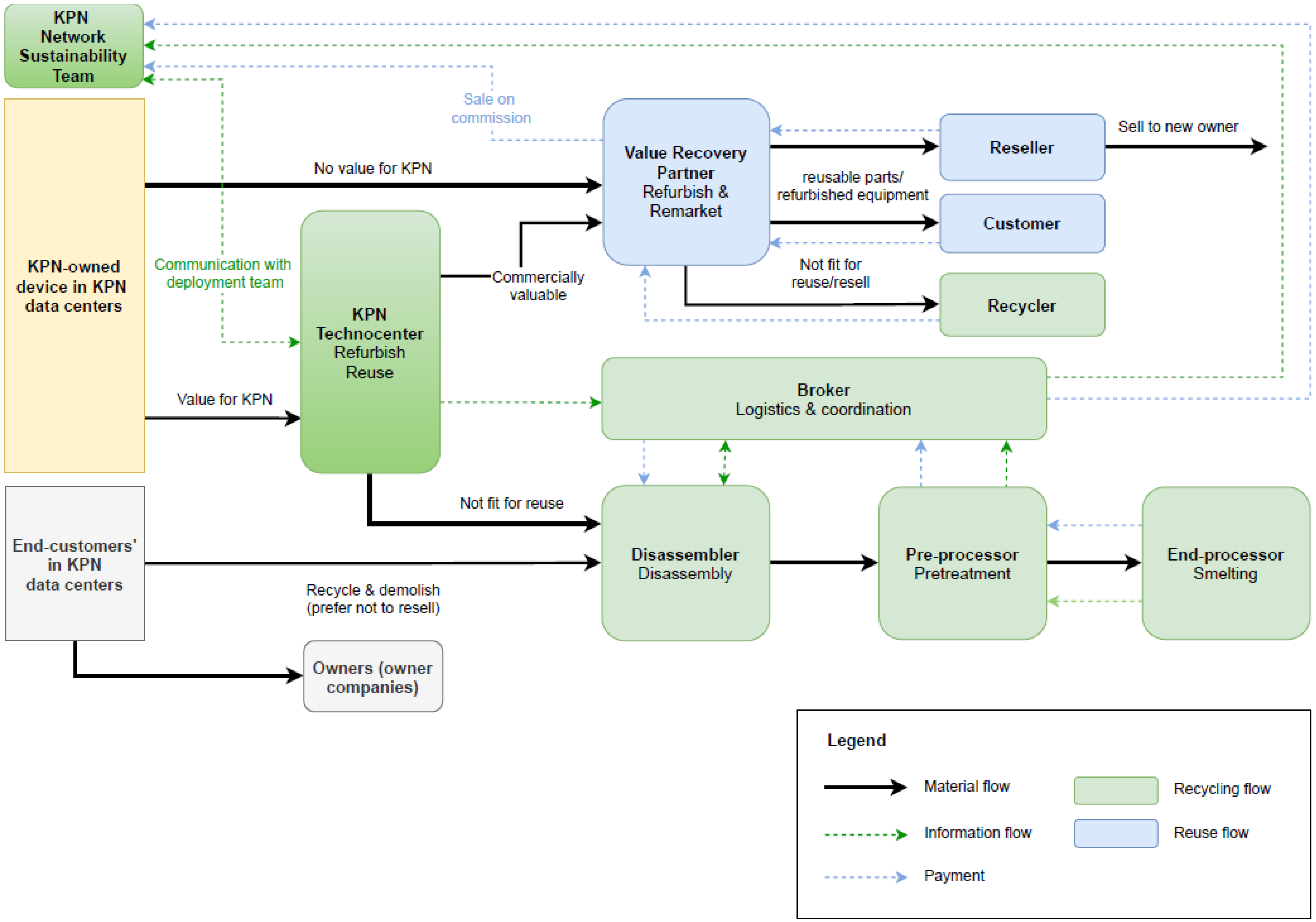


Figure 9. Standard downstream process of servers at KPN

Processes for servers owned by KPN

Once a set of IT devices, including servers that need to be replaced or removed from KPN's data centers, are not used anymore, questions indicated in Figure 10 are examined to decide where the server will be sent for either reuse (remarketing), or recycling.

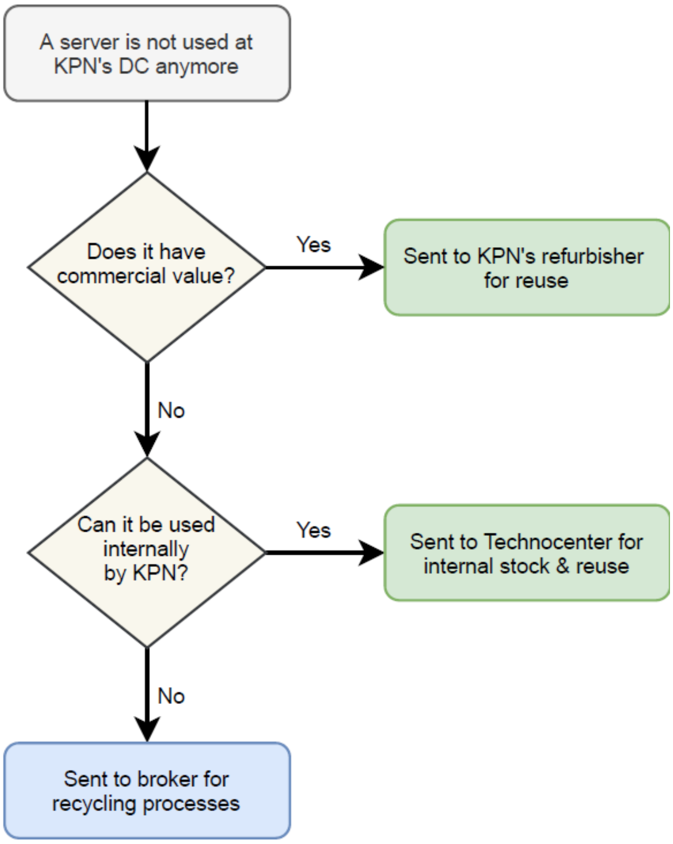


Figure 10. Decision making process for downstream processes of servers at KPN

For the decision, the product owners in charge at the data center will conduct an onsite inspection on the device. First the commercial value of the device will be examined. If all of them are examined to have commercial value, then they will be directly picked up by and sent to the After Market Service Provider & Value Recovery Partner (VRP) who conducts examination and refurbishment of the used device and sells them to other parties. If some of them have commercial value but some do not, they will be sent to KPN's Technocenter, which is an internal coordination center that takes back equipment from KPN and customer premises and reuses parts of them. The decision will be made at the center on which device to keep for internal reuse and which ones to send to VRPs. If necessary, the decisions will be consulted together with a dedicated deployment team from Technocenter. The Technocenter team's decision on whether to send the device to the center or not will be based on whether the device can be used for KPN internally, for e.g. spare part management and reuse for existing infrastructures. If the Technocenter finds the device unfit for reuse, it is sent to an external broker for further recycling.

The downstream processes are thereby split into two streams as can be seen in Figure 8: firstly, the reuse flow where the device is sent to VRP for the resale of the device or its sub-assemblies, and secondly, the recycling flow where the device is disassembled, dismantled, shredded and smelted for the recovery of materials and energy. Each stream is explained in detail in the next chapter on reuse and recycling.

Processes for servers owned by KPN's end customers

The treatment of end-customer's servers at KPN data centers are determined by the customers themselves. Sometimes customers request to have their device returned to them. Different from the processes KPN's own device goes through where the reuse is encouraged, the customers prefer not to resell the device but to send them for the demolition and recycling, mainly due to data security concerns.

3.2.1.2. Reuse

Overall process at Value Recovery Partner

When the server arrives in the logistics center of the Value Recovery Partner (VRP), it goes through a set of processes depicted in Figure 11. First a data removal process is applied to safely destroy and remove the data in memory slots and hard drives, such as HDD, SSD, SD card, and DIMM. Secondly the functionality check is conducted, as the software used to wipe the data from memory and storage components provides a functionality report on each sub-assembly within the server. It will inform which sub-assembly does not meet the functionality standard and therefore needs to be removed from the unit. Later the servers or the parts of servers will be sent to customers for reuse. Reusable devices and parts will be sent to traders who resell them within the reselling communities. Obsolete servers that do not meet European market needs are sent to charity organizations. Some devices and parts are stored in internal stock for future cases when customers request devices or parts for the same models or similar applications. Lastly, devices too obsolete for charities and dysfunctional sub-assemblies are sent to the VRP's designated recycler. Often all sub-assemblies within the server are removed and only the motherboard and heatsink are sent to the recycler for recycling processes (VRP A, personal communication, April 19, 2021).

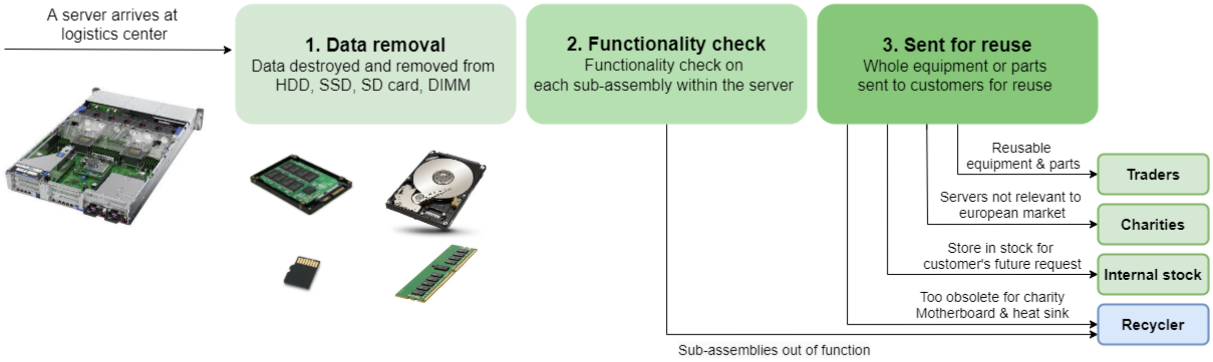


Figure 11. Treatment processes at the refurbisher for reuse of servers

Processes applied to Motherboard and HDD

Further details on the processes applied at VRP and lifetime of motherboard and HDD were gained as in Table 9.

	Process applied	**Technical lifetime**	**Market value lifetime**	**Extended lifetime**
	Types of process applied	*Technically possible lifetime*	*Until when the market value remains*	*Lifetime extended after the process at VRP*
Motherboard	• Direct reuse • Repair • Disposal after harvesting board-level components	• 7-10 years (VRP A, personal communication, June 4, 2021)	Until the motherboard resale value becomes lower than recycling value	Depends on the first lifecycle, but sending to VRPs helps reaching the maximum lifetime of 10 years
HDD	• Reuse after data wiped & status graded	• 5 years of usage time (power-on hours) (VRP B, personal communication, June 7, 2021) • 6-10 years (Rademaker et al., 2013)	Until the usage time reaches 5 years (Usage time identifiable via SMART indicator)	Depends on how much usage time left in HDD (Graded based on the amount of usage time left)

Table 9. Processes applied at VRPs and lifetime of servers

In general, a VRP would reuse the received device directly or sell it as a refurbished product, rather than selling a single component separately as those options produce maximum value. However multiple types of sales exist: Firstly, server as a whole with configuration and specifications required by their customers, secondly, the separate harvested components, thirdly, motherboard and chassis together as they are required for corresponding server system units. Motherboards alone are rarely sold individually, however this can happen if there is a company that harvests the motherboard and the user is looking for one to replace for its own server.

In the case of the motherboard, it is mostly directly reused. Sometimes it is repaired, and if the repair is found to be costly, it is sent to the disposal process with its board-level components (BLC) such as integrated circuits harvested. The collected BLCs are seen to still have substantial economic value, and are therefore collected and sold to a manufacturer (VRP B, personal communication, June 7, 2021). The technical lifetime of the motherboard is assumed to be 10 years, with its warranty provided for 5 years in general (VRP A, personal communication, June 4, 2021). The market value of the motherboard remains until the recycling of the sub-assembly becomes higher than its resale. The motherboard from a model older than 10 years can still have resale value, as the chips on the board can have higher value than the value retained from recycling the board. It is difficult to define a generic extended lifetime of a motherboard after it is processed by the VRP as the length of its first life cycle differs per usage time of the first user. Still, sending the device to VRP helps sub-assemblies to attain their maximum lifetime of 10 years (VRP B, personal communication, June 7, 2021).

For HDD, testing software is used to wipe the data and grade it based on its functionality status. SMART indicator, the monitoring system included in HDD provides information on diverse attributes that helps to determine the reliability of HDD. Via the 'power-on hours' attribute one can also find out the remaining lifetime of HDD. This attribute indicates the total hours the sub-assembly was in power-on state (Acronis, 2021), and the total lifetime of HDD is defined as 5 years of power-on hours (Hard Disk Sentinel, 2021). Depending on how much of its lifetime is left, the HDD will be graded, and most of the time there exists demand for different grades of HDD. For these reasons, the market value of the HDD will remain until it exhausts the remaining lifetime, and the extended lifetime after the process at VRP also depends on how much usage time is found to be left after its first lifecycle. Its market value also is influenced by the specification of the model, which constantly changes over the years. Currently the HDD over 600 gigabyte (GB) is seen to have market value, whereas depending on its interface version (e.g. SAS 12GB/s) the ones with lower storage can also have market value. Considering that a few years ago the market value standard was at 200GB, the standard is expected to continue evolving.

Remanufacturing of servers

A process called 'remanufacturing' exists at certain VRPs and OEMs. The process of remanufactured product can be defined as putting parts of a discarded product into a new product (Potting et al, 2017) with an aim to make a product 'as-new' or 'better than new.'

The process can be conducted by the OEM itself or in partnership with VRP. Once the used products are taken back with reverse logistics, sub-assemblies inside the server are harvested. Some of the harvested sub-assemblies are put into a new server, usually DIMM and CPU. The motherboard and HDD are generally not reused in this process, as for motherboard it is more costly to test the full functionality than to place new motherboard into the new product. In the case of HDD, it is not reused as the end-user can easily identify its usage history via SMART technology (VRP B, personal communication, June 7, 2021).

Described as servers offering the same reliability, functionality, and warranty as new servers, the remanufactured servers bring substantial cost advantage, for example at least a 15% cost advantage at one of OEMs (HPE Renew - Stock Info, 2021). The remanufactured products are not available for all models, but often the ones that have been on the market for a certain amount of time, for which enough stock of reused devices become available (VRP B, personal communication, June 7, 2021)

3.2.1.3. Recycling

Recycling of servers

In the recycling stream, the used network device goes through four processes operated by four different recycling partners. First, the used equipment is collected and picked up by the broker or logistics partner of the broker and sent to the disassembly center. In the disassembly center, the arrived devices, including servers are dismantled and divided into different material flows which are sent to the pre-processor. At the pre-processor, each material flow goes into different pretreatment processes where the e-waste is transformed into intermediate e-waste for the next process. For example, in the case of the motherboard of a server, it is put into shredding and separation processes. In the end the processed e-waste is sent to the end-processor where the final recycling step is conducted. At this process the e-waste is converted into refined materials via smelting which can be used for new products.

At the disassembler, the dismantled parts of a server are largely sorted into eight material flows: High-grade circuit board, Low-grade circuit board, Aluminium, Plastic, Iron, Cable, Power supplies, and Aluminium-copper coolers. Other components with distinctive value and material composition, such as Hard drives, CPUs, DIMMs, batteries, and SFF transceivers are collected and separated into individual containers. Except for iron and hard drives, the rest of the flows are sent to the pre-processor. Iron is sent to a local iron recycler, whereas hard drives are sent back to KPN to be shredded.

Recycling of Motherboard

The motherboard of the server is identified as a high-grade circuit board, which indicates that the board is estimated to contain more than 100 to 200 grams of gold per ton of the boards (End processor A, personal communication, May 6, 2021). At the pre-processor the board is first routed into a shredding process with other high-grade circuit boards, as depicted in Figure 12. The purpose of the initial shredding process is to enable the removal of less valuable ferrous metals or hazardous components to maximize the ratio of precious metals (Au, Ag, and PGMs) contained in the mix. After the initial shredding the parts whose economic value is recognized as low at the end-processor, such as iron, aluminium, capacitors, and batteries are removed. The rest of the shredded circuit board mix goes through the second shredding process, where the mix gets shredded into smaller pieces of about five centimeters.

Once the processed high-grade circuit board mix arrives at the end-processor, they are separated into three material fractions of circuit board mix, ferrous material, and non-ferrous material. Later each material fraction goes through different smelting processes. First, the circuit board mix goes through a smelting process with a focus on copper recycling. From the smelting process 75% of the mix is recycled as copper fraction, whereas the rest 25% of the mix are not recycled but incinerated with energy recovery. Types of materials recovered from the circuit board mix differ between end-processors, however in general the end-processor pays the pre-processor for the recycled amount of five types of materials: Cu (copper), Au (gold), Ag (silver), Pd (palladium), and Pt (platinum) (Pre-processor A, personal communication, April 19, 2021; Pre-processor B, personal communication, April 29, 2021).

Recycling of HDD

When dismantled from used servers arrived at the disassembler, hard drives such as HDD and SSD are collected and sent back to KPN to be shredded. Data security concerns, requests from end-customers, and low market value are found to be the main reasons for the shredding of the sub-assembly (Pre-processor B, personal communication, April 29, 2021; End-processor A, personal communication, May 6, 2021). Once shredded by KPN, the pieces are sent to the pre-processor where the pre-processor again sends the shredded parts to a recycler specialized in hard drive recycling. The magnetic fractions from the shredded HDD are separated from the other fractions such as circuit board mix and aluminium via magnetic separation. The final output fractions separated at the end-processor are defined to be plastic, ferrous metals, non-ferrous metals, and PCB. While the ferrous metals and non-ferrous metals are recycled 100%, 100% of the plastic and 82% of PCB is used for energy recovery.

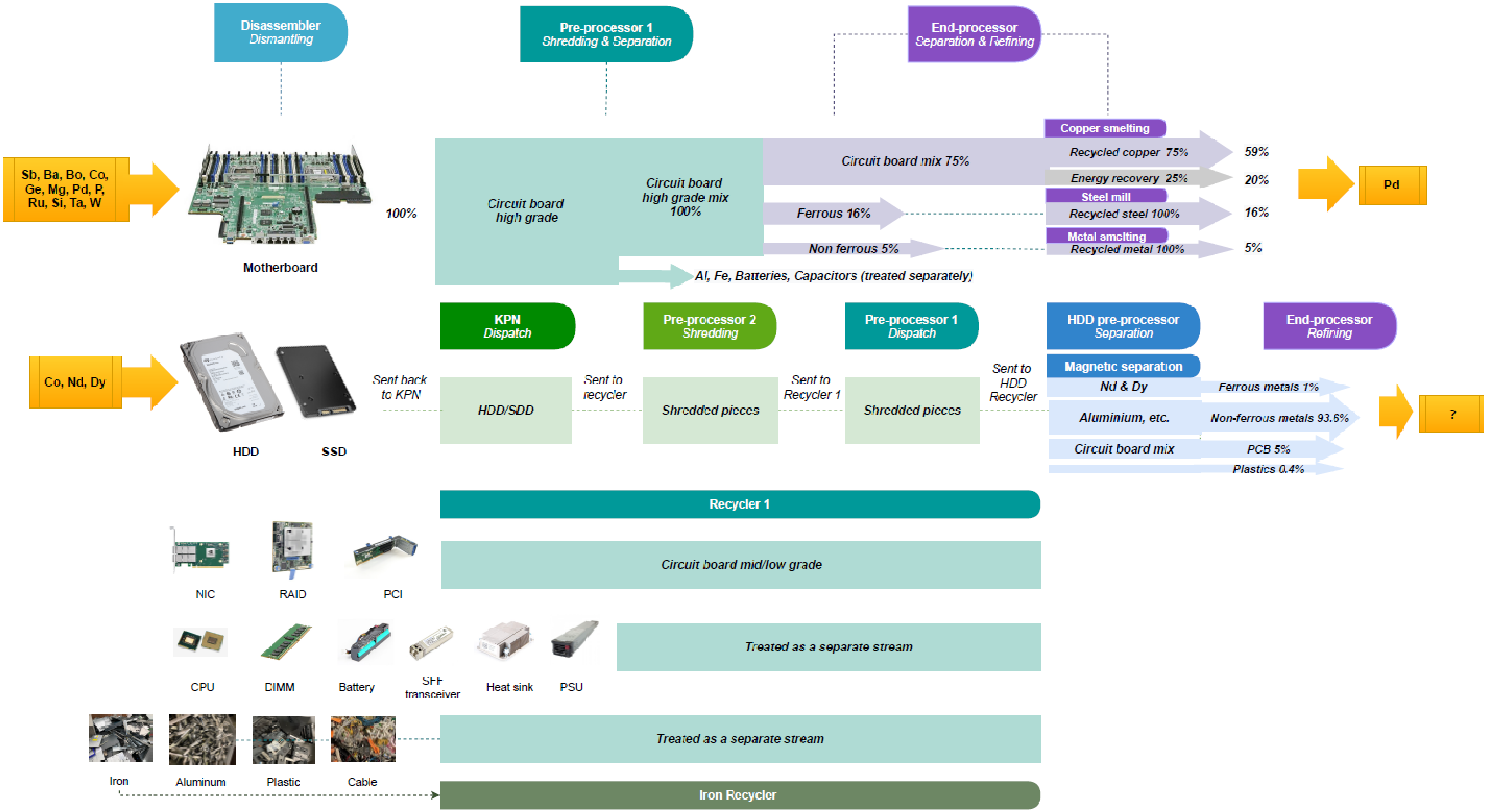


Figure 12. Server recycling process and its impact on material fractions and contained CRMs

CRMs identified in the recycling process

i. Motherboard

The focus on mass materials and precious metals (Au, Ag, and PGMs) makes it challenging to identify what types of CRMs are contained in each output fraction of involved recycling processes. While some amount of them could be lost during the shredding and separation process at the pre-processor, the majority of remaining CRMs are assumed to be contained in the PCB mix fraction which are separated from non-ferrous and ferrous materials at the end-processor.

When the fraction is sent to the end-processor, the focus lies on the recovery of Cu, Au, Ag, Pd, and Pt. Depending on the specialty of smelters, CRMs such as Sb, and In can be recycled together with copper and other precious metals. However, these CRMs are usually contained in low amounts in the input of the smelting process as shown in Table 10. While the recycling rate of Pd and Pt remains higher than 90%, the rest of the CRMs – Sb and In - have a lower recycling rate. The recycling rate of Sb and In is identified to be 'much higher than 50%.' However, the specific percentage could not be disclosed as it is regarded proprietary (End processor A, personal communication, May 6, 2021). The recycled amount is also influenced by different types of e-waste mixes that are put into the smelting process, as smelters often put different grades of circuit board mixes and e-waste together into the process.

Smelting *Case of PM refining expert*		
Recovered CRMs	**Input amount**	**Output recycling rate**
Pd	5-50g per ton circuit board	more than 90%
Pt	0-20ppm	more than 90%
Sb	below 1%	much higher than 50%
In	below 200ppm (vast majority not contained)	much higher than 50%

Table 10. Recyclable CRMs and the amount at End-processor A

As shown in Table 11, out of various CRMs contained in the motherboard, Pd is identified to be the only type of CRM that is definitely recovered at the end of the recycling process, while Sb can also be recovered together depending on the capability and interest of the end-processor. According to End-processor A, from the three collector metals of Cu, Ni, and Pd, PGMs such as Pd are usually collected from Cu fractions and partly from Ni-fractions, while Sb tends to be recovered from Pb refining (End processor A, personal communication, July 7, 2021).

Dismantling		**Shredding & Separation**			**Separation**			**Smelting**		
Disassembler		*Pre-processor*			*End-processor*					
Output fractions (OF)	**Contained CRMs (CRMs)**	**OF**	**%**	**CRMs**	**OF**	**%**	**CRMs**	**OF**	**Recycled %**	**CRMs**
Motherboard	**Sb, Ba, Bo, Co, Ge, Mg, Pd, P, Ru, Si, Ta, W**	High grade circuit board mix	100	Assumed to contain CRMs	PCB mix	79	Assumed to contain CRMs	Copper	75	**Pd** Sb
					Ferrous	16	Not identified	Steel	100	None
					Non-ferrous	5	Not identified	Metal	100	None

Table 11. CRMs identified in each recycling process

ii. HDD

It was difficult to identify whether the CRMs in the NIB magnetic parts of the HDD are recycled as separate fractions in practice, as recycling partners withheld information due to proprietary reasons. However, the literature explains that no commercial process exists for the recycling of HDD magnets (Charles et al., 2020; Ueberschaar & Rotter, 2015; Yang et al., 2017), while recycling of industrial NIB scrap is possible when the sufficient amount of up to 184,000 NIB magnets are guaranteed (Charles et al., 2020)

As it was the case with the recycling partners of KPN, HDDs are often shredded as a whole, due to data security reasons and as it is regarded as the most economical way to separate the bulk materials out of the fractions. However, this procedure transfers the magnetic REE fractions to other ferromagnetic fractions and therefore results in the 100% loss of the REEs (Ueberschaar & Rotter, 2015).

Additionally, several reasons are shown in Table 12. To explain why the recycling practice of REEs remains rare. Shredded rare earth magnets have little market value as they remain brittle and vulnerable to oxidation when coming into contact with air (The Economist, 2021; Ueberschaar & Rotter, 2015). Low primary material cost of REEs and low price for recycled REEs scrap gives less reason for processors to focus on the recovery of the materials. Lack of capacity among end processors in smelting and converting Nd & Dy into new magnetic parts can be another factor. While liberating the REE magnet from HDDs remains crucial for a high-quality recovery of REEs, the timely and costly characteristic of manual separation makes it difficult to be applied to commercial processes.

Reason for the rarity of REE magnet recycling
• Brittleness of shredded REE magnets (The Economist, 2021; Ueberschaar & Rotter, 2015)
• Low primary material cost for REEs (End processor R) & Low price for REE scraps (Sprecher et al., 2014; Ueberschaar & Rotter, 2015)
• Lack of REE smelting and converting technology among end-processors (End-processor A, personal communication, May 6, 2021)
• Timely and costly liberation of REE magnets from HDD (Charles et al., 2020; Ueberschaar & Rotter, 2015)

Table 12. Factors contributing to the rarity of REE magnet recycling

In the case of PCB inside an HDD, a traditional pyrometallurgical process is regarded as suitable. For example, End-processor A requests pre-processors to separate PCBs from HDD units, as they can be processed together with PCB mix from other WEEE in their smelting process (End-processor A, personal communication, May 6, 2021). While the recycling of PCB is seen to contribute to the recovery of contained high-value metals such as Ag, Au, and Pd (Ueberschaar & Rotter, 2015), it remains highly doubtful whether the extremely low amount of CRMs are recovered throughout the process.

While the recycling of NIB magnets in HDD in the current market remains rare, literature explains diverse types of advanced recycling processes have been proved effective for the recovery of CRMs in the magnetic part, which are introduced in detail in chapter 3.2.2.

3.2.2. Other possible CE strategies

3.2.2.1. Substitution potential

Reduction is positioned at the top of the hierarchy of CE principles (Potting et al., 2017). Substitution can be seen as a way of reducing the consumption of certain materials, while a successful contribution to reduction happens under certain conditions. Substitution needs a careful approach so that the substitution of one material does not end up in equal or more consumption of another material. At the same time, it needs to be ensured that the impact of modification in contained materials does not lead to additional environmental impact. The proper recycling of the substitute material should follow, while excessive production – as seen in rebound effect – need to be avoided.

Therefore, constraints exist regarding substitution as a CE strategy. Despite such limitations, the substitution method is included in this section, as the method is actively discussed in the literature as a pathway to substitute CRMs with another type of material that can deliver a similar function. In this section, the substitute material for each CRM contained in the motherboard and HDD of the server were investigated respectively via literature review. The gathered data on substitution potential has been shared with the supplier of each sub-assembly with the survey format seen in Appendix A.3., for cross-checking of the data from industry experts. However, it is found to be challenging for the motherboard supplier to answer the survey due to immense complexity in the upstream value chain, while the data on HDD was checked by its suppliers. The compiled data is shared below, with details on the barriers for motherboard suppliers' feedback is described in chapter 4.1. as part of the gap analysis.

i. Motherboard

The potential substitution data found in literature is summarized in Table 13, with detailed description and sources described in Appendix A.2. Out of 12 types of CRMs identified to be contained in the motherboard, substitutes for 10 materials except for Ba and P were identified. Sometimes literature pointed out substitutes for the same application the material is used for in the motherboard, while some substitutes were mentioned in a broader but relevant application area. In the cases where no substitute was identified, either the literature clearly mention that no substitute is available for the material's application, or the application the material is used for in the motherboard was not mentioned (e.g., magnesium's role as circuit encapsulant not discussed as main application area in literature). The lack of substitution data indicates the need for further research that investigates substitutes for the specific application each material on the motherboard is used for.

Notable consequences of substitution found among the data were potential loss in performance and increase in cost. As indicated in Table 13 with check marks, some substitute materials are seen to bring a decrease in performance compared to the current materials. Literature predicts potential increase in cost, which leads to low chance of using them as substitutes in real practice. One example can be substituting Ru with either Ir, Pd, or Rh, other types of PGMs with high market price.

Another limitation in applying substitution methods is that often the substitutes of one CRM are other types of CRMs. As examples are shown in the table in column 'Other CRMs' this limits the efforts to reduce the demand of CRMs by substitution. This indicates the need to focus on finding substitutes that are not CRMs.

CRMs contained in motherboard	**Potential substitutes**	**Potential loss in performance**	**Potential increase in cost**	**Other CRMs**
Silicon (Si)**	GaAs, Ge, graphic layers, carbon nanotubes	✓	✓	Ga, Ge
Boron (Bo)**	Na, other forms of Bo, other CRMs			Bo, other CRMs
Barium (Ba)**	.			
Tantalum (Ta)*	Al, Nb, ceramics	✓		Nb
Magnesium (Mg)*	Other CRMs			Other CRMs
Phosphorus (P)*	.			
Cobalt (Co)	Ni or Fe-based alloys, ceramic & carbon-based composites, etc.	✓	✓	
Antimony (Sb)	Organic compound, hydrated Al_2O_3s, $Al(OH)_3$, $Mg(OH)_2$, zinc borate	✓		Mg
Ruthenium (Ru)	IrO_2, Rh, Pd, Ir	✓	✓	Rh, Pd, Ir
Palladium (Pd)	Ni, other types of PGMs	✓		PGMs
Germanium (Ge)	Si	✓		Si
Tungsten (W)	BN, Mo	✓	✓	Bo

*Contained amount: ** higher than 1000mg, * higher than 100mg*

Table 13. Potential substitutes for CRMs in motherboard found in literature

(CRMs listed in the order of contained amount: largest to lowest)

ii. HDD

In the case of HDDs, a functional substitution has been already taking place as the SSD is expected to overtake the HDD demand in the market in the coming 10 years (Supplier A, personal communication, June 24, 2021). As indicated in Appendix A.1., the CRMs contained in SSDs – Si and Ta – are therefore expected to substitute the role of CRMs in HDDs, with a much lower amount.

To examine material substitution potential, substitute data for CRMs contained in HDD was first collected from literature and shared with two HDD suppliers to cross-check the feasibility of substitution and reduction of the materials.

As seen in Table 14, Samarium-cobalt (SmCo) magnets were identified as potential substitutes for NIB magnet, the part that contains the largest REEs in the HDD. While a few materials were identified as potential substitutes for cobalt, no substitute was mentioned for Dy in literature. Adding to the information in the table, Ueberschaar & Rotter (2015) explains that Nd is substituted by Dy Pr and Co up to a certain level depending on the material's market price and physical properties. For example, it is explained that Pr has a potential to substitute Nd up to 20-25%, when it used to have a cost advantage over Nd.

CRMs contained in HDD	**Potential substitutes (in literature)**	**Substitution possibility in practice**	**Reason**
Neodymium (Nd)* **	Samarium-cobalt magnets (for neodymium magnets)	Not possible	• Higher vulnerability compared to NIB magnet • Higher supply dependence on one country • Higher market price
Dysprosium (Dy)**	no substitute identified	Dy not contained in recent models	Dy not contained in recent models
Cobalt (Co)*	Barium or strontium ferrites, neodymium-iron-boron, or nickel-iron alloys (for magnets)	Not possible	Cobalt content might increase if NIB is substituted with SmCo

*Contained amount: *** higher than 9000mg, ** higher than 1000mg, * higher than 100mg, (Large Form Factor HDD)*

Table 14. Potential substitutes for CRMs in motherboard found in literature

Whether the identified substitution can be implemented in practice was checked by two HDD suppliers, with detailed response available in Appendix A.4. Both suppliers confirmed that it is not possible to replace the contained CRMs with suggested substitutes, due to multiple reasons. In the case of NIB magnets, SmCo magnet is more porous therefore embeds higher risk to contamination compared to NIB magnet. Due to its brittle characteristic, it is in general used for smaller components such as sensors. Another risk in using SmCo as a substitute comes from the fact that its supply is dominated by one country. 99% of Sm is supplied from only one country – China (European Commission, 2020a) – while in the case of Nd up to 60% is sourced from China and still 40% of them supplied from various countries. Also, the price of SmCo magnet is about two times higher than NIB magnet, which leaves little reason to practice the substitution. One supplier answered that there have been efforts to reduce virgin Nd material demand by recovering Nd from magnet scraps via recycling. However, the cost element becomes a barrier to the recycling practice due to the low price of the commodity.

Cobalt takes up a very small portion of the NIB magnet, less than 0.9%. When the NIB magnet is replaced with SmCo, the cobalt content will increase to 50% of the magnet. This will eventually contradict the goal of reducing the CRM content and increase the risk associated with the supply of cobalt. Another supplier of HDD also confirmed that the substitute materials mentioned for cobalt are not implementable in practice.

One notable point is that both HDD suppliers are not using Dy in their recent HDD models anymore. One supplier explains that the magnet supplier continuously works on research and development for material efficiency while keeping the specifications of the product. There have been efforts to reduce the amount of Dy in the magnets, and eventually the element has been completely removed from the recent models. Dy used to be added into the magnet to assist retaining its power for smaller magnets. However, since current models have larger magnets with higher cap, Dy is no longer required.

With the growing demand for SSDs over HDDs and the drive market's migration to SSD, it is suspected that the manufacturers are not giving attention to HDD production beyond next 10 years (Supplier A, personal communication, June 24, 2021). This indicates that SSDs have a high chance of replacing the material demand for HDD, by delivering the same kind of function with lesser and different CRM composition.

3.2.2.2. Advanced recycling technologies

i. Motherboard

The recycling of the motherboard, so-called printed circuit board assembly (PCBA) or in short printed circuit board (PCB), is often discussed under the term WEEE (Waste from Electrical and Electronic Equipment) in literature. WEEE goes through a pretreatment process and metallurgical process for the recovery of contained materials (Işıldar et al., 2018; Sethurajan et al., 2019). As shown in Figure 13. pretreatment includes dismantling of the end-of-life (EoL) product, physical treatment which consists of shredding and separation, and chemical treatment before moving onto the metallurgical process. The final step is the metallurgical process. Literature mainly introduces three types of metallurgical process of pyrometallurgy, hydrometallurgy, and biohydrometallurgy. Majority of current industrial WEEE treatment is based on the physical treatment and pyrometallurgical processes which incorporate smelting. Hydrometallurgical processes also take place but only to a smaller extent (Işıldar et al., 2018).

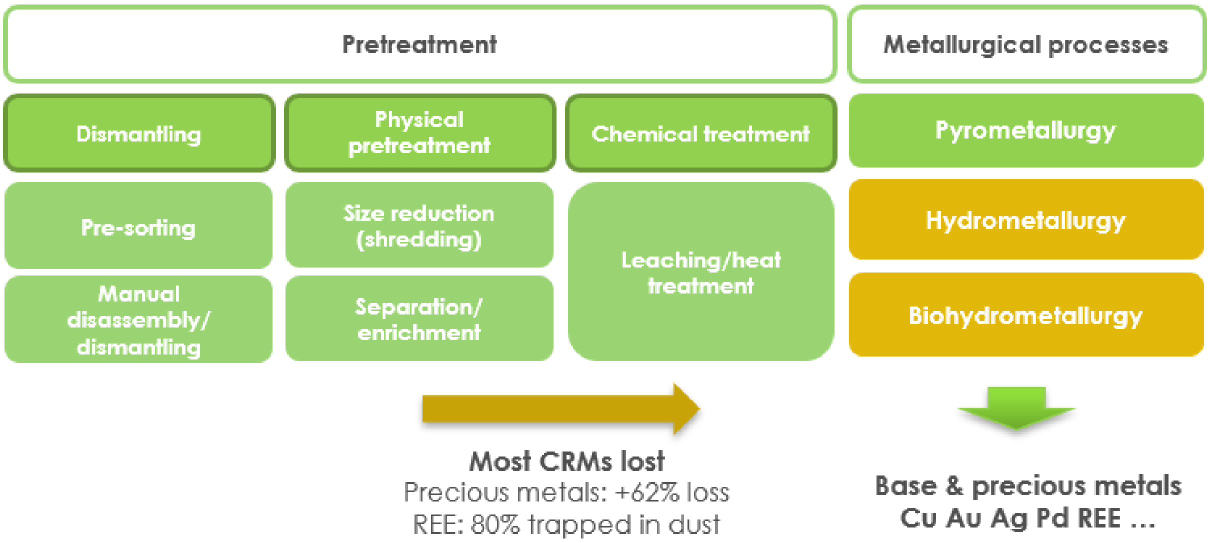


Figure 13. WEEE treatment processes for the recovery of contained values
(based on Işıldar et al., 2018; Sethurajan et al., 2019; Chancerel et al., 2009; Marra et al., 2018)

Pretreatment process

The pretreatment process of disassembly, size reduction, and separation is seen as indispensable for the selective recovery of components with economic potential and possibility of pollution (Sethurajan et al., 2019). At the same time, from the perspective of CRMs retention the design of pretreatment method is critical, as the decisions made during this process determine the possibility of their recovery throughout the recycling process (Charles et al., 2020).

After the size reduction or shredding of WEEE, different types of separation process can be employed to separate metals from other materials fractions before routing them into metallurgical processes. The processes are developed based on the physical properties of each material fraction, for example of their magnetic susceptibility, conductivity, brittleness, and specific gravity (Sethurajan et al., 2019). The types and function of each method is described in Table 15.

Method	Exploited property	Separation of materials
Magnetic separation	Magnetic susceptibility	Ferrous metals (ferromagnetics) from non-ferrous metals and non-metals (para-/dia-magnetics)
Electrostatic separation	Electrical conductivity	Metals (conductive) from non-metals
Eddy-current separation	Electrical conductivity/specific gravity	Light metals (i.e. Al) from conductive but heavy (base and precious) metals and non-conductive materials (plastics and ceramics)
Gravity separation	Specific gravity	Metals from non-metals
Flotation	Suface properties	Non-metals (hydrophobic) from metals

Table 15. Physical separation methods for metal recovery from WEEE (adapted from Sethurajan et al., 2019)

Magnetic separation is usually put in as the first separation technique to remove ferrous metals. Later air classification can be employed to separate fine plastic fractions or fluffy materials. Eddy-current separation helps to separate light metals with high conductivity or density such as Al from non-conductive or non-metallic materials. Electrostatic separation can be used to separate heavy non-ferrous metals, such as base and precious metals from non-metals. Inspired by different size and density of each material, gravity separation via table sharking, jigging, etc. helps separating metals from non-metals. Flotation can be a useful separation method to recover metals from fine material fractions (Sethurajan et al., 2019).

Fate of CRMs during pretreatment process – the case of PGM and REE

While the size reduction helps to liberate metals from the collected WEEE, it leads to significant metal losses (Sethurajan et al., 2019). The metal loss is identified to be substantial especially in the case of CRMs such as REE or precious metals. According to the study of Chancerel et al. (2009), the precious metals concentration in PCBs was found to be 7% less after pre-shredding. The gap became much larger at 62% of additional precious metals loss between the pre-shredded and shredded PCBs. The example concentration data of Pd is shown in Table 16.

Concentration of metal	Palladium (g/t)
Unshredded printed circuit boards	50
Preshredded printed circuit boards (<8 mm)	48
Shredded printed circuit boards (<2.5 mm)	18

Table 16. Precious metals concentration in PCBs output from each pretreatment stage (adjusted from Chancerel et al., 2009)

Along with precious metals, significant loss of REE during pretreatment of WEEE was identified in the study of Marra et al. (2018). As depicted in Figure 14, it was revealed that around 80% of REE in WEEE are trapped in the dust that originated from the air cleaning process, which is destined to end up in landfill. More detailed metal distribution data on Figure 15. more clearly proves different types of REEs largely lost in the dust from WEEE's output fractions from the pretreatment. It also identified a major loss in precious metals, as only a third of precious metals end up in copper fractions that are sent for smelting, with the rest 68% lost in either dust or plastic or aluminium fractions. The study pointed out the potential for the lost materials in dust to be used as secondary material. As the materials have less impurity with a fine size below 2mm, they can be further refined via hydro or bio metallurgical processes after pulverization.

Studies prove that more physical treatment does not always lead to a better recovery of precious metals and REEs. According to End-processor A specialized in precious metals recovery, for this reason the end-processor tries to discuss in detail the proper amount of pre-treatment to be processed before the WEEE is sent to the end-processor. The best condition of waste PCBs for smelting, from the perspective of an end-processor would be that the PCB dismantled the equipment either via manual or automatic method, and its components pulled out, without shredding applied. The end-processor explains that additional separation processes tend to be added at pre-processor to reach fewer complex outflows sellable to different end-processors, or to increase the recycling rate of mass materials such as Al, Fe, and plastics. However, these extra pretreatment processes contradict precious metals recovery at the final smelting process, therefore closer coordination is necessary for the higher recovery of precious metals (End-processor A, personal communication, May 6 2021).

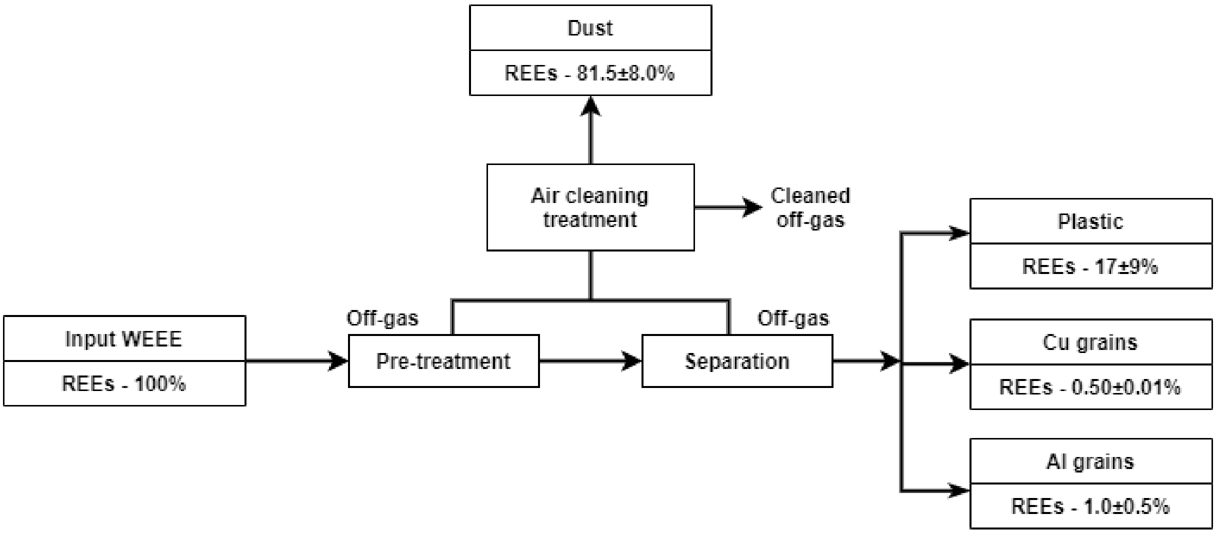


Figure 14. Mass flow diagram on the distribution of REEs in different fractions (redrawn from Marra et al., 2018)

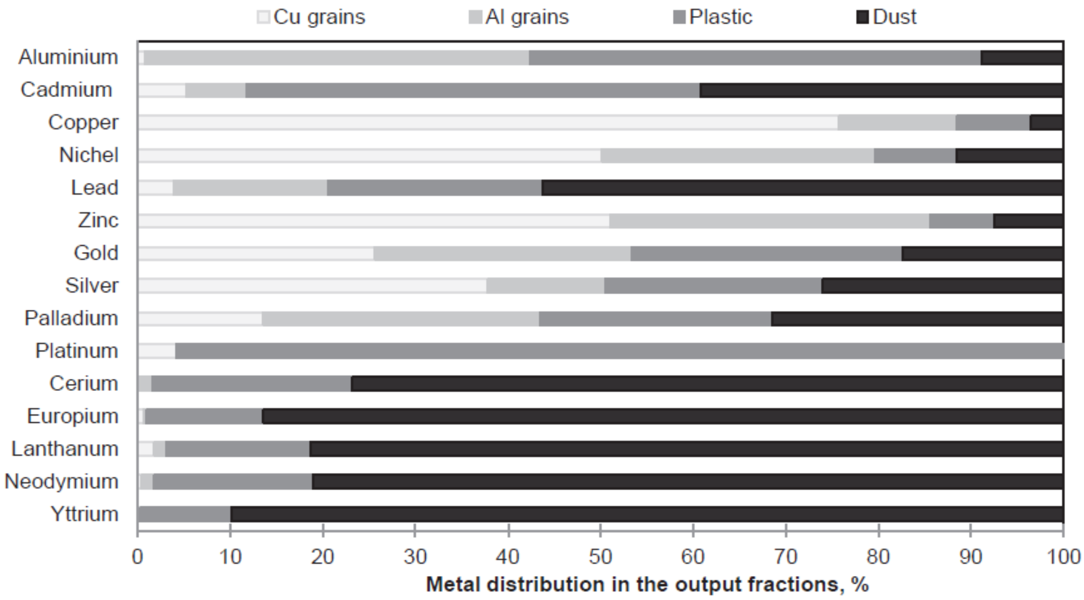


Figure 15. Distribution of selected metals including precious metals and REEs in output fractions (from Marra et al., 2018)

Metallurgical process

After the pretreatment is applied to WEEE at the pre-processor, the PCB mix is sent to the end-processor for final separation and metallurgical processes. In current practice PCBs are usually treated by traditional pyrometallurgical processes, and sometimes with an extent to hydrometallurgical processes (Işıldar et al., 2018; Srivastava et al., 2020). Adding to existing practices, studies have investigated the potential of hydrometallurgical and biohydrometallurgical processes for the enhanced recovery of selective materials from WEEE.

Pyrometallurgy, encompassing smelting and pyrolysis, is seen as the current best available technology with high maturity. Numerous works have been done on the technology and there already exist a few full-scale plants processing WEEE with pyrometallurgy, as seen in Table 17. In the advanced practice by Umicore, total 17 materials are recovered via combined process of pyrometallurgy and hydrometallurgy, including CRMs such as PGMs (Pt, Pd, Rh, Ru, Ir), Sb, Bi and In.

End-processor, Country	Input material	Applied process	Recovered material
Boliden Rönnskär, Sweden	PCB	Copper converter	**Cu, Ag, Au, Pd, Ni, Se, Zn**
Outotec, Finland	WEEE	Copper/lead/zinc smelter	**Au, Ag, Cu, Cd, Ge, In, Pb, Zn**
Umicore, Belgium	PCB	IsaSmelt furnace + hydrometallurgy and electrowinning	**Au, Ag, Pt, Pd, Rh, Ru, Ir, Pb, Cu, Ni, In, Se, Te, As, Sb, Bi, Sn**

Table 17. Type of materials recovered at current industrial end-processors (based on Işıldar et al., 2018)

Pyrometallurgical process is regarded as the most efficient process, as non-metallic fractions can be effectively removed from PCBs through thermal decomposition (Ning et al., 2017). However, the process entails high environmental impact due to high gaseous and toxic emissions, and high amount of secondary waste generated (Srivastava et al., 2020).

Distinct from pyrometallurgical processes, hydrometallurgical processes extract metals via oxidative leaching, separation, and purification (Işıldar et al., 2018). As indicated in Table 18, hydrometallurgical processes have an advantage over pyrometallurgy in lower emissions and toxic residues, and higher selectivity of recovered materials. However, the process still raises environmental concerns due to its use of high volume of toxic reagents and generation of effluents and solid wastes (Tunçuk et al., 2012). Biohydrometallurgy uses microorganisms such as bacteria or fungi to recover metals from PCBs (Işıldar et al., 2018; Ning et al., 2017). While it has similarity with hydrometallurgy in that they both incorporate a leaching process, biohydrometallurgy uses chemicals produced by microorganisms rather than leaching reagents. For this reason, the process has lower environmental impact and higher social acceptance. Biohydrometallurgy has been recognized as a less efficient recycling technique due to longer time required compared to conventional processes (Ning et al., 2017). However, it is nowadays seen as a promising technology for metal recovery with its recent development in advanced engineered processes (Işıldar et al., 2018).

Parameters	**Pyrometallurgy**	**Hydrometallurgy**	**Biohydrometallurgy**
Cost	High	Low	Medium
Required time	Short	Medium	Long
Selectivity	Low (only a fraction of metals)	High	High
Environmental impact	High (gaseous emissions)	Moderate (toxic chemicals)	Low
Social acceptance	Low	Medium	High
Final residues, amount	Slags, high	Circulated water, low	Circulated water, low-to-none
Process conditions	Harsh thermal treatment conditions	Harsh corrosive acids	Safe condition (low-to-nontoxic chemicals)

Table 18. Comparison of pyro, hydro, and biohydrometallurgical processes
(based on Işıldar et al., 2018; Ning et al., 2017)

Difficulty in recovery of CRMs

It is highly challenging to identify one unified process that recovers all types of CRMs from PCBs. Charles et al. (2020) and Sethurajan et al. (2019) explains the reasons behind the difficulty in selective recovery of CRMs in the recycling process as in Table 19. The heterogeneous types of material composition, in general in extremely low concentration, makes it difficult to develop a recycling pathway that recovers wide types of contained CRMs. Eventually, the recycling process focusing on mass fractions or precious metals will lead to the loss of other critical elements in the process. While the detailed disassembly is seen to substantially improve the recovery potential of the materials, it is not commonly practiced as the manual assembly is highly time and labor-intensive (Charles et al., 2020; Sethurajan et al. 2019).

Barriers to recovery of CRMs
• Poor product design for end-of-life recycling process
• Heterogeneity of WEEE
• Constant change in the composition of WEEE
• Time & labor intensity of manual sorting
• Low concentration of CRMs (in mg, ppm)
• Losses of CRMs in pretreatment and pyrometallurgical process

Table 19. Factors hindering selective recovery of CRMs
(based on Charles et al., 2020 and Sethurajan et al. 2019)

Types of CRMs recovered through advanced recycling processes

While existing practices focus on the recovery of mass materials, base metals and PGMs, other studies experiment on the recovery of selective materials depending on the physical property and material concentration of different types of WEEE. Although not specifically focused on server PCBs only, in Table 20., examples of metallurgical processes focusing on the effective recovery of certain CRM have been compiled.

Target materials	Advanced technology	Types of CRM recovered	Recovery rate
WEEE	Physical crushing and separation + (bio) hydrometallurgy	**In**	>90%
WEEE	Thermal treatment (pyrolysis)	**Bi**	Not provided
WEEE	Physical treatment + hydrometallurgy	**Pd**	>95%
WEEE	Physical treatment + hydrometallurgy	**Ce, Tb**	>95%
WEEE	Physical treatment + hydrometallurgy	**Eu**	>95%
WEEE	Physical treatment + hydrometallurgy	**Y**	>95%

Table 20. Advanced metallurgical process of example CRMs with highest recovery efficiency
(adjusted based on Işıldar et al., 2018)

Additionally, literature focusing on advanced technologies to recover specific types of CRMs has been identified. Descriptions of recycling technologies corresponding with specific types of CRMs contained in the server's motherboard are shown in Table 21 with further details in Appendix A.5. However, the identified technologies are limited in that the input materials' applications do not always match the material's applications in the motherboard. Although some technologies deal with circuit-related components such as MLCCs, IC chips, and Ta capacitors, it remains unclear to which extent it can be implemented in industrial practice, where different types of WEEE are treated together for efficiency.

Type of CRM	Example recycling technology	Recovery rate	Source
Barium (Ba)	• BaCl2 recovery from chloride metallurgy, leaching, electrostatic separation	Up to 98.76%	(Niu & Xu, 2017)
	• BaTiO3 recycling from waste MLCCs via one-step ball milling		(Niu & Xu, 2019)
Boron (Bo)	• Adding Al powder to recycle boron carbide		(Gao et al., 2018)
	• Sintering and organic solvent treatment for old propulsion engine	79.7%	(Shim et al., 2019)
Germanium (Ge)	• Ge from Ge lenses and PV cells via separation and hydrolysis	Above 97wt%	(Bumba et al., 2018)
Silicon (Si)	• Silica production from copper smelting slag via in situ modification		(Qinmeng Wang et al., 2020)
	• High-purity silica from nickel slag, via reduction treatment method		(Hai-yang Liu et al., 2020)
	• Separating silica from discarded ICs via physical processes	Up to 84%	(Baarnwal & Nikhil, 2020)
Tantalum (Ta)	• Recycling Ta capacitors with heat and size screening	70%	(Fujita et al., 2014)

Table 21. Advanced recycling technologies per type of CRM identified in literature

ii. HDD

For a successful employment of advanced recycling of REE magnets, the separation of the magnets from the other parts of HDD is required. The construction of HDD makes the disassembly challenging: the two magnets located in voice-coil actuators are bonded to a carrying steel plate, their magnetic fields locking each other (Ueberschaar & Rotter, 2015). To reach the spindle motor magnets, the top part of the platter needs to be removed. Likewise, the physical binding structure and the glue makes it difficult to separate the magnets from WEEE scrap. As thermal separation leads to generating hydrocarbon vapors around the magnets, a non-thermal separation process would be preferred (Binnemans et al., 2013).

While manual disassembly can be an option, it is not regarded as economical. The workers can on average disassemble only 12 HDDs per hour (Sprecher et al., 2014), and the low price for REE scrap makes the process unprofitable (Ueberschaar & Rotter, 2015). Mechanical disassembly technology was developed by Hitachi, where the HDDs are shaken in a drum unit where the unit eventually is taken apart into components, enabling workers to remove the magnets manually (Binnemans et al., 2013). With this technology up to 100 HDDs can be processed per hour, however this process is applicable only for the voice-coil magnets and does not solve detaching the magnets from steel carrier plates (Ueberschaar & Rotter, 2015). Cutting the corner of the HDD where the voice coil magnets are located can be another way of disassembly. This way most of the magnetic volume can be removed, although not to the complete volume (Sprecher et al., 2014).

Once magnets are liberated, multiple types of processes are available for the recycling of REE content within the magnet. According to Erust et al., (2021) numerous researches have been conducted on the REE content recovery. It introduces 14 processes which describe various methods that can recover up to 95-100% of Nd, Pr and Dy. While multiple processes have been proven effective in theory, this section focuses on five commonly discussed types of processes, shown in Table 22.

Method	Input	Output	Advantages	Disadvantages
Direct reuse in current form	Intact and liberated magnets	Single magnets for reuse, with same chemical and physical properties	• Most economical way of recycling with low energy input and no chemical consumption • No waste generated	• Practicable for only large quantities • Only applicable for same products, for large easily accessible magnets
Re-sintering after hydrogen decrepitation	Liberated magnets with same chemical composition Magnet material without coatings	Magnet powder with same chemical and physical properties, new magnets in eligible forms	• Less energy input compared to hydrometallurgical and pyrometallurgical routes • No waste generated • Especially suitable for HDD (little compositional change over the years)	• Not applicable to mixed scrap feed • Not applicable to oxidized magnets • Coatings (Zn Sn Cu or Mg) need to be removed
Hydrometallurgical methods	All types of NIB magnets with different alloys	Mixed REE concentrate, single REE concentrates, and high purity REE	• Applicable for all types of magnet compositions, including oxidized alloys • Same process as extraction of primary REE	• Complex processes • High amount of water and chemicals required, and wastewater generated • High energy input depending on the process
Pyrometallurgical methods	All types of NIB magnets with different alloys	REE alloys, REE concentrates	• Applicable for all types of magnet compositions • No wastewater generated • Fewer processes than hydrometallurgical methods • Direct melting allows obtaining master alloys • Liquid metal extraction allows obtaining REEs in metallic state	• High purity of input material required to prevent solid waste • High energy input • Not applicable to oxidized magnets depending on process

Gas phase extraction	All types of NIB magnets with different alloys	REE concentrate for selected elements	• Applicable for all types of magnet compositions • Applicable to both oxidized and non-oxidized alloys • No wastewater generated	• Subsequent processing of residues • High quantity of chlorine gas required depending on process

Table 22. Recycling options for NIB magnets (based on Binnemans et al., 2013 and Ueberschaar & Rotter, 2015)

Direct reuse of NIB magnets would be the most economic recycling option. However, it is not applicable to magnets in HDDs but only to easily accessible large magnets such as in wind turbines, electric motors, and generators in electric vehicles (Binnemans et al., 2013). The hydrometallurgical process is the same as the process applied during the extraction of primary REE from ores. While it is applicable to all types of magnet composition, it has significant environmental disadvantages as it converts metallic Nd into chloride and once again converts it back to the metallic form. This results in high amounts of water and chemical usage and generates a substantial amount of wastewater (Sprecher et al., 2014). The gas phase extraction method, where Nd is vaporized to be extracted, was developed to improve on the disadvantages of the hydrometallurgical methods. While no wastewater is generated, the process similarly converts Nd into chloride. Diverse types of pyrometallurgical methods are applicable, such as direct remelting of REE alloys (direct melting), extracting REE content from transition metals (liquid metal extraction), or recycling REEs from the magnet alloys that are partly oxidized (electroslag refining and glass slag method). While the pyrometallurgical methods involve less processes than hydrometallurgical methods, it commonly requires high energy input.

Resintering of the REE magnet powder after hydrogen decrepitation is regarded as the most convincing method for HDD recycling for the recovery of contained NIB. By using hydrogen, the method turns magnets into powders with their particle size similar to the one used for primary magnet production. It eases the removal of Ni coatings around the magnet, as Ni does not react to hydrogen in the same way. As such, the magnets can be separated from the rest of HDD in powder format, with less energy and no costly disassembly required (Sprecher et al., 2014). The method has also been actively researched and leveraged to a commercial scale in recent years. For example, SUSMAGPRO (Susmagpro, 2021), an EU Horizon 2020 project, is currently running pilot projects in four different locations in Sweden, United Kingdom, Slovenia, and Germany. The process is applied to the voice-coil (linear motor) magnet, not on the spindle motor, as the spindle motor magnet is embedded within the design, therefore hard to sense and separate. They first sort NIB containing materials with sensing and robotic technologies, where a magnetic sensor captures the voice-coil part and cut the magnetic part out, helping the voice-coil magnet to be exposed to hydrogen. The Hydrogen Processing of Magnetic Scrap technology then turns the materials into powders, and the powders are eventually reprocessed into new magnet products. It is estimated that over 90% of the NIB magnet alloy can be recovered from the process magnets (R. Kleijn, personal communication, June 24, 2021).

There also exists a business case aiming to close the loop of NIB magnet. An enterprise named Urbanmining in the United States produces new NIB magnets from end-of-life equipment. First, they collect NIB magnet waste from diverse waste streams of operation, pre-consumer, and post-consumer stage. Then the magnetic parts are extracted from the collected equipment without shredding. After automated sorting of individual material fractions, the waste magnets are recycled and put into a new production as a feedstock, from which new magnet products are made and sold. Urbanmining offers a possibility of closed loop of NIB magnets for their customers, and supply resilience of the REEs by utilizing secondary materials (Urbanmining, 2021).

3.3. CE strategies’ effect on CRMs

3.3.1. Effect per CE strategy

Type of effect from each CE strategy

Each CE strategy is found to bring different effects to CRMs contained in the focus sub-assemblies, as seen in Table 23. However, the effect of each strategy also comes with its own limitations.

The ‘reduce’ strategy – either via removal or miniaturization, can potentially reduce the CRMs demand and the associated risks. However, the miniaturization trend also poses a potential to jeopardize the recycling potential of on-board components, as seen in the case of Ta capacitors (Ueberschaar et al., 2017). The ‘substitute’ strategy also brings similar potential in CRMs demand and risk reduction. However, this effect only applies under certain conditions, e.g., that the substitution does not lead to the use of larger amount of substitute materials. The strategy also comes with limitations that other types of CRMs can be used as a substitute for one CRM, or the substitution comes with lower performance or economic feasibility, as discussed in chapter 3.2.2. The ‘reuse’ strategy extends the lifetime of CRMs that are contained in each sub-assembly. However, the lifetime extension potential is limited to the technical lifetime. At the same time, the effect depends on the actual length of extended lifetime, which depends on the decision of the first and the next users. ‘Recycling’ helps recover the materials for their secondary use. However, in current recycling practices, the majority or all CRMs found to be lost, in the case of motherboard and HDD respectively.

CE strategy	**Reduce**	**Substitute**	**Reuse**	**Recycle**
Effect on CRMs	*Removal & miniaturization:* Reduction in CRM demand and potential reduction in associated risk	Reduction in CRM demand and associated risk under certain conditions	Extending the lifetime of CRMs contained in each sub-assembly	Only few types of CRMs recovered as secondary materials
Limitations	*Miniaturization:* Influence on recycling potential	CRMs being substituted by other CRMs, or substitution leading to more material use	The lifetime extension limited to technical lifetime and actual period of extension	Significant loss of CRMs in the recycling process

Table 23. Each CE strategy’s effect on CRMs in focus sub-assemblies and its limitations

Examining the degree of effect

Next, the degree of each CE strategy’s effect was measured via multiple indicators as depicted in Table 24. First, indicators suitable for each strategy were defined. In most cases a strategy’s effectiveness was measured by ‘the number of CRMs affected.’ However, in some cases different indicators were applied. For example, the average usage time was compared with maximum potential usage time for motherboard ‘reuse’ strategy. Later, the effectiveness was determined via comparison between the current indicator and maximum indicator. The degree of effect was determined either ‘little, limited, significant, or high.’ In some specific cases, the degree was evaluated as one lower level even though the result was high due to limitations involved with identified potential.

In the case of the motherboard, the degrees were set as little as no reduction case was specified for contained CRMs except for the miniaturization trend in Ta capacitors. The substitution strategy showed clear potential in possible practices, as substitution options were identified for 10 CRMs out of total 12 CRMs. However, considering that the substitution methods are associated with several limitations, the degree of its effect was determined as 'limited.' The 'reuse' strategy also is found to bring a clear effect in CRMs lifetime extension. While the current average usage time of the server and motherboard at KPN is identified as 7 years (Internal Expert #4, personal communication, August 17, 2021), the maximum lifetime of the motherboard is identified as 10 years. This indicates the potential of saving new CRMs necessary for 3 years of motherboard usage in case the motherboard's lifetime is successfully extended to 10 years via VRPs and next customers. As the potential effect is clear yet coming under certain conditions, the level of 'reuse' strategy's effect is set as 'limited.' The effect of current recycling practice remains low, as only Pd and sometimes to the extent of Sb is recovered throughout the recycling process. However, notable CRMs recovery potential was found in possible practices, as indicated for 8 CRMs. However, as four out of 8 CRMs recovery technology has less relevance to the motherboard or feasibility, the degree of the effect is set at 'limited.'

For HDDs, a reduction of one out of 3 CRMs has been already implemented as seen in the removal of Dy in recent models. For this reason, 'limited' degree was given to the current reduction strategy. 'Functional' substitution was noticed in the SSD replacing the function of HDD. Considering that HDDs consist of at least 342-2480t of Nd per ZB while SSDs contain 0.02t of Si and 0.6t of Ta per ZB (Ku, 2018), it can be calculated that SSDs require at least 99% less CRMs compared to HDD per ZB. This is a significant reduction in material demand, from the perspective of the amount of CRMs required for the same level of service. While the substitution brings high potential in CRMs demand reduction, its degree is set at 'significant' rather than 'high,' as effective reduction can only happen under certain conditions, e.g., the prevention of rebound effect such as overproduction or overconsumption of SSDs, and with assurance that such substitution brings less environmental impact. Material substitution of CRMs in HDDs' degree of effect is determined to be 'little.' The material substitution of NIB magnet was suggested as a possibility in literature; however this was confirmed to be unfeasible by HDD suppliers. In terms of 'reuse,' on average 95% of HDDs used by KPN are sent for reuse with the other 5% being shredded (Internal Expert #4, personal communication, August 17, 2021). Considering that the reuse practice can be further promoted within the company, the degree of effect is set at 'limited' for the reuse strategy. The maximum reuse rate is set at 99% not 100%, considering that some obsolete HDDs might not have any market value left at the end of their lifecycle thus cannot be reused. The biggest potential was identified in the advanced HDD recycling technology, where one to three types of CRMs in NIB magnet alloy can be recovered. For this reason, the only 'high' degree of effect was given to the recycling technology.

Legend: Degree of effect of each CE strategy

Little	**Limited**	**Significant**	**High**

	CE strategy	**Reduce**	**Substitute**	**Reuse**	**Recycle**
Mother board	*Indicator*	*No. of CRMs affected*	*No. of CRMs affected*	*Current lifetime /maximum lifetime*	*No. of CRMs affected*
	Current practice	1/12 CRMs (Ta capacitor miniaturization)	0/12 CRMs (None identified)	7 year/10 year (Average usage time at KPN)	1-2/12 CRMs (Pd and Sb recovery)
	Possible strategy	0/12 CRMs (None identified)	10/12 CRMs (None identified)	10 year/10 year (Technical lifetime)	4-8/12 CRMs (Recovery from advanced practices)

	CE strategy	**Reduce**	**Substitute (functional)**	**Substitute (material to material)**	**Reuse**	**Recycle**
HDD	*Indicator*	*No. of CRMs affected*	*CRMs weight reduction % (t/ZB)*	*No. of CRMs affected*	*Current reuse rate /maximum reuse rate*	*No. of CRMs affected*
	Current practice	1/3 CRMs (Removal of Dy)	Higher than 99% reduction in CRMs (CRMs content comparison between HDD and SSD)	0/3 CRMs (None identified)	9.5/10 HDD reuse (Average reuse rate at KPN)	0/3 CRMs (None identified)
	Possible strategy	0/3 CRMs (None identified)		0/3 CRMs (None identified)	9.9/10 HDD reuse (Improved reuse rate at KPN)	1-3/3 CRMs (Recovery of NIB magnet alloys)

Table 24. Each CE strategy's degree of effect

3.3.2. Effect on CRMs in each sub-assembly

In this section, the effect of each CE strategy was reviewed per type of CRM contained in each sub-assembly. The details are described in Table 25 and 26.

i. Motherboard

CE strategy	Reduce	Substitute	Reuse	Recycle	
Contained CRM	Current practice	Substitution potential found	Direct reuse	Current practice	Advanced recycling technology
Silicon (Si)**	.	● (CRMs)	Extends the lifetime of all CRMs contained	.	○
Boron (Bo)**	.	● (CRMs)		.	○
Barium (Ba)**	.	.		.	○
Tantalum (Ta)*	●	● (CRMs)		.	○
Magnesium (Mg)*	.	● (CRMs)		.	.
Phosphorus (P)*	.	.		.	.
Cobalt (Co)	.	●		.	.
Antimony (Sb)	.	● (CRMs)		○	●
Ruthenium (Ru)	.	● (CRMs)		.	●
Palladium (Pd)	.	● (CRMs)		●	●
Germanium (Ge)	.	● (CRMs)		.	●,○
Tungsten (W)	.	● (CRMs)		.	.

*Contained amount: ** higher than 1000mg, * higher than 100mg*

● : Applied case exist

○ : Less definite case exist

(CRMs) : Substitute contains another CRM

. : Not identified

Table 25. [Motherboard] Types of CRMs each CE strategy has effect on
(CRMs listed in the order of contained amount: largest to lowest)

Among the 12 types of CRMs identified in the motherboard, possible recycling technologies are found to be lacking for Si, Bo, Ba, Ta, Mg, P, Co, and W. A few advanced recycling technologies were identified for components and commodities containing Si, Bo, Ba, Ta, but they either lack relevance to motherboard recycling, or lack possibility whether it can be applied to industrial practices. Therefore, either CE strategies under 'reduce' category, or further recycling strategies for especially Mg, P, Co, W, and to an extent of Si, Bo, Ba, and Ta will need to be sought after.

In the case of 'reduce' strategies, reduced amount of Ta in Ta capacitors and its substitution potential with niobium has been identified (Ueberschaar et al., 2017). Substitution potential for other CRMs have been found in literature except for Ba and P, however, the potential comes with limitations: 1) that the majority of them except for Co have another type of CRM as part of substitutes, and that 2) its implementation possibility could not be checked with supplier of each component, due to complexity in the value chain. Still, it remains clear that substitution efforts will be crucial, considering the difficulty in CRMs recovery in the recycling stage. Reduction or removal strategy for especially Ba and P will be needed, with efforts to find non-CRM substitutes for the other materials.

Ii. HDD

CE strategy	**Reduce**	**Substitute**	**Reuse**	**Recycle**	
Contained CRM	Current practice	Substitution potential found	Direct reuse	Current practice	Advanced recycling technology
Neodymium (Nd)***	.	.	Extends the lifetime of all CRMs contained	.	●
Dysprosium (Dy)**	●	N/A		.	○
Cobalt (Co)*	.	.		.	○

*Contained amount: ***higher than 9000mg, ** higher than 1000mg, * higher than 100mg*

● : Applied case exist

○ : Less definite case exist

(CRMs) : Substitute contains another CRM

. : Not identified

Table 26. [HDD] Types of CRMs each CE strategy has effect on
(CRMs listed in the order of contained amount: largest to lowest)

In the case of HDDs, advanced recycling technology has potential to recover over 90% of NIB magnets (R. Kleijn, personal communication, June 24, 2021). At the same time, HDD supplier A explains a closed-loop recycling practice by a NIB magnet supplier who recovers Nd from scrap magnets for a less virgin material demand. While a few substitution potentials for Co and Nd were found in literature, its implementation is confirmed as not possible by HDD suppliers. Still, the removal of Dy from recent HDD models has been identified. At the same time, SSD's replacement of HDD in the drive market in the next 10 years have been forecasted (Supplier A, personal communication, June 24, 2021). The upcoming replacement implies the CRMs in SSDs – Si and Ta (Ku, 2018b) - substituting the function of CRMs in HDD. The findings also implicit the importance and high potential of employing advanced recycling technology of CRMs within HDDs already in the market. Especially converting used NIB magnets into new magnet via hydrogen decrepitation technology, either for same application or other applications such as wind turbines and electric motors (Charles et al., 2020) is expected to support meeting the increasing demand of the REE magnets for low-carbon technologies, while HDD demand is gradually superseded by SSDs. Maximum reuse of remaining HDDs in the market will also need to be encouraged to extend CRMs' function and lifetime for its maximum period. Sending HDDs to the advanced recycling facility with capacity to convert the magnetic parts into another product, after use or reuse, will remain crucial.

3.3.3. Effect on risks associated with CRMs

While it is challenging to reach absolute quantification of the strategy's effect on the risks, each CE strategy is expected to influence the supply risk and environmental impact associated with CRMs to a different extent depending on multiple factors described in Table 27.

CE strategy	Reduce	Reuse	Recycle
Dependent factors for supply risk mitigation	Removal | Supply risk associated with additional substitute	Length of extended lifetime	Input rate of domestically recycled materials
	Substitution | Supply risk associated with substitutes	Location of secondary commodity	Location of recycling (domestic or not)
	Reduction | Miniaturization's effect on recycling	Proper recycling after the final use	Import supply mix redistribution potential
Dependent factors for reduction in environmental impact	Env. Impact associated with producing/sourcing of substitute, and modification in production process	Length of extended lifetime	Env. Impact associated with each type of recycling process
	Env. Indicator of production process of each supplier	Proximity and efficiency of commodity exchange (location)	Location and applied technologies of recycling
		Proper recycling after the final use	

Table 27. Risk mitigation potential of each CE strategy and factors influencing the extent of mitigation

Effect on supply risk associated with CRMs

As the supply of CRMs is inherently affected by the geopolitical factors (Griffin et al., 2019), the supply risk mitigation potential of 'Reduce' strategy will also be dependent on the location of each component's production. In case the production takes place in the region where it heavily depends on the import of CRMs, the strategy is expected to bring a more substantial reduction of the supply risk, depending on certain factors. The removal of CRM from the original design of a component is expected to take away the supply risk associated with the material. However, it should be examined whether additional material needs to be added to complement the role of CRM, and in that case whether the new material entails another supply risk. A similar condition needs to be applied for substitution strategies as well. Efforts to substitute CRMs with non-CRMs, and materials with less supply risk need to be accompanied to maximize the supply risk mitigation. Reduction in the CRMs amount contained in the application also can help reduce the supply risk by reducing the demand, however its potential in reducing recycling potential need to be reviewed together as seen in the case of on-board component miniaturization.

The 'Reuse' strategy is seen to contribute to the reduction of supply risk of all CRMs contained in each sub-assembly, as the strategy substitutes the need for primary CRMs in new products. However, the extent of contribution will mainly depend on 'how long' the sub-assembly is further reused. At the same time, the location where the secondary commodity is available will affect the amount of mitigated supply risk. Sending the product to proper recycling partners with most advanced recycling practice for CRMs will remain crucial, as it determines the contained CRMs' potential in further reducing the supply risk by being used as secondary material in the economic system.

The 'recycle' strategy has potential to reduce the supply risk of CRMs, however its extent depends on several factors. According to Santillán-Saldivar et al. (2021), the supply risk mitigation potential of recycling differs per every type of CRM, as each CRM entails different levels of supply risk and end-of-life recycling input rate. The authors examine domestic recycling's potential in CRMs supply risk mitigation via two mechanisms: 1) the reduction it brings to the total import of the material (reduction effect) and 2) the potential in redistribution of import shares among supplier countries (redistribution effect). The study stresses that for a maximum risk mitigation, recycling should happen domestically with the recycled material put back into the domestic economy. In addition, it mentions the importance of considering the redistribution of supply mix – readjusting the import shares among supplier countries based on each country's supply risk level – as for some CRMs the redistribution effect is found to be higher than reduction effect. This point reflects that the diversification of suppliers based on material criticality assessment on firm level remains significant.

Effect environmental risk associated with CRMs

Considering the substantial amount of energy and water use required for the extraction of different types of CRMs from ores (European Commission, 2018), the 'reduce' strategy is expected to reduce environmental impacts associated with the extraction and processing of primary materials. However, the environmental impact involved with the production of substitute or additional material need to be considered together. Life cycle impact assessment (LCIA) part of life cycle assessment (LCA) can help identifying the environmental impact associated with the raw material use on a more accurate extent (Kolotzek et al., 2018), while conducting a complete LCA is challenging due to lack of transparency in raw materials supply chain (Guinée et al., 2011).

The 'Reuse' of sub-assemblies is expected to contribute to reducing the environmental impact associated with the production of CRMs, by replacing the need for other CRMs in a new product. However, its extent will depend again on the length of extended lifetime, and the disposal method applied to it after its final use. Also, factors related to the exchange of used sub-assembly in the resale market will matter, on 1) whether the exchange happens in close proximity and 2) whether the exchange processes happen in efficient and truly circular manner, without a same product ending up in the hand of similar parties after exchanges among multiple traders (VRP A, personal communication, April 19, 2021)

'Recycling' CRMs from scraps or via recycling of used sub-assemblies is expected to save significant reduction in environmental impact associated with primary material production. This is especially because the sub-assemblies contain much higher concentration of certain CRMs compared to their concentration found in ores. Chancerel et al. (2009) explain the environmental impacts in the case of precious metals extraction, that the process involves significant greenhouse gas emissions, and energy, water, and land usage. Compared to this, the impacts from the production of secondary material from the recent processes are found to be much lower. European Commission (2018) provides examples on less energy and water use for secondary CRMs production from scraps in comparison to extraction from ores as explained in Table 28. While the abovementioned environmental advantages are expected from recycling, a few factors need to be considered to maximize the advantage. The environmental impact associated with each recycling process needs to be examined, as for certain advanced recycling technology – such as biohydrometallurgical and hydrogen decrepitation – is found to have lower impact compared to others. At the same time, the location and infrastructure for advanced recycling practice will matter. It is estimated that 16-38% of WEEE collected within the EU are sent to and processed in developing countries. The recycling of WEEE in developing countries happens in a highly informal method, therefore ending up in the release of hazardous chemicals contained in the WEEE(Işıldar et al., 2018). For this reason, the firms in charge of the disposal need to ensure that the recycling happens in a responsible manner, according to regional regulations.

Metal	**Energy use** (MJ per kg of metal extracted)		**Water use** (m^3 per tonne of metal extracted)	
	Scrap	Ores	Scrap	Ores
Magnesium	10	165-230	2	2-15
Cobalt	20-140	140-2100	30-100	40-2000
PGM	1400-3400	18,860-254,860	3000-6000	100,000-1200,000
Rare Earths	1000-5000	5500-7200	250-1250	1275-1800

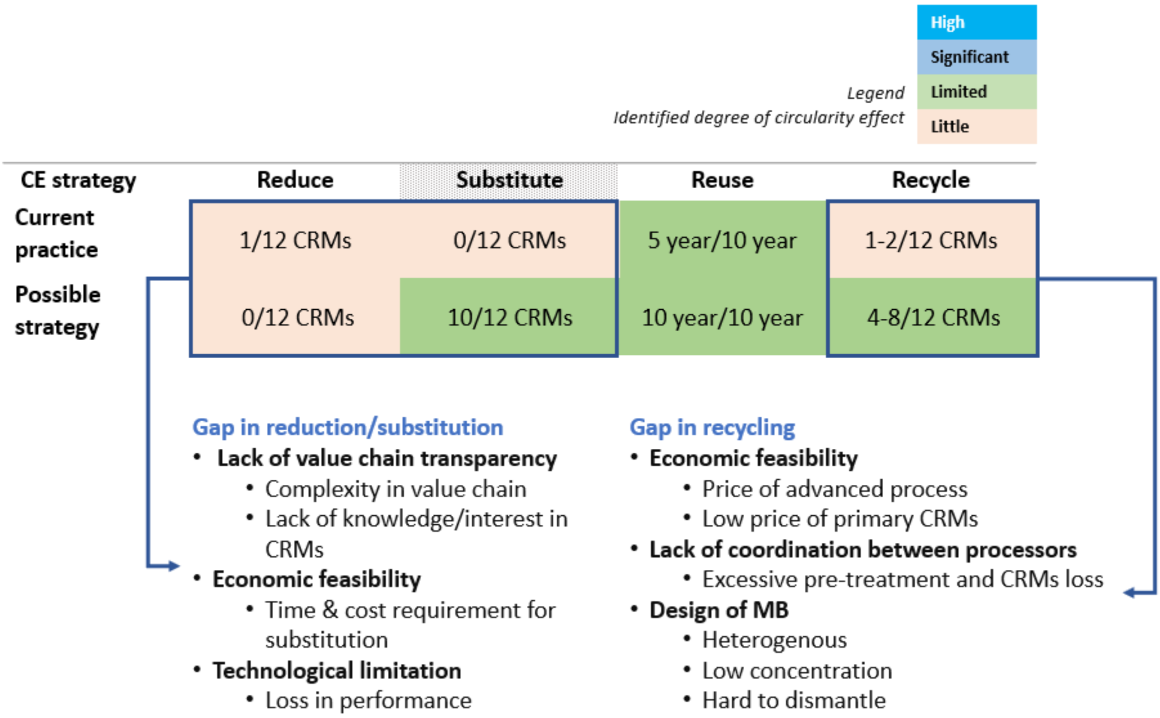
Table 28. Comparison of energy and water use in production of metals from scrap and ores in (European Commission, 2018)

4. Discussion

4.1. Analysis of the gap between practices and possibilities

In this section, an overview of circularity potential identified in current practice and possible strategies of each sub-assembly is given, with an analysis on the reasons behind the gap between practices and possibilities.

i. Motherboard



CE strategy	Reduce	Substitute	Reuse	Recycle
Current practice	1/12 CRMs	0/12 CRMs	5 year/10 year	1-2/12 CRMs
Possible strategy	0/12 CRMs	10/12 CRMs	10 year/10 year	4-8/12 CRMs

Gap in reduction/substitution

- **Lack of value chain transparency**
  - Complexity in value chain
  - Lack of knowledge/interest in CRMs
- **Economic feasibility**
  - Time & cost requirement for substitution
- **Technological limitation**
  - Loss in performance

Gap in recycling

- **Economic feasibility**
  - Price of advanced process
  - Low price of primary CRMs
- **Lack of coordination between processors**
  - Excessive pre-treatment and CRMs loss
- **Design of MB**
  - Heterogenous
  - Low concentration
  - Hard to dismantle

Figure 16. [Motherboard] Circularity potential found in possible strategies and reasons behind the gap

In the case of motherboard, further potential in CRMs circularity was mainly found in substitution and recycling strategies. While the implementation possibility of substitution and the reduction potential of CRMs and substitute material need to be examined, substitute potential for ten CRMs out of 12 CRMs identified in server's motherboard were introduced in literature. Another potential for CRMs circularity was observed in advanced recycling technologies. While it remains unclear whether the identified recovery method of specific CRMs can be incorporated in industrial practices, advanced metallurgical processes designed for specific types of CRMs pose possibility for a further recovery of CRMs from WEEE in future (Işıldar et al., 2018).

Three factors are found to be main reasons behind challenges in implementing reduction or substitution of CRMs in the motherboard: lack of value chain transparency on CRMs data, lack of economic feasibility in modifying existing production processes, and technological limitation. The motherboard's value chain is extremely complex with more than 100 suppliers involved, as can be seen in the example motherboard value chain of Supplier A in Figure 17. The OEM designs its motherboard towards functional specifications defined by its PCB design team. The suppliers for necessary components are selected among the vendors approved by the OEM, which run to up to 3 figures. Considering that each supplier in the list sources necessary materials and sub-components from its own suppliers who have their own supplier in the next tier, the difficulty in tracking exact material composition of each sourced component grows with the complexity of the value chain. For this reason, OEMs' knowledge on the exact type, amount, and amount of contained CRMs can be not yet matured in a complete scope. At the same time, it is recent that the interest on the topic of CRMs started increasing among business partners, and that the OEM set up a team to investigate material criticality much more in-depth (Supplier A, personal communication, March 2, 2021) Economic feasibility and technological limitation were other main influencing factors. According to Supplier A, the reduction of certain constituent material brings challenges as it requires substantial modification to existing production facilities which entails significantly high cost. Another barrier for reduction or substitution is that it brings a potential in compromising the specification of the product. The complete requalification of the adjusted production pathway will require substantial effort. At the same time, development of new metallurgy is seen to take years of effort. Potential loss in performance loss and cost advantage are often stated as limitations for CRMs substitution in literature, as described in Appendix A.2.

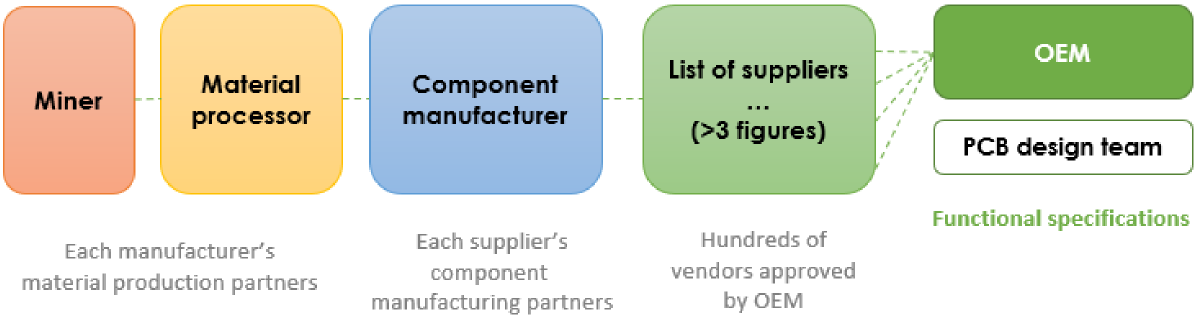
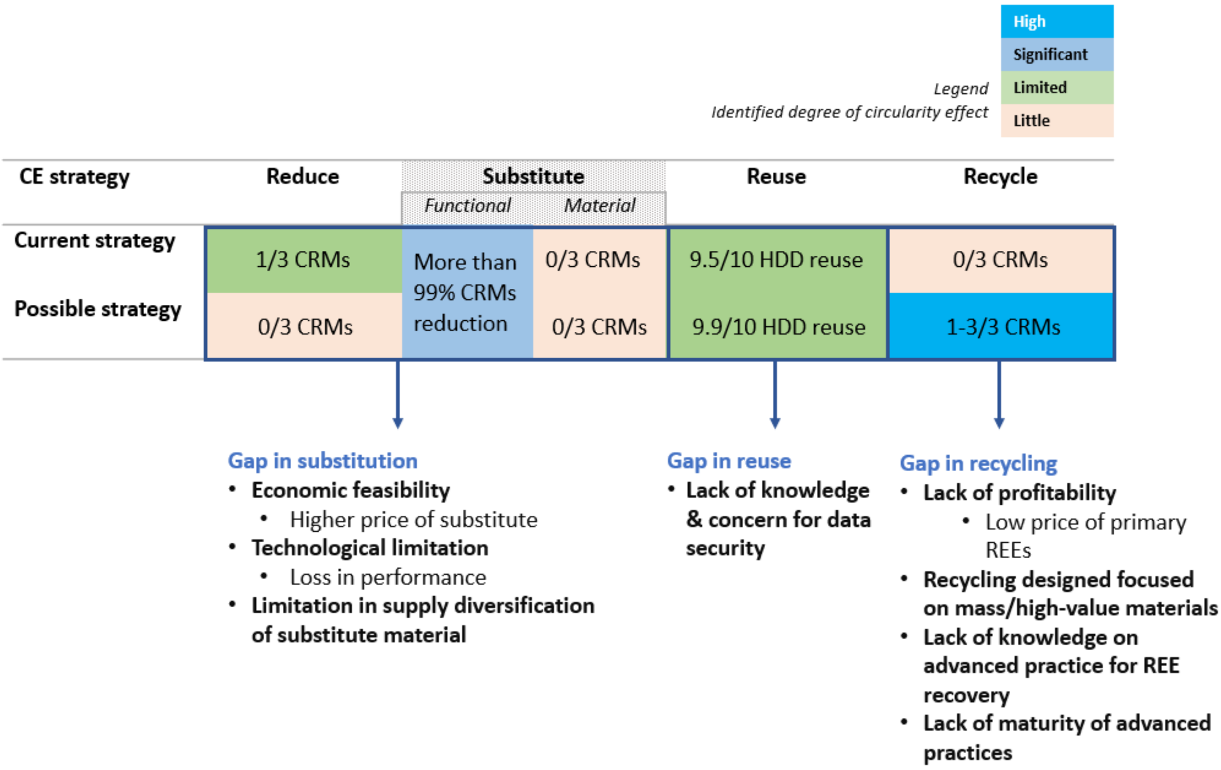


Figure 17. Simplified motherboard value chain depiction of Supplier A

Economic factors play a major role in deciding whether advanced metallurgical processes are incorporated into existing industrial practice. According to End-processor A, hydro or biohydrometallurgical processes are found to be not optimal for the smelter's practice as it lacks economic profitability and robustness in material purity. The advanced processes are especially not suitable for WEEE with complex composition, such as motherboard. The requirement of additional processes due to the complex composition of the motherboard can eventually diminish the environmental advantage of the process such as less CO2 emissions. Recovery of CRMs often brings low cost-competitiveness, as primary CRMs can be cheaper than the recycling of the materials. While the technologies are most of the time available for the recovery of different types of CRMs, it is often not implemented in practice due to the low cost-competitiveness. A pre-processor will often decide the material to focus for the recovery as recovery of one material can contradict the recovery of others. For economic reasons, the pre-processors often choose materials with higher economic value, as seen in current recycling practices focusing on Ag, Au, and PGMs. At the same time, coordination between the pre-processor and end-processor remains crucial for CRMs and precious metals recovery, as less pre-treatment enables more recovery of these materials at the smelting processes. End-processor A explained that the physical processing is more suitable for mass materials such as plastics, Al, Fe, and Cu. For high-grade PCBs such as server motherboards, least to no pretreatment makes the materials most suitable to the smelting process (End-processor A, personal communication, November 24, 2020). The inherent characteristics of motherboard design also adds limitations to CRMs recovery in recycling processes. The heterogeneous, complex mixtures of materials contained in low amounts make it challenging and costly to recover diverse types of CRMs on the motherboard. Rather, a recovery pathway targeted for certain material fractions will lead to the loss of CRMs (Charles et al., 2020; Sethurajan et al., 2019). The design of motherboard not fit for recycling processes (Charles et al., 2020), for e.g. via components glued to the board via resin (Internal Expert #5, personal communication, August 19, 2021) adds barrier to further recovery of CRMs. Considering that the decision on CRMs recovery is made depending on the 1) price of primary CRMs and cost for their recovery process 2) level of CRMs concentration in the target WEEE and 3) other materials co-existing within CRMs containing components (End-processor A, personal communication, November 24, 2020), it can be inferred that the low price of primary CRMs and low concentration within motherboard leaves little reason for end-processors to focus on CRMs recovery.

ii.HDD



Legend
Identified degree of circularity effect

- **High**
- **Significant**
- **Limited**
- **Little**

CE strategy	Reduce	Substitute *Functional*	Substitute *Material*	Reuse	Recycle
Current strategy	1/3 CRMs	More than 99% CRMs reduction	0/3 CRMs	9.5/10 HDD reuse	0/3 CRMs
Possible strategy	0/3 CRMs		0/3 CRMs	9.9/10 HDD reuse	1-3/3 CRMs

Gap in substitution
- **Economic feasibility**
  - Higher price of substitute
- **Technological limitation**
  - Loss in performance
- **Limitation in supply diversification of substitute material**

Gap in reuse
- **Lack of knowledge & concern for data security**

Gap in recycling
- **Lack of profitability**
  - Low price of primary REEs
- **Recycling designed focused on mass/high-value materials**
- **Lack of knowledge on advanced practice for REE recovery**
- **Lack of maturity of advanced practices**

Figure 18. [HDD] Circularity potential found in possible strategies and reasons behind the gap

For HDDs, further potential for CRMs circularity was found in substitution, reuse, and recycling strategies, with especially high potential identified in advanced recycling technologies. While material to material substitution potential was mentioned for contained CRMs such as Co and Nd, its practical implementation was confirmed not possible by HDD suppliers. However, the upcoming functional substitution of HDDs by SSDs has been identified among OEM and VRP, indicating that the Si and Ta contained in SSD can potentially substitute the CRMs content of the HDD in the coming 10 years. Under the reuse strategy, further refurbishment and reuse potential of HDDs used by KPN was identified as some HDDs are currently preferred to be shredded and disposed rather than sent for refurbishment due to concern on data security. In the recycling processes, current practice of shredding the entire HDD and smelting not specifically focused on REEs is identified to result in the loss of all contained REEs. However, a significant potential for REEs recovery was revealed among advanced recycling technologies. Hydrogen decrepitation method which converts NIB alloy powders into new magnetic parts can recover over 90% of the materials contained in the NIB magnet.

Economic feasibility, limitation in performance and supply diversification were explained as main factors limiting the implementation of substitution potential for NIB magnet. The SmCo magnet features higher market price and higher supply dominance by one country compared to NIB magnet. At the same time, it entails higher risk of contamination and brittleness, potentially posing less robustness in the performance.

In current practice, some of HDDs used at KPN are shredded and sent to recycling flow, rather than going through the reuse process by refurbishment of VRP. It is due to multiple reasons, 1) by end-customer's request of decommissioning coming from lack of knowledge about reuse potential and concern for data security, 2) from internal departments dealing with sensitive information preferring to shred HDDs rather than wipe and reuse them, 3) Technocenter's decision on reuse or recycling and 4) out of market value due to HDDs' obsoleteness. Despite the concern on data security, VRP A explains that the HDDs arrived at KPN's partner VRP get wiped 7 times to ensure high security, while one time of wiping is regarded as safe enough (VRP A, personal communication, June 4, 2021). The guaranteed safety of the refurbishment process conducted at the VRP suggests a potential for further reuse of HDDs, extending the lifetime of CRMs while preventing the loss of existing market value left in the sub-assembly.

While there exist advanced recycling technologies for the recovery of REEs contained in HDDs, multiple factors can be inferred for their absence in current practices related to KPN. First of all, the low market price of primary REEs (End-processor A, personal communication, May 6, 2021) suggest little reason to design the recycling processes targeting the materials. One HDD supplier explained that there have been efforts by NIB magnet suppliers to reduce virgin Nd material demand by recovering Nd from magnet scraps via recycling. However, due to the low price of the commodity, the cost element sometimes becomes a barrier to the recycling practice as indicated in Appendix A.4. For this reason, it is shown that non-ferrous metals are found to be a major output fraction of current HDDs recycling process, together with plastic, ferrous metals, and PCB. Considering the shortage of information on REEs' fate in current recycling processes and on advanced recycling technologies from pre-processors (Pre-processor B, personal communication, June 3, 2021), the lack of knowledge and interest on REEs recovery can be suggested as another reason behind the gap. At the same time, taking into account that the advanced practices such as the hydrogen decrepitation process by SUSMAGPRO have been put into pilot projects in recent years, less maturity and availability of advanced practice can be another reason for the existing gap.

4.2. Points of leverage

4.2.1. Leverage points across product value chain

i. Motherboard

In the upstream of the motherboard's value chain, it remains crucial that the detailed data of CRMs contained in the motherboard is made available across the chain, as it will be the foundation that unlocks the potential of other leverage points. However, considering the business proprietary concerns and the complexity and multitude of tiers of suppliers involved in its production, the collection of overall data poses substantial challenges. Mobilizing blockchain technology, thereby making the CRMs-specific data available with anonymity, is gaining attention as a potential method to enable the data sharing (*Circularise Uses Blockchain Technology to Trace Raw Materials*, 2021). At the same time, the fact that some component manufacturers make each product's detailed material report fully available online (Maxim Integrated, 2021) brings the possibility for better CRMs data sharing, if further collaboration among tiers of suppliers can be forged. Sharing of CRMs data is expected to bring substantial synergy for recycling as well, as it can help recyclers develop a process closely suited for the recovery of specific materials.

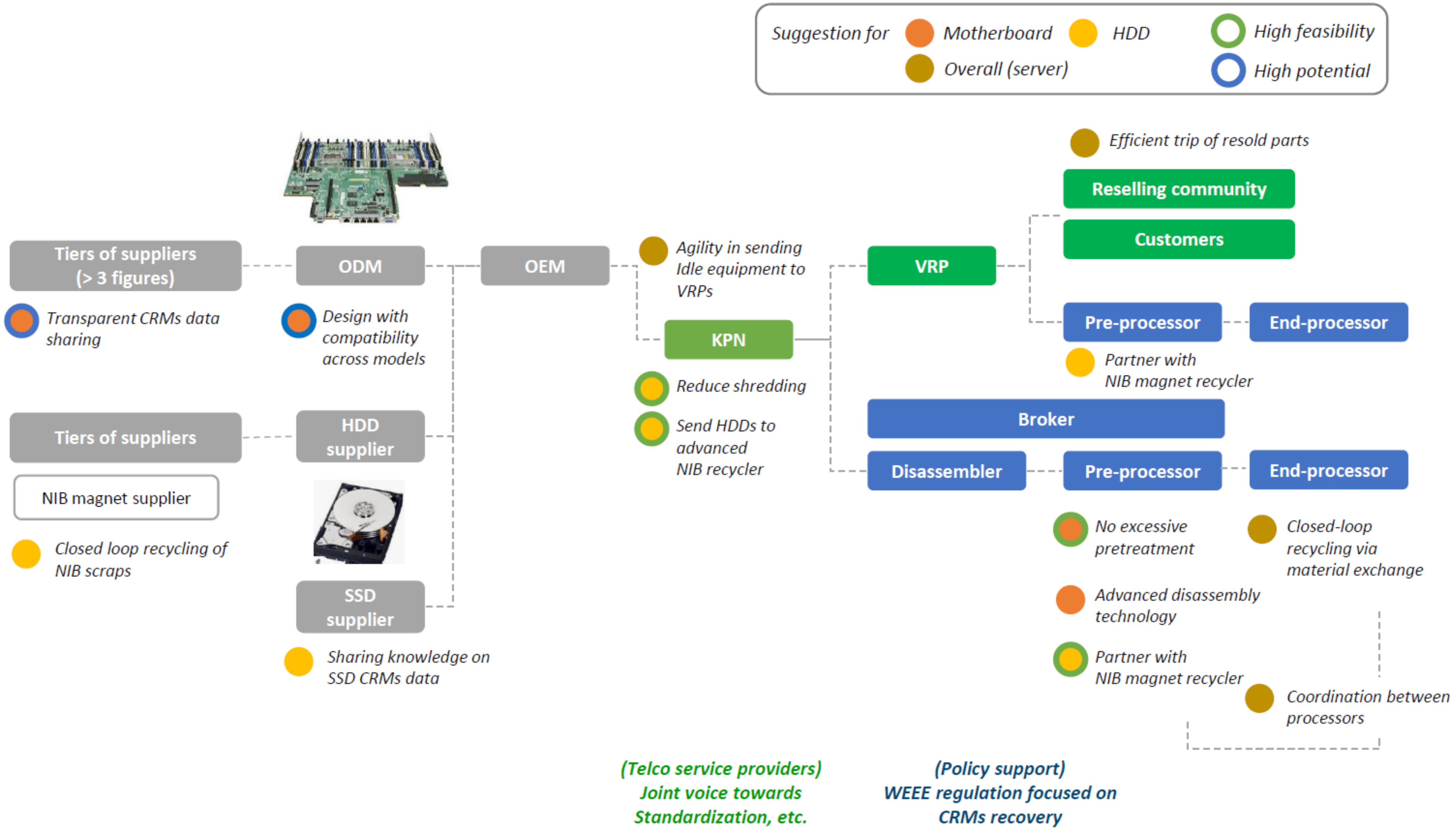


Figure 19.Points of leverage found across the value chain

At the same time, the efforts from OEM in designing the motherboard more compatible across model generations will encourage further reuse of other sub-assemblies. When the servers are upgraded to new generations, often the new design comes with low compatibility with sub-assemblies used in previous generations. This can be witnessed in the HDD's input-output cables on the motherboard not suiting to the format anymore, or slots to put in DIMM becoming smaller (VRP A, personal communication, April 19, 2021). As the motherboard is designed with collaboration between OEM and its suppliers (Supplier A, personal communication, June 1, 2021), consideration for compatibility should be exercised from the partners from the product design phase.

In the recycling processes, as proved in literature and by end-processor, no excessive pretreatment is recommended for a better recovery of CRMs, or precious metals. Therefore, a close coordination between pre-processor and end-processor will be necessary to design the entire recycling process fit for the recovery of more CRMs. Advanced disassembly methods (Charles et al., 2020) – especially the automated processes in development via geometric measurements and spectroscopic analyses (ADIR, 2021) – is expected to add potential in effective recovery of CRMs from waste PCBs. In addition, potential for realizing closed-loop recycling of precious metals and CRMs via exchange of materials stocked at end-processors' accounts has been suggested. End-processors can put the materials recovered from its client in stock at their material account. If such a process can be properly documented with full administrative capacity, the material account can be used as a medium to sell recycled materials to manufacturers, thereby achieving a closed loop recycling within applied regions (End-processor A, personal communication, November 24, 2020).

ii. HDD

A potential for closed-loop recycling was observed in the upstream of HDD production, as one supplier explained a case of NIB magnet producer who recycles the magnet scrap to reduce primary material demand in its production. As SSDs will substitute the function of HDDs in the coming years, the CRMs composition of SSDs will need to be more transparently shared across the value chain to develop CE strategies designed for SSDs.

There are a few highly feasible leverage points the service provider KPN can apply. First of all, reducing the shredding of HDDs and further promoting the reuse of HDDs is expected to not only extend the lifetime of contained CRMs, but to bring back higher market value left in HDDs to KPN. For such a change, above all the knowledge on the safety of HDD refurbishment process will need to be clearly communicated both internally among departments and externally with end-customers.

As advanced recycling technology to recover NIB magnets from HDDs is identified as a strategy with clear potential, it is recommended to find an HDD recycling partner with such specialty. It can be more efficient for KPN to collect HDDs for recycling firsthand during the internal inspection phase and send them to the NIB magnet recycler. At the same time, it can be suggested to introduce NIB magnet recycler, or such technology to recycling partner of KPN, or recycling partner of the VRP, to help KPN's HDDs flow into the intended recycling process in the end. It needs to be further checked whether partnering with NIB magnet recycler would be possible, as the practice can be still at its pilot stage. Still, it is highly notable that the technology is growing into a commercial scale, so when applicable the companies can apply the up-to-date technology to their downstream processes.

iii. Additional leverage points

Sending the equipment or sub-assemblies that are not used anymore under KPN's scope to VRPs as soon as possible is always recommended, as it can retain the market value left in them and thereby promote the reuse as much as possible. Considering that refurbished products often end up at similar endpoints after being circulated through multiple traders within Europe, a system that enables the tracking of their trip is necessary to make the exchange truly circular and more efficient (VRP A, personal communication, April 19, 2021).

4.2.2. System-level support

In the long term, support from system-level, such as requirements by regulations is seen to be one of most effective strategies to bring intended change in the industry (Supplier A, personal communication, June 3, 2021). Efforts to enhance CRMs data transparency have been made, as seen in recent updates in Ecodesign regulations for servers and data storage products by the European Commission. In accordance with the EU's action plan for the circular economy, suggestions to address the aspect of CRMs in Ecodesign requirements have been made. As a result, from March 2020 it has been required for suppliers to indicate the weight range of Nd in HDDs and Co in batteries to third parties involved in the maintenance, reuse, and recycling of servers. In addition, the Commission announced a review of the information requirements for CRMs of Ta, Ga, Dy and Pa in the product, considering the need of recyclers by March 2022 (European Commission, 2021).

In addition, there needs to be an effort to update WEEE legislation with further consideration on CRMs recovery. Penttilä (2020) points out the limitation of current EU WEEE legislation which focuses on recycling a higher percentage of the total mass of waste, which does not suit the recovery of CRMs contained in low concentrations in complex electronic products. The study makes several suggestions to tailor WEEE legislations to CRMs resource efficiency, including the idea of supplementing the current WEEE recovery targets with setting 1) mandatory recovery targets for CRMs 2) incentive system for higher CRMs recovery and 3) requirements on % of secondary CRMs in new products.

In Article 10 of WEEE legislation stipulates a set of conditions for the shipment of WEEE (Directive 2012/19/EU). The aim of the conditions is to distinguish between EEE (Electrical and Electronic Equipment) with legitimate purpose and WEEE illegally exported out of the EU region, following the intention of Basel Convention on the Control of Transboundary Movements of hazardous wastes and Disposal. The illegal trade of WEEE from EU is in fact found to be a major issue, as in 2012 total 1.3 million tons of WEEE is identified to be shipped from EU to external regions without documentation (Penttilä, 2020). While the purpose of such conditions is regarded as legitimate, the industry leaders in the capital equipment sector expressed the need to adjust the condition as the legislation can hinder their large-scale circular business operations (PACE, 2021). The coalition explains how the conditions on transboundary movement can hinder the movement of devices and sub-assemblies intended for reuse as part of circular business ambitions. For this reason, they stress the need to distinguish the 'resource' from the term 'waste,' and readjust the legislation to support the companies' ambition to extend and add the lifetime of sub-assemblies and devices. While the exchange of devices at a closer proximity contributes to the environmental aspect of circularity, such suggestions indicate the need to ease transboundary movement of equipment within the region for an efficient implementation of circular business models.

4.2.3. Envisioning future actions for enhanced circularity of CRMs

Throughout the research it was found out that the knowledge about CRMs is still in development across the value chain, so are the plans to enhance their circularity. It is also identified that business factors and proprietary issues play an important role among stakeholders in considering future actions. Still, the material criticality is an apparent issue for current and future businesses and the firms need to take further mitigation strategies (Gaustad et al., 2018), for example actions specifically designed for the circularity of CRMs. Therefore, a roadmap for enhanced circularity of CRMs is drawn as shown in Table 29 and 30, where potential actions each actor in the value chain can take are suggested in the timespan of short, mid, and long-term periods.

	Suppliers (OEMs)	**Service providers**	**Recyclers**
Short-term	**CRMs content investigation** *Suppliers	**CRMs content identification and price volatility monitoring**	**Coordination between processes** *Pre and end-processors
	Material criticality assessment *Suppliers, researchers	**Inform and connect partners on CRMs and mitigation strategies**	**Advanced disassembly technologies**
			Price forecast system
Mid-term	**Reduction strategies for target CRMs** *Material scientists, architects	**Joint request to the industry and policymaker**	**Advanced recycling technology for target components or CRMs** *Manufacturers, researchers
	Reduced environmental impact in CRMs usage and manufacturing *Researcher, engineers		
	Design for recycling *Architects (designers), recyclers, researchers		
	Sourcing from suppliers with CRMs circularity advantage *Suppliers	**Extend the use of devices & Use PAAS/take-back system or find credible VRP and recycling partners**	
	Design for lifetime extension *Researcher, architects, engineers		
	Expand Product As A Service (PAAS) and connect it to recycling processes *Customers, logistic services		
Long-term	**Systematize circular economy strategies and share knowledge**	**Product selection considering advantages on CRMs circularity**	**Exchange of material stock at smelters**

**: Partners to collaborate with for suggested actions*

Table 29. Future actions recommended for enhanced circularity of CRMs [Case of motherboard]

The role of suppliers, especially of OEMs will remain significant as they are in charge of the product design and coordination of the supply chain in the upstream. Therefore, manufacturers have both responsibility in taking initiatives and capability to bring effective mitigation strategies into actions. First of all, the suppliers and OEMs should become fully aware of the CRMs content in their own sub-assemblies such as motherboard and its on-board components. Investigation of material composition on a component level is recommended for OEMs, which can be conducted in close collaboration with their suppliers. Assessing each material's criticality can be taken as the next step, to identify CRMs with high relevance and risk to the firm's business. Based on the assessment, the firm can draw out its own CE strategies to reduce the risks associated with identified materials. Ways to reduce the amount of CRMs contained in the motherboard without losing its original properties will need to be investigated with collaboration between material scientists and PCBA architects. The design of the motherboard should be modified with careful consideration to enable the next life cycle of the CRMs contained in each component. This would for example include easing the disassembly of on-board components and modifying the component and board design (e.g., incorporating modularization) tailored to target materials' recovery processes. Active collaboration between product designers, recyclers and researchers will remain significant for this process, so that the new design enables an efficient recycling process that is economically viable and does not hinder the recovery of other economically valuable materials. Additionally, OEMs can take initiatives to source components from suppliers who are found to incorporate CRMs reduction or substitution in their production processes. At the same time, as certain components or manufacturing process can entail much higher environmental impact (Dell, 2019), efforts to assess the overall environmental impact associated with the production phase and to modify the process based on the findings should follow. For example, a methodology such as life cycle assessment (LCA) will help assess environmental impact associated with certain CRMs or manufacturing process, and inform which part of the design or production processes needs to be modified. As the extended product life cycle can extend the lifetime of CRMs as well, initiatives to extend the lifetime of each sub-assembly and the overall device without losing functional specifications or energy efficiency, will remain crucial. The transition of the existing business model towards Product As A Service (PAAS) should be continued among OEMs, but at the same time OEMs should be able to link the PAAS with up-to-date remarketing and recycling services when the used products are collected under their logistics scheme. In the long-term, the suppliers' strategy to reduce, maximize the reuse, and recycle CRMs should be embedded into each business as a systematized process.

Telecom service providers like KPN, or by extension, IT service providers handling a large number of servers, have a unique position and role as they sit in the middle of the product value chain. As customers to suppliers, VRPs, and recyclers, service providers can firsthand inform about issues regarding CRMs and suggest future actions. At the same time, they can help connect partners in the upstream and downstream so that CE strategies concerning the entire lifecycle and the next life cycles of contained CRMs can come into reality. To identify potential effects of CRMs on their business and mitigation strategies, the service providers can first try to identify CRMs in the products they use, with the help of suppliers. Monitoring the price volatility of materials most relevant to their businesses can be a helpful device to keep an eye on potential threats to their own businesses and suggest CE strategies to relevant parties to avoid the risk. For the suggestions from service providers to be heard and reflected in the industry practices, a joint voice among service providers will be necessary in the mid-term. Unified, specific suggestions from a group of service providers to suppliers and policymakers, such as standardization recommendations would influence the market more effectively. The service providers can firsthand try to extend the lifetime of the devices under their business scope. If it is difficult to extend the initial usage time due to technological advancements (Internal Expert #4, personal communication, August 17, 2021) or energy efficiency they need to incorporate, the service providers should make sure to send the used devices to partners that ensure their reuse with the best recovery of remaining value. This can be done by using the PAAS and take-back systems of OEMs, or by organizing their own downstream flows with credible value recovery partners. The choice should be based on detailed environmental factors together with economic factors to establish a more circular downstream business model. Examples of the factors would be the location of the take-back service and environmental impact associated with the partner's value recovery services. Sending the obsolete devices to advanced recycling services will be crucial for CRMs recovery. While trying to set up a partnership with recyclers with most advanced disassembly and refining technologies, it should be considered whether the OEMs and VRPs who take charge of the reuse process have advanced recycling practices set up in their downstream. In the long-term, service providers can add an influence by choosing products with advantages in CRMs circularity over other products, when such options become available from suppliers.

For recyclers, first the coordination between pre- and end-processors will be significant in improving the recovery rate of target materials throughout the recycling processes. Pre-processors can start looking into advanced automated disassembly technologies in development, such as the technology invented by ADIR (ADIR, 2021). The establishment of a price forecasting system will help recyclers to focus on preparing recycling technologies for more diverse types of CRMs whose demand will become more crucial in near future. In the mid-term, recyclers can try identifying the material composition of on-board components in collaboration with suppliers. With the initial understanding, recyclers can develop separation and recycling technologies targeted for specific on-board components that is designed for more efficient recycling. As witnessed in the advanced recycling technologies for Ba-containing MLCCs and Ta capacitors described in Appendix A.5., there exists substantial potential for an effective CRMs recovery, if specific types of on-board components can be collected and processed separately. In the long-term, when more diverse types of CRMs are recovered at smelters, the exchange system for CRMs stocked at smelter's account would accelerate the domestic use of secondary CRMs. Such an exchange in domestic or regional proximity is expected to contribute to closing the regional CRM loop with less environmental impact, and at the same time reduce the supply risk of CRMs whose supply is dominated by few countries.

	Suppliers (OEMs)	**Service providers**	**VRPs**	**Recyclers**
Short-term	**[HDD] Design for disassembly** *Architects (designers), recyclers	**[HDD] Promotion of reuse and avoiding shredding**	**[Overall] Resale route tracking system**	**[HDD] Commercialization of advanced recycling technologies** *policy-level support, industry-wide partnership
		[HDD] Cost-benefit analysis on advanced HDD recycling	**[HDD] Inform resale community of advanced recycling option**	
Mid & long-term	**[SSD] Study on CRMs reduction/substitution potential** *Architects (designers), recyclers, researchers	**[HDD] Partnership with advanced HDD recyclers**	**[HDD] EoL HDD collection program among resale communities**	**[SSD] Advanced recycling technology** *Manufacturers, researchers

	[SSD] Design for recycling and optimized recycling process *Architects (designers), recyclers, researchers	**Switch from HDD to SSD**		**Expansion of recycled REE & CRMs market**

*: Partners to collaborate with for suggested actions

Table 30. Future actions recommended for enhanced circularity of CRMs [Case of HDD and SSD]

In the case of HDDs, suppliers can first map out design possibilities to ease the dismantling of the sub-assembly. It was noted that the liberation of the spindle motor magnet at the center of the HDD is considered more difficult than voice-coil magnets and therefore not included in advanced recycling technology of SUSMAGPRO (R. Kleijn, personal communication, June 24, 2021). Taking this into account, design efforts to ease the liberation of spindle motor magnets are expected to significantly increase the REE magnet recycling potential. As SSDs are expected to substantially substitute the function of HDDs in the upcoming years, the suppliers can already start investigating ways to reduce the amount of CRMs contained in SSDs, or substitute them with less amount of non-CRMs. At the same time, the suppliers will need to confirm whether SSDs brings both less CRMs demand and environmental impact compared to HDDs, and continue to find ways to reduce environmental impact associated with the production of SSDs. Discovering recycling technologies specifically designed for the recovery of CRMs in SSDs in collaboration with recyclers and researchers will contribute to the enhanced practice among recyclers.

Service providers such as KPN can promote the reuse of HDDs among internal departments and their business customers, by informing about the security of the HDD refurbishment process conducted by VRPs. In the case of servers that belong to the business customers of the service provider, stipulating the preference for refurbishment of HDDs as part of the contract with the customers can be an option to prevent the shredding. Sending obsolete HDDs to recyclers with REE magnet recovery technologies will be an important action point in the mid-term. However, as economic feasibility matters to service providers and as the advanced recycling businesses are still in development, service providers can first conduct a cost benefit analysis to find how the process can become economically viable to their business. If the specifications and business factors work with service providers, switching HDDs to SSDs can be an option to reduce the amount of CRMs required for similar amounts of device storage. However, such a replacement should take place under the assurance that it brings reduction in CRMs demand and overall environmental impact associated with the sub-assembly.

Considering that often the remarketed device or parts end up at a similar endpoint in the resale market after going through multiple traders, a system that enables the tracking of parts is regarded as necessary. Such a system can help reduce unnecessary trips and promote the exchange to happen at closer proximity, preferably domestically as much as possible (VRP A, personal communication, April 19, 2021). In addition, the VRPs can inform their own resale communities of advanced HDD recycling options. In the longer term, VRPs can assist setting up a HDD collection partnership with advanced HDD recyclers, so that obsolete HDDs at resale communities or at their customers can be directly picked up by the recyclers.

The presence of advanced HDD recycling technology should first become well known among recycling communities in the region. For this, the businesses need to grow with the technology becoming commercialized at a larger scale. If the current technology is too costly to meet the margin for customers, subsidy or incentive programs from policy level could help bring the technology into the recycling market. Eventually, with the growth of the recycling technology, the market growth for secondary REE magnets will follow, helping to meet the REE demand across industries.

5. Conclusions and recommendations

As concerns on the risks associated with CRMs increase, employing CE strategies as a way to mitigate the risks has been actively suggested in academic, business, and political arena. To examine such expectations, this paper investigated the effect CE strategies have on CRMs inside servers, via a case study of a Dutch telecom company. The research focused on the two sub-assemblies inside the server, the motherboard and HDD. It reviewed the CE strategies in two ways, by studying the current CE strategies in place among KPN's partners and possible CE strategies that are implemented in advanced practices or discussed in literature. Each strategy was described using the definition from 9R framework of CE strategies however categorized under 3R framework of reduce, reuse, and recycle,

In the case of motherboard, limited circularity potential was identified mainly in the substitution and recycling strategies. In the upstream, one reduction strategy was identified with the miniaturization of Ta capacitors. While such a trend is expected to bring less material demand and risk, it also comes with a potential to impact the recyclability of the material. Substitution potential for 10 CRMs out of 12 CRMs were identified in literature, with difficulty in cross checking its feasibility with suppliers due to the complexity in the value chain. While substitution method has potential to bring reduction in CRMs demand, it comes with multiple limitations: 1) that the majority of substitution cases include other types of CRMs as potential substitute, 2) the potential performance loss and cost disadvantage reduce its feasibility, and 3) that its substitution with other types of material might lead to less circularity in case it requires larger amount of material with less recyclability. In the 'reuse' strategy, direct reuse or sometimes repair are found to be applied to motherboards at VRPs. The reuse strategies can technically contribute to extending the lifetime of the motherboard up to 10 years, with its extent depending on what happens after its first life cycle. Current recycling of motherboard (PCBs) focuses on Cu, Ag, Au, Pd, and Pt, with Sb recovered depending on the capacity of end-processors. The recycling process lacks focus on CRMs due to low economic benefit, and it is found that most of CRMs such as REEs and PGMs are lost during the pre-treatment process. While advanced technologies such as hydro and biohydrometallurgical processes have potential to recover broader types of CRMs, it remains challenging for the practices to be implemented in industrial practice due to low economic feasibility and complexity of the processes. A substantial CRMs recovery potential was identified among advanced recycling technologies; however, their potential was limited as some of advanced technologies come with less relevance to the motherboard, with their feasibility remaining unclear. While recycling technologies have gained high attention as a potentially effective strategy for CRMs circularity, these findings convey a message that recycling itself cannot be a one-route solution for the circularity of CRMs. Substantial efforts to enhance the reduction, lifetime extension, and reuse of CRMs need to be accompanied from other parts of the value chain. The role of upstream players is seen as crucial, as the manufacturers hold capacity to design products with better consideration for reduction, lifetime extension, reuse, and recycling – e.g. accommodating substitution with less amount of non-CRMs, easier disassembly of board-level components, designing the models with extended lifetime, enhanced durability and compatibility with previous models. In addition, the collaboration between manufacturers and recyclers will remain significant to enhance the recovery of CRMs at the end of the motherboard's life cycle. Above all, it needs to be stressed that active collaboration across the value chain will be the key in finding the most effective way for circularity out of complex interests. Therefore, every stakeholder in the value chain will have a significant role to play.

For the HDD, a major potential for CRMs circularity was found in the functional substitution by the SSD and advanced HDD recycling strategy. In the upstream, a removal trend was observed in Dy content in NIB magnet. No material substitution method was identified as implementable in practice, while ongoing functional substitution of HDDs is witnessed via growing demand in SSDs. The functional substitution is expected to bring significant reduction in CRMs demand, as SSDs require more than 99% less CRMs per ZB compared to HDDs. Further HDD reuse potential was identified, as some HDDs at KPN are preferred to be shredded rather than going through a refurbishment process for reuse. However, the potential of HDD reuse is limited to 5 year of power-on hours. No CRM was identified to be recovered in current recycling practice. The REE content of NIB magnet is assumed to be all lost in other ferromagnetic fractions or to lose its market value due to the shredding process. However, a significant potential was suggested in advanced recycling practices, especially in the hydrogen decrepitation process which recovers over 90% of REEs in NIB magnets in HDDs. Likewise, it was observed that HDDs are being replaced by SDDs which require significantly less CRMs and that advanced HDD recycling technology is growing into commercial scale. These two factors signify that replacing HDDs with SSDs for new products and maximizing the reuse and recycling of HDDs that are already in the market can be a strategy to push forward for circularity, under assurance that the replace entails less environmental impact as well. Especially the role of advanced recycling practice will be crucial, as converting used NIB magnets into a new one can support the increasing demand for the magnets not only in the ICT sector but also in other low-carbon technologies.

The CE strategies' potential in reducing the supply risk and environmental impact associated with CRMs were discussed as an additional step. All three strategies of 'reduce,' 'reuse,' and 'recycle' are expected to have potential in reducing the two risks, with its extent dependent on multiple factors. For example, to maximize the supply risk mitigation potential of recycling strategy, whether the recycling happens domestically and whether the recovered materials are put back into the domestic economy will remain crucial. At the same time, the environmental impact of advanced technologies will need to be reviewed as well, as complexity of the process or toxic chemicals involved with the process can offset the advantage of CRMs recovery. The reduction of CRMs in the production process is expected to reduce the environmental impact associated with primary CRMs. However, this will also depend on potential environmental impact associated with resulting changes in production, such as changes in production technologies, tooling, and substitute materials. Therefore, to clarify the environmental advantage of reduction strategies, a thorough examination will be required via methodology such as life cycle assessment (LCA). Likewise, to identify each strategy's potential in supply risk or environmental impact mitigation, another set of detailed, full-scope case studies will be needed.

Overall, an active cross-chain collaboration is recommended to enhance the circularity of CRMs contained in the motherboard. An active communication between suppliers in the upstream and VRP and recyclers in the downstream will play an important role in designing the equipment with further considerations for CRMs circularity. Data sharing on CRMs is currently a major challenge due to proprietary reasons and the complexity in the value chain. However, efforts to find a reasonable, effective way of data sharing, such as applying blockchain technology with anonymity will be necessary, as the data acts as a fundamental requirement in enhancing CRMs circularity. For HDDs, replacing HDDs with SSDs, improving the reuse of HDDs, and finding recyclers specialized in NIB magnet recycling will remain significant. In addition, legislative support should be accompanied to encourage necessary changes across the value chain, such as adjusting WEEE legislation with conditions on recovery rate of CRMs and updating conditions for transboundary movement of equipment.

KPN holds a unique position in the middle of the product value chain, as a customer to both the manufacturers in the upstream and to downstream partners. For this reason, KPN can deliver a role of 'intermediary' actor who encourages cross-chain collaboration, helping smooth exchange of opinions among stakeholders, and demanding necessary changes to the industry via joint voice among telecom service providers. It can also deliver the changes implementable under its business scope, such as promoting further reuse of HDDs by reducing the shredding and partnering with advanced NIB magnet recyclers. Keeping the agile delivery of unused devices to VRPs and recommending pretreatment pathways optimized for CRMs recovery to its pre-processor can be additional options.

Initiative to enhance the circularity of CRMs via CE strategies is therefore not a simple route of change. The findings show that each strategy brings different effect, feasibility, potential, and leverage point, depending on the type of CRMs and characteristics of each sub-assembly. Therefore, further in-depth investigation will be necessary to design the product and applied CE strategy that aligns most closely with intended circular motivation.

A further study is therefore recommended in the realm of all three CE strategies. First, an investigation on methods to enable CRMs data sharing among value chain partners with anonymity will need to be sought for. A study to identify materials most crucial to the firm's business by translating material criticality index into the level of financial risk would help identify which specific material and component CE strategies need to focus on. When designing CE strategies targeting the most critical materials, separate studies will be necessary to clearly identify how much reduction the strategy brings to the supply risk and environmental impact associated with the material. At the same time, reduction and substitution methods that correspond to the material's application in specific sub-assemblies will need to be investigated, as indicated from the lack of data for substitution methods. To redesign the sub-assembly with aspects improving CRMs recycling, a joint study between the suppliers and recyclers will be necessary. A material flow analysis identifying which CRMs are contained in the production phase and where they eventually get lost, is expected to provide insight on what modifications should be applied while promoting the design for recycling. Synchronizing the design of the sub-assembly with the recycling processes will thereby contribute to efficient CRMs recovery in the downstream processes. At the same time, pre-treatment methods customized for on-board components of the motherboard will show better guidelines for further CRMs recovery in the recycling processes. A research into extending the lifetime of the product without compromising energy efficiency and technical properties will need to be accompanied, as this will extend the product's first life cycle even further before its reuse. At the same time, mapping the process and trips each sub-assembly goes through after refurbishment will help find ways to make the resale process more efficient. As economic factors are crucial for the business of value chain partners, further research looking into economic factors that drive or hold back the implementation of CE strategies from each body will be immensely helpful for providing economically viable options for business stakeholders to move towards.

Interest on employing CE strategies for the circularity of CRMs has been gaining substantial attention, however with a lack in thorough review on what effect each CE strategy brings to CRMs contained in each equipment or sub-assembly. Through a case study of a Dutch telecommunications service provider with a product focus on servers, this study revealed that CE strategy in practice, such as miniaturization and recycling, in fact does not always contribute to the circularity of CRMs. The study also discovered that there exists a lack of data and case-specific study for advanced CE strategies or substitution methods, while significant potential for CRMs circularity was identified in different CE strategies for the two focus sub-assemblies. Through the identification of the limitations and potential of each CE strategy per sub-assembly, one thing became clear: that enhancing the circularity of CRMs is a complex challenge. To enhance the circularity of CRMs, each CE strategy needs to be designed with intricate detail, with active cross-chain collaboration and system-level support. More than the attention and expectation for CE strategies to bring an absolute solution for CRMs risk mitigation, further work needs to be conducted with a focus on 'how' each party can design each CE strategy to mitigate the risks, how the options can be promoted in economically viable way, and to what extent each strategy brings the reduction in the risks associated with CRMs.

Personal reflection

Looking back on my first individual research project, I came across multiple points I would like to remind myself of in my next research, which are also things I would like to share with other fellow students who are preparing their thesis project.

I would recommend interviewing as many relevant stakeholders as possible in the beginning without too much hesitance. I would also recommend keeping the questions for the initial conversation open and go there with a mindset to learn and explore what is out there, rather than already setting a sharp agenda or predetermined conclusions. This would help gaining overall understanding of the topic and business context, and help building rapport with stakeholders which will be immensely helpful for the rest of the research.

Time management is crucial for a successful delivery of intended research output. At the same time, detailed and realistic planning is fundamental for a successful time management. I would recommend conducting a week-long scoping of the whole research once the initial research questions are shaped. This means looking up and skimming through all the relevant information and literature to understand how much time will be required to complete each step of the research. Such an exercise will help allocating a realistic amount of time for the research and determining the scope of research that fits into the given timeline.

When deciding on methodology, I would recommend double checking in each research step whether the predetermined methodology is the best way to answer the sub-research question. When designing a survey, it will be helpful to test answering the survey with peers, to examine whether the survey requires an appropriate amount of time and whether it is asking the right question.

I would like to suggest leaving the reference of each source with final the citation format while writing from the beginning. This will save a lot of time in the writing process. Finding a stable citation software that can assist the function throughout the research process would be another tip. Most of all, I would recommend using a mapping platform such as Miro, to organize key information from each source. This will help keep numerous data and information at hand, and help connect similar information from different sources to solidify findings.

Last but not least, I would recommend keeping the plan realistic and making sure to set a time to take a break each day and during weekends. A research project can be a long working process; therefore, a well-balanced mind and physical strength will eventually keep it strong until the end!

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Appendix A – Supplementary data (Excel)

A.1. Data on CRMs in servers

A.2. Substitution data for CRMs in the motherboard

A.3. Survey format used for motherboard CRMs substitution data

A.4. Substitution data for CRMs in HDD and survey format

A.5. Advanced recycling technology information for CRMs in the motherboard

Appendix B – Interview summary

112420 | Call with Project & Supply Manager | End-processor A, medium to large multinational materials technology company

- **Hydro & bio metallurgical processes are not found to be the optimal process for smelters**
    - Lack of robustness in terms of material purity
    - Economic feasibility/profitability
    - Especially not suitable for WEEE with complex composition such as PCBs (then the advantage of less CO2 diminishes as it requires additional processes)
- **Smart fluid (using fluid to separate materials per density)**
    - Happens at the process of pre-processors, not of smelters
    - More suitable for 'mass material,' materials with high weight contribution
    - For materials with low concentration such as precious metals (PMs) and CRMs – not suitable, as it might be lost with residues
- **For PMs/CRMs recovery, better recovery implies an optimal instead of maximal pre-treatment**
    - Mechanical/physical processing – more suitable for mass materials (e.g. plastics, aluminium, iron, copper, and etc.)
    - Also depends on the grade of WEEE (e.g., least treatment asked for high-grade IT equipment, shredding/extra treatment allowable for low-grade small PCBs such as consumer goods)
    - Especially most PCBs from ICT device is fit for the smelting process (up to 50x50cm, can be shredded into e.g. 10x10cm for better transport, but recommend avoiding pretreatment)
    - Sometimes modems with no pre-treatment were treated at the end-processor, as its composition is very simple (case, connector, and PCB)
- **Decision on which type of materials to recover (mass materials, PGMs, or CRMs) heavily depends on economic factors**
    - Often a pre-processor needs to choose which materials to focus for the recovery, as a recovery of one might (e.g. mass materials) contradict that of the others (e.g. PMs)
    - From smelter's perspective the choice affects the pre-processor most since he has to pay for treatment and the returned value depends on the content of i.e. PM's.
    - PMs/PGMs are often selected over other mass materials due to its high economic value

    - While the technologies are most of the time available for the recovery of different CRMs, it is often not implemented due to low cost-competitiveness (e.g. treatment/recycling more costly than the purchase of primary CRMs)
- **Decision on CRMs recovery depends on multiple conditions**
    - Price of primary CRMs & the cost of the material's recovery process
    - Level of CRMs concentration in the WEEE
    - Co-existing materials within CRMs containing components
- **OEMs/Businesses-claimed ownership of products will enable the systemic circularity of PMs/CRMs in future**
    - B2C format, clients not owning but renting the equipment from the businesses (Product as a service)
- **Closed loop recycling of PMs/CRMs might come into reality via exchange of metals stocked at smelters' account.**
    - Pre-processors/clients can either get paid for recovered materials, or let smelters put the metals in stock at their material account
    - When the process is documented and administratively ready, this metal account can be used as a medium to sell recycled metals to manufacturers, which will realize the first cases of closed loop recycling/supply chain of PMs/CRMs

030121 | Call with Internal Expert #1 | Advisor Sustainability and Circular Economy ACN Sustainability & Support, KPN

All hardware devices, from our datacenters are picked up by VRP A and processed by them for reuse, resell, refurbish or recycling. Remaining Telecom Infrastructure equipment (originated from fixed core network) are sent to Technocenter. At Technocenter they check the status based on agreements and based on suitability they either refurbish and reuse the device within our network, or decide to send it to Broker A for external reuse/recycling. Broker A will keep certain spare parts for KPN or resell them to third parties. All IT device such as servers that are sent to VRP A will go through an upfront check of everything - e.g., server card wiping, etc. - then the party decides to reuse(resell), refurbish, or recycle. If reuse is not possible, then the device is sent to recycling. The procurement team is involved in the downstream flows in special occasions when a big replacement of devices is expected.

030221 | Call with Sustainability Team | Supplier A, Original equipment manufacturer, large multinational IT company

On the circular economy perspective

A modification of design due to concerns on specific materials has happened previously, which was mainly due to supply chain responsibility. It is not easy to reduce the amount of certain material contained in current and future products due to the 1) cost to modify production tooling and factory processes, 2) requalifying the new path 3) the availability of alternative materials.

Mid-life product roll required if regulations change in the middle of current model out in the market (e.g. server's lifespan, longer than consumer equipment such as laptop, for e.g. 3 years – in between if the regulation on certain material sourcing/use is updated, then the replacement/upgrade (for e.g. component swapping) needs to happen.

Expansion of leasing system is in progress, with a plan to provide the entire product portfolio as a service in 2022.

The interest on CRMs has increased among customers recently, especially among Nordic and Northern European countries. The supplier has recently set up Materials Mapping Team to investigate the criticality/risk assessment of the materials.

030321 | Call with Internal Expert #2 | Advisor Sustainability and Circular Economy ACN Sustainability & Support, KPN

In terms of server's downstream, the refurbishment/reuse flow goes to VRP A, while the recycling flow goes to Broker A. It's the role of the deployment team at data centers to look over what equipment needs to be replaced, and it's under Technocenter's domain to help decision whether it needs to be sent to Technocenter or not. For IT device like server, there are few product owners in charge. First, if a set of IT device need to be replaced/or removed from data center, onsite inspection on the device by the product owner at data center on its value will be conducted. If all of them have commercial value, then they will be directly picked up by VRP A. If some of them have commercial value and some not, they will be first sent to Technocenter and Technocenter decides which one to use and which one to send to VRP A. If needed, the decision will be consulted with techno center team beforehand, on whether they would be useful to Technocenter. Techno center's decision will be based on if they can be used for KPN' internally, such as for spare part management and reuse of existing infrastructure. If it's not the case, then will be sent to VRP A.

040921 | Email with Internal Expert #3 | Architect Telco Cloud & Datacenter Services, KPN

On the role of the server at the telecom service provider:

In general the role of the server at the Telco is a compute platform with multiple processor units built in to process instructions of code in order to provide a direct function (like providing an operating system Linux as is most commonly used in Telecom) on which subsequently telecom functions as software applications/programs are installed and run and that are thus able to provide their intended function. The processing of instructions is supplemented by local memory – this is where the processor fetches its program instructions from during program execution and is commonly called RAM memory. Telecom applications typically need a lot of RAM in order to provide the needed performance because if programs are not in RAM, the server needs to obtain the code from storage (disk, like SSD disks) which is a much slower medium than RAM. A last function in the server is the network card: it provides connectivity to the outside world over copper or glass ethernet networks. Therefore, the server = processor, RAM memory, storage and network card. As you can feel, different program types need different specs from the server. This results in some variations in Telco as software vendors make different choices to the brands of hardware they guarantee their performance testing results on and different choices on the exact sizing of processor (# cores, GHz of the cores), RAM sizing, local disk sizing, network card interfaces and amounts.

On the role of servers per platform, especially for IMS & OMC:
IMS has 2 server types:

1. General purpose compute server for handling customer traffic and the control

2. Specific purpose compute server for storage of data objects such as programs and configurations

OMC has 3 server types:
1. General purpose compute server
2. Specific purpose compute server for passing through mobile user traffic
3. Specific purpose compute server

041221 | Email communication with Life Cycle and Circular Economy Analyst | Telecom service provider A, large multinational telecom company

There will be some CRMs which are related to electronics components that can be found in all sorts of electronic devices/sub-assemblies:

- The Pt/Pd potentially contained in MLCC
- The Tantalum contained in the capacitors (identified in some models of SSD for example)
- The CRMs contained at semiconductor level (check for instance the IRDS "More Moore" reports – available here https://irds.ieee.org/), such as Ti, Co, Ta, Hf or Ge
- The misc ones like Ru/Pd/Bi in certain types of SMD resistors or Ta/W/Co in oscillators

041921 | Call with Manager & Senior Accountmanager | Pre-processor A, small to medium recycling company

Current server recycling practice at Pre-processor A:

Every parts of server except for HDD & smart battery are shredded together. HDD usually does not come with servers. The battery is separated as it might cause fire. The two sub-assemblies are separated and sent to other facilities

1. In the first shredding, below material fractions come out:
    - Plastics
    - Iron (ferrous)
    - PCBs
    - The rest (cable, and etc)
2. Magnetic separation is conducted to separate iron
3. Electronic magnetic field separation is conducted to separate plastics
4. The rest of the materials except for plastics are sent to smelters
    - Non-ferrous metals
    - Clean iron
    - PCBs

Then the smelter takes out copper, precious metals (platinum, palladium, silver, and gold), rhodium, and tin, from the fractions. The smelter probably recovers other materials as well, but further information is not provided. In general, the smelter pays the pre-processor for the below 5 materials recovered (e.g. per ton of smelter fractions)

- Copper
- Platinum
- Palladium
- Silver
- Gold

One request is made from smelter, to separate aluminium (Al) from HDD. This is because Al has absolving quality to absorb gold. For this reason, the Al containing heat sink is also pulled out before further processing. However, PCBs don't have much aluminium contained in them.

041921 | Call with Director & Senior Accountmanager | Value recovery service partner A, small to medium IT company

Current practice works as below:

1. Hardware arrives in the logistics center

2. Remove and destroy all the data in HDD, SSD, SD card, and DIMM

3. Functionality check to test all hardware

- The software used to wipe data also provides a functionality report on each sub-assembly, and tells which one does not meet the functional standard, and need to be removed
- Make the inventory for customers, for the second life of the hardware

4. The parts or products are sent for a second use to:

I. Customers
    a. Traders: for products or parts
    b. Charity partners: old servers not relevant to EU anymore
II. Hardware for VRP A's own stock
    a. Store in stock for future cases when customers request specific parts. Customer sends it to VRP A but later might need the same parts for other servers or similar applications
III. Recycling: send them to a certified recycling partner
    a. Very old hardware which are too old for charity
    b. Broken sub-assemblies
    c. Remove all the assemblies inside and send only motherboard and heatsink

Points of leverage:

1. Customer's requirement/request that prefers shredding of HDD rather than wiping for reuse

I. Conducted according to the customer's request
II. Could be a request from KPN or KPN's business customers

2. Servers are kept in storage for so many years, therefore loses market value for reuse

I. Servers are sometimes already phased out for many years when picked up by VRP A. Therefore, they need to be sent to VRPs as soon as possible to retain the market value

3. Upgrade of product in new generations comes with low compatibility with previous sub-assemblies

For e.g., parts in the 2015 generation server cannot be used in the most recent generation servers:

- II. HDD: input-output cables on the motherboard wouldn't suit anymore, as it comes with other compatibility formats than earlier generations
- III. DIMM: slots become smaller, speed of DIMM processing continues to change as well

4. Need to check the entire trip of reused parts

Reselling community within Europe is very small. Members of this community share their inventory, which is not open to the outside world. Reseller sends an email to the inventory and check the inventory data, to see the market demand. Sometimes the parts eventually end up in the similar endpoint, after going through multiple traders (E.g. KPN – Supplier - Trader - Trader – VRP A). Because of the country code the hardware and parts eventually stay in the similar region it came from (Vendors can't export the product outside EU due to legislation). Therefore, the products can sometimes go through unnecessary trips, which makes the process not truly circular. A holistic, life cycle approach is needed, and the parties need to track where the parts are going and indicate the trip the parts have made. Also, it would be better to keep the devices domestically as much as possible.

Other facts about reuse:

1. SSD overtaking HDD in new market demand

SSD is the new standard for new servers. HDD requires a lot more power, more noise, with lower speed. HDD demand is still significant for old computers that are only compatible with HDDs.

2. Trend of reuse increasing in recent years

- I. Company owning less servers themselves

  Long time ago, company owned many servers on its own. Then companies preferred to have less servers with improved functionality. Later, they started to move toward public cloud. Now the trend is coming back to having their own infrastructure

- II. Also other trends in
  - a. Using more servers with the growth in blockchain technology
  - b. Individual users' demand for server increasing
- III. For these reasons, demand for used server is increasing. 5-7 years ago, used servers tend to end up as waste, and if phased out, were sent to recycling. However, with circularity policies being promoted and the existence of many other used servers, demand for the second life server is increasing. For this reason, stocked parts are seen to be in good use.

042121 | Email communication with Sustainability Team | Supplier A, Original equipment manufacturer, large multinational IT company

On the question on CRMs contained in dual in-line memory module (DIMM):

For memory (DIMM), Cerium Dioxide in the Chemical Mechanical Polishing process (CMP) to create a flatter surface on the wafers. The Cerium Dioxide does not remain on the wafer at the end of the process. The amount used is proprietary.

042921 | Interview with International Trader | Pre-processor B, small to medium recycling company

On the recovery of Critical Raw Materials (CRMs):

Rather than the amount of mass contained, the main issue is the fact that when one type of material is recovered, the others are lost.

Therefore, current recycling practices focus on the recovery of the materials with highest value: **Copper, silver, gold, palladium, platinum** are recovered from the fractions sent to smelters. Price per material always fluctuates based on the market.

Processes applied to the motherboard:

1. Dismantling by hand (conducted at the disassembler in case of KPN's flow)
2. First shredding
3. Separation (Iron, aluminium, capacitors, and batteries): separating the non-payable, non-ferrous metals to make precious metals (PMs) % higher, and purer. Also, capacitors might contain hazardous content inside
4. Second shredding: on the rest without the separated fractions, into about 5 cms
5. Sent to smelters

Difference between dismantled and non-dismantled servers:

- If not handled properly, or broken, the server might lose value and end up getting shredded as a whole
- Much more value can be recovered by dismantling, as parts are separated and processed in a way where more value can be achieved.
- For servers that come in as a whole, the pre-processor conducts dismantling itself

Processes applied to HDD:

HDDs from KPN are shredded by KPN. After being shredded by KPN, the pieces are sent to the pre-processor B where the pre-processor B again sends the shredded parts to a recycler specialized in HDD recycling. The magnetic fractions from the shredded HDD are separated from the other fractions such as circuit board mix and aluminium via magnetic separation.

When sent to a smelter the preprocessor receives some downstream information, but details on which materials are specifically recovered is not available.

Additional comments on CRMs and ICT device recycling:

- Circular design for products would be helpful for enhanced recovery of CRMs. However, due to the product lifetime of the new product with circular design, there is a high chance of waiting several years until the new products reach their end of lifetime. In the meantime, current recycling process will continue.
- WEEElabex is taken very seriously in the Netherlands and in Europe in general.

- Economic analysis on CRMs recovery would concern 1) the price of primary CRMs, and 2) the price of recovered CRMs minus process cost & logistics fee.
- For recyclers it is difficult to create another administrative flow for reuse themselves, as often the suppliers demand the equipment they send to be destructed. Also, recyclers would prefer to focus on recycling. If want to promote reuse, the supplier (companies) themselves will need to arrange two administrations, 1) for reuse and 2) for recycling.
- Customers pay the recycler to destroy the storage device, due to security reasons. Likewise, the data security is a significant concern for them.

050621 | Call with Project & Supply Manager | End-processor A, medium to large multinational materials technology company

- 4 processes of recycling
    - Collection, pre-processing (dismantling, shredding/sorting), end-processing
- Pre-processing: crucial for precious metals (PMs) recovery, but mostly output fractions are focused on mass materials and the process is not optimal for PMs – this is where they can be lost if pre-processing is too extended.
- End processing: the materials converted into new materials, used as new materials for new products (refining process)
- Good discussion (alignment) & coordination between processes enhance the recovery of target materials and overcoming limitations

- Difference between high-grade (HG) and low-grade (LG) PCBs
    - Recyclers either mix LG & HG PCBs to make the margin met (if only LG are sent to smelter, the margin for pre-processors remain thin)
    - Smelter: process and cost for both LG & HG similar. Not much of a difference, but to make the metallurgical process profitable the smelter does supply management and determine the amount of LG & HG they need to put into the process
- E-scrap (such as motherboards and other PCB's) and other waste and industrial residues are put into the process together (perhaps this can be seen as making it difficult to track how the recovery of materials from each preprocessor turns out, but this can be estimated via conducting detailed sampling & assaying before they are received and put into the process
    - Bill of materials given from smelters, on the estimate of each materials
- HDD
    - The end-processor focuses on PMs, therefore ask preprocessors to not send HDD as a whole, but separate the rest fractions (iron, aluminium, magnets) and send HDD's PCB fractions with other PCB fractions.
    - On the recovery of neodymium (Nd) and dysprosium (Dy) in current recycling market:
        - It is assumed that HDD might be shredded and separated
        - But maybe it is assumed that in the end the Nd and Dy fractions are treated together with ferrous fractions (iron) and get lost in the smelting process (iron recovery process)
        - It is difficult to specifically identify processors specialized in Nd and Dy recovery, as the price of primary rare earth elements (REEs) are low and the cost to recycle Nd & Dy make secondary Nd & Dy not competitive yet.

        - It can be also assumed that in current market there exists a lack in sufficient capacity for the end processing of Nd and Dy, or to use them to make new permanent magnets
- Pre-processing suitable for the end-processing of PMs
    - A continuous discussion between the pre-processor and end-processor on the amount of pre-treatment necessary for different types of e-waste is needed
    - Pre-treatment and WEEE condition best for PMs recovery at end-processing would be to:
        - First, dismantling (manual/automatic) of a device
        - Secondly, pulling out of PCBs, no shredding applied, and irrelevant components pulled out
    - Preprocessors tend to add extra process (e.g., separation, first and second shredding, milling, granulating, and water table method) to produce less complex outflows in order to 1) make the fractions easily sellable to different end processors, or 2) raise the recycling rate of mass materials such as aluminium and plastics. However, it should be noted that these extra processes contradict with the potential for PMs recovery

050621 | Email communication with Sustainability Team | Supplier A, Original equipment manufacturer, large multinational IT company

On the question on CRMs contained in Solid State Drive (SSD):

Ceria is used as a hardening agent in one of their slurries used in the frontend manufacturing processes. The specific amount of use is proprietary.

051021 | Call with Internal Expert #2 | Advisor Sustainability and Circular Economy ACN Sustainability & Support, KPN

In the recycling process, HDD is excluded from the other flows and treated separately. It is either sent to destruction for recycling flow or reused.

Destruction (shredding) of HDDs happen in below cases:

1. End-customer's request of decommissioning: by order they request decommissioning at the end-of-life stage, probably less knowledge about reuse potential
2. Internal departments of KPN dealing with a lot of customer information: with hard drives containing customer data, prefers to shred than to wipe and reuse
3. Old & obsolete HDDs – no market value left
4. Additionally, Techno center's decision on whether to be reused or destructed also has influence

060121 | Call with Sustainability Team | Supplier A, Original equipment manufacturer, large multinational IT company

Response to the request on the survey for CRMs substitution/reduction potential for the motherboard and Hard Disk Drive (HDD):

Complete data of CRMs contained in the motherboard is highly challenging, due to the complexity of the value chain. Response on HDD would be easier, as the survey can be shared with HDD suppliers.

Last year, when the first CRMs data on the motherboard was provided from Supplier A to KPN, it took substantial effort and time as it was an initial attempt to gather the CRMs data spread out among multiple vendors involved in the motherboard production. For this reason, to answer the substitution survey, it will take at least months of time and a substantial workforce, to identify vendors for specific material/component, send and receive, and compile their feedback.

Currently, Supplier A designs its board towards specifications designated by its PCBA design team, via selecting suppliers for components among the vendors approved by Supplier A.

Reduction of certain constituent material entails challenges, as seen in the supplier's effort on previous initiatives, as 1) it may require substantial modification to the production tooling which requires high cost, 2) requalification may be required from the manufacturer's side, and 3) the development of new metallurgy in general takes years of effort.

Solutions are seen to become effective only in the long-term when advanced technologies – such as recycling becomes economically viable.

Substitution or reduction of certain materials is not an easy take for OEMs. As the change might compromise the specification of the product. The most effective way would be to have an industry-wide change driven by consortium – agreement among the entire industry, or requirements by regulations, or to have alternative options widely used/observed from suppliers which tech engineers would advise to take into the production process.

060321 | Call with International Trader | Pre-processor B, small to medium recycling company

On the details of HDD recycling flow:

All the info on the shared spreadsheet of HDD is everything the HDD processor can provide. Maybe smelters do not easily open full information of recycling streams as it is treated confidential. Maybe the Nd Dy are included in non-ferrous recycling stream.

060421 | Call with Director & Senior Accountmanager | Value recovery service partner A, small to medium IT company

- Sometimes HDDs are shredded when the preference or request is indicated by KPN/customers.

- Technical lifetime of entire server and motherboard would be 7-10 years. For motherboard at least 5 years (so longer than 5 years) as the warranty remains for 5 years.
- HDD
    - As its partner bodies agreed on the Safety Software A, VRP A is using the software. Shredding also is a safe option for data removal but it has negative impacts on the environment
    - You can wipe the disk multiple times. Wiping it once already is safe enough, but for KPN the software wipes HDD 7 times to ensure high security
    - Market value: HDD with more than 600GB storage space is regarded to have market value at the moment. But of course, this will change in the coming years, with the advancement of technologies. For e.g., a few years ago 200GB HDD still had market value, but not anymore.
    - Firmware: the concern about firmware does not apply to VRP A, as VRP A has technology to delete the existing firmware and install another one for different software system. (Firmware – some HDDs can only be used in specific system with firmware corresponding with the system.)

060721 | Call with Sales Director | Value recovery service partner B, small to medium IT company

What VRP B offers: When there's an end-of-life product, they decommission them, bring into facility and test the product. Of course, in the value chain either 1) reusing it directly or 2) selling as refurbished product produces maximum value, therefore is preferred.

- Overall process
    1. Test a complete unit:
        - Reset
        - Run the testing software
        - Wipe the HDD
        - DIMM, CPU, ports on the motherboard are tested
        - If fully functional – resell it as complete unit to bring back maximum return
- Types of resell
    1. Server as a whole with configuration & specifications
    2. Harvested components (HDD, CPU, Memory, etc) (motherboard barely sold as single unit, but with chassis)
    3. Motherboard & Chassis (chassis suit for the barebone server system): barebone system units – system (barebone server) consists of same motherboard and same enclosure (chassis) - which is important for the secondhand market
    4. Motherboard alone is rarely sold individually, but always with the chassis
- Motherboard
    - Resell types
        - Reused as it is (direct reuse)
        - Repair (sometimes)
        - If too expensive to repair, disposed but some board-level components are harvested and sold to OEMs to be used in remanufacturing processes.
    - How long can it have market value?
        - Motherboard old as 10 years can still have market value
        - It has market value until the recycling value becomes higher than reuse value

    - Lifetime extension:
      - General technical lifetime of servers: 10 years
      - First lifecycle length dependent on the first user
      - By refurbishing (sending the used ones to After Market Service Provider/Value Recovery Partner) it helps the actual usage time reach the maximum possible lifetime of 10 years
      - But cannot tell the actual extended lifetime of the server/component as it depends case by case (on the second user)
- HDD
  - Resell types
    - Wiped & graded
      - To get rid of the data
      - SMART parameters are given to inform the status of HDD: reallocated sectors, power on hours, defective sectors, and etc.
      - Graded as for e.g., A B C D, depending on actual usage time & the amount of usage time left
  - Lifetime: 5 years of actual usage time
    - Extended lifetime: depends on what's left after the first usage
    - Usage time: different from the time your computer remained powered on
    - But everyone uses HDD to a different amount of time in their first lifecycle, so really depends on the case
    - As long as it functions, there's mostly a demand for every grade
  - Reuse condition
    - Above 600GB – can be, but not true, depending on the interface type – SAS12, newest interface, might have market value even below 600GB
- Leverage points for a maximum reuse
  - Every different model comes with different motherboard design
  - Design of the motherboard dependent on the unit, as it needs to fit the unit – which sometimes become smaller
    - If generic design of motherboard is invented, which can be reused across different models or even across different manufacturers, that would extend the lifecycle of a product dramatically
- Remanufacturing process.
  - Not available with every model, as it takes quite a time for used ones to become available in the market
  - Functions as good as a new product, with an exterior hard to tell whether it's a new one or not
  - Much cheaper than the new products
  - VRP's partner OEM's remanufacturing service: 'fully certified remanufactured' product.
    - Reuse of sub-assemblies in a new product
      1. Products are taken back with reverse logistics
      2. Components (NIC, DIMM, etc) are harvested and some are put into the new product
      3. MB and HDD are usually not reused, while memory and CPU are often reused, put into the remanufacturing process
         - Why not for motherboard or HDD?

            - Motherboard: more expensive to test the full functionality compared to just put in the new motherboard
            - HDD: easy to identify that it is a reused one by the end-user, with SMART technology
- The refurbished products go to secondhand market
    - Dispositioning is already done from the beginning strategically, so most of them are reused/resold to:
        - Online market platforms
        - Customer base
        - Shops that sell to end-user
        - Integrators
        - Distributors

062421 | Email communication with Sustainability Team | Supplier A, Original equipment manufacturer, large multinational IT company

Answer on the request for a cross-check on substitution potential for the motherboard:

This would be a huge task. Reason: Supplier A controls Approved Vendor List. Given the list of suppliers could run to > 3 figures, it would likely incur a cost and take several months to complete.

I suspect, for HDD at least, with the continued migration to SSD, the manufacturers are likely not looking beyond the 10-year horizon.

062421 | Call with R. Kleijn | Associate Professor at Institute of Environmental Sciences (CML) at Leiden University

On the hydrogen decrepitation method applied to HDD at SUSMAGPRO:

- Application area: applied to voice-coil (linear motor) magnet, not on spindle motor, as spindle motor magnet is embedded within the design therefore hard to sense and separate.
- Disassembly method: magnetic sensor captures the voice-coil part and cut the magnetic part out, helps the voice-coil magnet to be exposed to hydrogen
- Recovery rate: over 90%
- Recovered material: the alloy from which the magnet is made. Basically NdFeB but some other rare earth elements might be present in the alloy like Pr and Dy, although the Dy content of HDD magnets is very low is most cases. But if it would be present it would also be recovered since it would be part of magnet alloy material and all that material is removed.

070721 | Email communication with Project & Supply Manager | End-processor A, medium to large multinational materials technology company

Details on where CRMs from PCBs end up in the smelting processes:

The processor uses 3 collector metals of copper (Cu), lead (Pb), and nickel (Ni). Platinum group metals are typically collected form the Cu-fraction but also partly from the Ni-fraction. Antimony tends to get recovered in the Pb refining.

081721 | Call with Internal Expert #4 | Datacenter Specialist and Senior Server and Cloud Consultant, KPN

The average usage time of servers at KPN can be described as in general 7 years, sometimes up to 8-10 years. The same average usage time can be applied to the motherboard and HDD. The servers are decommissioned by KPN not because they do not function anymore but because they are replaced by recent models to meet the best/much better specifications.

Among the HDDs used by KPN, it can be described that 95% of HDDs are sent for a refurbishment/reuse process at the Value Recovery Partners where they are securely wiped, and 5% are shredded.

081921 | Call with Internal Expert #5 | Strategic Lead Energy & Environment, KPN

The current design of motherboard, e.g., components glued to the board with resin, makes it difficult to separate the on-board components and thus act as a barrier to more efficient recycling of motherboard.