LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Business and Management
Master's Program in Strategy, Innovation and Sustainability

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IMPACT OF CRITICALITY AND AVERAGE PRODUCT LIFETIME ASSESSMENTS ON CIRCULAR ECONOMY

Examiner: First supervisor Kaisu Puumalainen
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ABSTRACT

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A circular economy and sustainable development need to become implemented into societies and businesses. The concepts of the criticality of raw materials, the average lifetime of the product, and the practical application of the circular economy strategies are studied in this thesis.

The analysis was carried out by applying the hypothetical formula and evaluating two business cases, which were backed by the theoretical review. The first part of the study focuses on analyzing the correlation between the criticality index and the average product lifetime of critical metals. The second section of the research was the cross-case analysis and incorporation of the circular economy into the business strategies of VOLVO and BMW.

Results of the study have shown that criticality, average product-lifetime and circular economy principles can be seen as a complex of interconnected concepts, and be integrated into the corporate strategies and policies. In future studies, metal criticality can be examined in depth within particular metal categories. However, the discussion concludes that the criticality of raw materials is a versatile term and depends on the sample and scope of the assessment.

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List of symbols and abbreviations

CRM – Critical Raw Materials

CE – Circular Economy

REE – Rare Earth Elements

HREEs – Heavy Rare Earth Elements

LREEs – Light Rare Earth Elements

PGMs – Platinum Group Metals

CM – Critical Metals

CI – Criticality Index

APL – Average Product Lifetime

EI – Economic Importance

SR – Supply Risk

EU – European Union

EC – European Commission

EP – European Parliament

GDP – Gross Domestic Product

WGI – World Governance Indicator

DoD – US Departament of Defence

DoE - US Departament of Energy

NSTC - National Science and Technology Council

NACE - National Association of Corrosion Engineers

1. INTRODUCTION

1.1 Background information

Nowadays, modern society is living in a century of great technological breakthroughs and radical improvements in mindsets. By generating steady demand growth and a scarcity of resource supply, technical advances drive the global economy. While globalization offers relatively easy access to the world's planetary resources, there is no increase in their quantity. For any person, raw materials are of great value to various industries, economies, politics, and the general quality of life.

The value of different raw materials is studied by governments and scientific communities and data analysis is given in accordance with their fields and orientation. These studies are united by the common aim of finding solutions that may eliminate potential problems related to criticality. Consequently, in the field of science, the concept of criticality arose as new criteria for the study of natural resources that can be defined as the most significant value from geological, economic, technological, environmental and social interests. Critical Raw Materials (CRM) are natural materials with high importance in various industries for manufacturing wide range of products. That concept provided a start for individual models of evaluations from different perspectives. (Graedel, 2019)

After confirmation of the reality of global warming, policymakers have begun to accept that time is limited in terms of financial, human and natural capital. International businesses have begun to lean more towards individual consciousness and responsible business operations in recent years moving to a circular economy. Sustainability of natural resources flows affects a company's operations, and it takes a big part of the product lifecycle assessment, which is one of the main instruments that make business operations looped. Nowadays, the circular economy concept is one of the most efficient solutions for managing criticality risks. Industrial companies have formed several circular economy-based strategies to mitigate risks related to criticality.

By taking into consideration the latest innovations and scientific researches, it is natural to seek for optimal assessment tool for criticality evaluation. If an analysis of critical raw materials will become universal, it will simplify solutions towards a more sustainable future.

1.2 Research gap

The literature review is based on main topics related to the critical raw materials and circular economy. Both topics are quite broad and conclude a wide range of elements that are highlighted through the analyses. Key sub-topics that were specifically chosen for this research are: criticality as a concept, economic impact index, supply risk index, environmental impact index, average product lifetime, circular economy, circular economy strategies.

After reviewing the collected data, several concrete aspects were chosen as a limiting factor. The first aspect is national – scope of this research is on the EU. The second aspect that narrows the scope of the paper is the target perspective – to scope the range of critical raw materials into critical metals. Overview of CRM areas of implementation has revealed that metals play a significant role with unique physical and chemical properties for most industries beyond other CRM. Also, metals have the most significant influence on the technological success of future innovations due to price volatility and availability (Graedel, 2019).

In order to collect the information regarding practical approaches of sustainability strategies implementation in the companies, the automative industry was chosen as an example for brief benchmark analysis. Based on Screen project (Deetman S. et al., 2017) and EC (EC 2017) reports, the automotive industry is one of the most dependent on critical metals, due to the constantly high demand for raw material supply. Business cases based on EU companies from these industries can provide a practical view on the topic from the mass manufacture point of view.

1.3 Research questions and objectives

Companies that follow the circular economy (CE) model are continually analyzing the manufacturing process as well as the final product lifecycle. It helps producers to find the most optimal solutions for the circular economy, by defining relevant strategy. CRM characteristics affect product lifecycle stages. At each stage of the cycle companies confront criticality-related risks that are more commonly based on time and cost efficiency of business operations.

The main research question: "How the criticality level of critical raw materials and average lifetime of products, that are manufactured from these materials, might affect or even improve the implementation of circular economy strategies?".

The main research question concludes a hypothesises that possible correlation between the criticality and APL of the CRM that might assist the company in establishing or developing the circular economy. In order to answer the main research question, key concepts can be structured and discussed in several sub-questions. The main subjects for the Sub-Q1 and Sub-Q2 are criticality and average product lifetime. The focus of the Sub-Q1 is on the theoretical aspect, while Sub-Q2 brings a quantitative aspect of the research - the innovation of the Criticality Index (CI) that will be based on the most essential criticality factors and calculation of the Average Product Lifetime (APL). Existence of correlation between these indexes might show the intensitvy and
CI will become a new index or ranking system for CRM. The following index that is needed for future analysis is APL that will include a list of products that consist of more than 80% of CRM.

Sub-Q1: "What are critical raw materials and criticality factors?
Sub-Q2: "How criticality factors can be formed into Criticality Index (CI) and is there a possible correlation with APL?

The main subjects of Sub-Q3 and Sub-Q4 are the circular economy (CE) and strategies. Finding the connection and interrelation of CE and CRM is essential for the main research question of this thesis. In addition to the theoretical side, both questions will be supplemented by two business cases based on the business case analysis.

Sub-Q3: "What CE related strategies are applied in main CRM fields of application?".
Sub-Q4: "What challenges companies that work with CRM face during the CE strategies implementations?

Completion of this master thesis may reveal a new connection between the CRM aspects (CI and APL) and CE strategies. The results of CI and APL ranking as well as CE theory and case analysis could bring new vision for future CRM assessments, sustainable production, consumption trends, lean manufacturing and circular economy approaches.

1.4 Theoretical framework

The theoretical framework of this thesis consists of two main topics that can be defined as two starting points of the thesis – criticality with average product lifetime and circular economy. These subjects can be divided into several sections that assist in keeping the structure of the thesis and clarify the objectives of each sub-question (Figure 1).

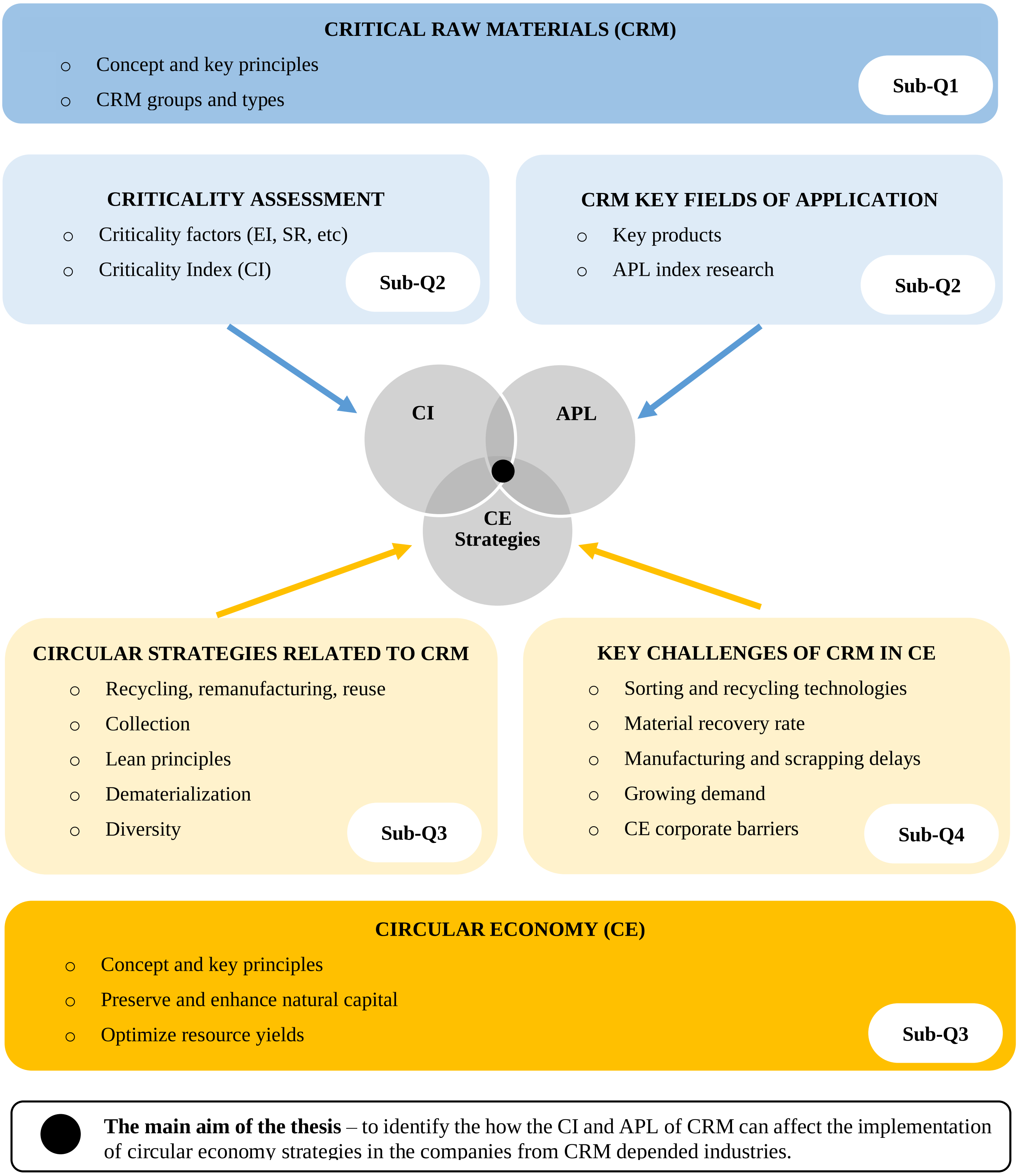

Figure 1. Research framework.

2. LITERATURE REVIEW

2.1 Critical raw materials

Raw materials always were valuable resources but due to massive consumption people start to face a shortage of these materials that makes them critical. At first sight material importance as a concept has a clear meaning, but material characteristics can be comprehensive when it is critical. Nowadays, there are several definitions of critical materials defined in various research, but none of them has been accepted worldwide (Jin 2016). One of the earliest explanations that can be identified as a definition, was provided by the U.S. Government Publishing Office. This definition works only for the U.S area and says that the term “strategic and critical materials” stands for materials that are necessary for the military supply, industrial or civilian emergency needs and are not found or produced in the needed quantities (U.S. GPO 1979). By this definition, the U.S. defined raw materials as “critical” or “strategic” only if it is essential to the nation’s economy, particularly for defence issues (Simandl, 2015). In contrast to the strong military point of view, a few years later, the Natural Research Council of USA suggests a more general definition of the critical materials. In its perspective material is critical only if its function cannot be replaced by a satisfactory substitute, if there is a high probability of supply restrictions that can lead to physical unavailability or prices rise in key applications (Natural Research Council 2008).

Also, criticality can be explained as a more broad concept. Raw materials criticality can be seen as a result of certain factors influence. The first factor is market imperfections in materials production or consumption. The second factor is secondary market actors, such as governments and investors. The third factor is the resource supply chain changes from operating dislocations, random, organizational or institutional disruptions. And the last factor is a set of feasible or alternative technologies that affect the functionality of different materials usage (Poulizac 2013).

In 2017, European Commission (EC) has defined critical raw materials that have high economic importance in the EU and a high risk of supply to the EU. In this way, current EU CRM is considered as “critical” due to high economic and trade importance and at the same time as “strategic” to a country’s supply or defence (EC 2017).

In 2018, the U.S. Department of Defence together in U.S. Geological Survey: have updated the definition of criticality. The critical raw material was defined as an essential nonfuel mineral to the economic and national security of the U.S., and vulnerable to supply disruption, as a material that is important for product manufacturing and that in case of substitution will cause essential consequences for the U.S. economy or national security (Fortier 2018).

Each definition was developed to respond to the main objectives of each of the researches, surveys or reports. At the end of almost every department that has completed, the work presents its individual list of critical materials. In this way, CRM lists differ because it can be based on criticality analysis of the general economy as EC, the military as the Department of Defence, or clean-air technologies. In addition technological breakthrough, political pressures and instabilities these are able to change these lists through time (Simandl 2015).

Even though all the researchers have been working on “criticality” aspects without the universal definition of criticality, it did not stop them from covering most raw materials. Current studies on CRM cover metals, non-metallic elements, compounds, and organic resources (Jin 2016).

It is possible to track the line of the research scope development of the CRM researches. For example, in the case of EC. In 2011, the study conducted by EC has identified “14 materials as critical from a starting list of 41 non-energy materials (EC 2011)”. In 2014, the list consisted of 54 materials where 19 materials were identified as critical. Besides the extended list included 7 new abiotic materials as well as 4 biotic materials and including coking coal. Plus, the Rare Earth Elements (REEs) were subdivided into “heavy” and “light” categories (EC 2014a,b).

The most recent and comprehensive studies about critical materials are conducted in the EU by EC and the USA by the National Science and Technology Council (NSTC). In 2017, the latest and the most extensive list of materials included 78 individual materials with 9 new materials (six abiotic materials and three biotic materials), 15 individual rare earth elements (REEs), 5 platinum-group metals (PGMs), excluding osmium. From 61 candidates, EC identified 43 raw materials as critical (EC 2017). After a year, the USA NSTC screening method was applied to 77 mineral properties to produce a new list of potentially critical minerals using USGS statistics. (NSTC 2018).

Table 1. Comparison of EC 2017 and NSTC 2017 CRM lists. [Source: EC 2017, EC 2020, U.S. 2018,]

Group	Type	CRM	EC 2017	U.S.2018	EC 2020
Abiotic material	Post-Transition Metal	Aluminum		✓	
Abiotic material	Metalloid	Antimony	✓	✓	✓
Abiotic material	Metalloid	Arsenic		✓	
Abiotic material	Non-metal	Barite	✓	✓	✓
Abiotic material	Non-metal	Bauxite			✓
Abiotic material	Alkaline Earth Metal	Beryllium	✓	✓	✓
Abiotic material	Post-Transition Metal	Bismuth	✓	✓	✓
Abiotic material	Non-metal	Borate	✓		✓
Abiotic material	Alkali Metal	Cerium	✓	✓	✓
Abiotic material	Transition Metal	Chromium		✓	
Abiotic material	Transition Metal	Cobalt	✓	✓	✓
Abiotic material	Non-metal	Cooking coal	✓		✓
Abiotic material	Non-metal	Fluorspar	✓	✓	✓
Abiotic material	Post-Transition Metal	Gallium	✓	✓	✓
Abiotic material	Metalloid	Germanium	✓	✓	✓
Abiotic material	Transition Metal	Hafnium	✓	✓	✓
Abiotic material	Non-metal	Helium	✓	✓	
Abiotic material	Post-Transition Metal	Indium	✓	✓	✓
Abiotic material	Alkali Metal	Lithium		✓	✓
Abiotic material	Alkaline Earth Metal	Magnesium	✓	✓	✓
Abiotic material	Transition Metal	Manganese		✓	
Abiotic material	Non-metal	Natural graphite	✓	✓	✓
Biotic material	Non-metal	Natural rubber	✓		✓
Abiotic material	Transition Metal	Niobium	✓	✓	✓
Abiotic material	Non-metal	Phosphate rock	✓		✓
Abiotic material	Non-metal	Phosphorus	✓		✓
Abiotic material	Non-metal	Potash		✓	
Abiotic material	Transition Metal	Rhenium		✓	
Abiotic material	Alkali Metal	Rubidium		✓	
Abiotic material	Transition Metal	Scandium	✓	✓	✓
Abiotic material	Non-metal	Silicon metal	✓		✓
Abiotic material	Alkaline Earth Metal	Strontium		✓	✓
Abiotic material	Transition Metal	Tantalum	✓	✓	✓
Abiotic material	Metalloid	Tellurium		✓	
Abiotic material	Post-Transition Metal	Tin		✓	
Abiotic material	Transition Metal	Titanium		✓	✓
Abiotic material	Transition Metal	Tungsten	✓	✓	✓
Abiotic material	Actinide	Uranium		✓	
Abiotic material	Transition Metal	Vanadium	✓	✓	✓
Abiotic material	Transition Metal	Zirconium		✓	
PGMs	Transition Metal	Iridium	✓	✓	✓
PGMs	Transition Metal	Osmium		✓	
PGMs	Transition Metal	Palladium	✓	✓	✓
PGMs	Transition Metal	Platinum	✓	✓	✓
PGMs	Transition Metal	Rhodium	✓	✓	✓

PGMs	Transition Metal	Ruthenium	✓	✓	✓
LREEs	Lanthanide	Cerium	✓	✓	✓
LREEs	Lanthanide	Lanthanum	✓	✓	✓
LREEs	Lanthanide	Neodymium	✓	✓	✓
LREEs	Lanthanide	Praseodymium	✓	✓	✓
LREEs	Lanthanide	Samarium	✓	✓	✓
LREEs	Lanthanide	Promethium		✓	
HREEs	Lanthanide	Dysprosium	✓	✓	✓
HREEs	Lanthanide	Erbium	✓	✓	✓
HREEs	Lanthanide	Europium	✓	✓	✓
HREEs	Lanthanide	Gadolinium	✓	✓	✓
HREEs	Lanthanide	Holmium	✓	✓	✓
HREEs	Lanthanide	Lutetium	✓	✓	✓
HREEs	Lanthanide	Terbium	✓	✓	✓
HREEs	Lanthanide	Thulium	✓	✓	✓
HREEs	Lanthanide	Ytterbium	✓	✓	✓
HREEs	Transition Metal	Yttrium	✓	✓	✓

Visual representation of the latest lists of CRM is presented in Table 2. This table represents 43 elements identified as critical in 2017 by EC and 55 critical elements in 2018 by NSTC. Both reports identify the following groups of materials: abiotic, biotic materials, HREE, LREE and PGM. Even though criticality definitions have different focuses, these studies have 38 similar elements that where 34 of them are metals. In 2020 EC has published new CRMs list that includes 26 of the CRMs identified in 2017. Helium is the only CRM from 2017 that has dropped off the list. In contrast to the 2017 CRM list, three new raw materials have been listed as critical and have been added to the 2020 CRM list: bauxite, lithium, and titanium. Strontium is one of the five new contenders on the 2020 list.

From Table 2 it is possible to answer the first sub-research question. Critical raw materials are materials that have strategic and economic value. Criticality depends a lot on the purpose of the assessment, context, and scope, but metals are the most common. Despite differences in definitions of studies, there are commonly used groups of materials in assessment methodologies that help categorize the materials.

2.2 Circular economy

A circular economy is an approach that directs company business operations into the loop. The traditional economy compares to the circular economy can be defined as a linear approach, which consists of “take, make, dispose”. The circular economy has the same stages as a traditional economy but at the same time differs from it by its’ sustainable solutions to the environmental, economic, and social issues related to resource usage, waste generation, natural resources depletion, and so on. The simplified flow of company operations based on the circular economy model is shown in Figure 3 (EC, 2018).

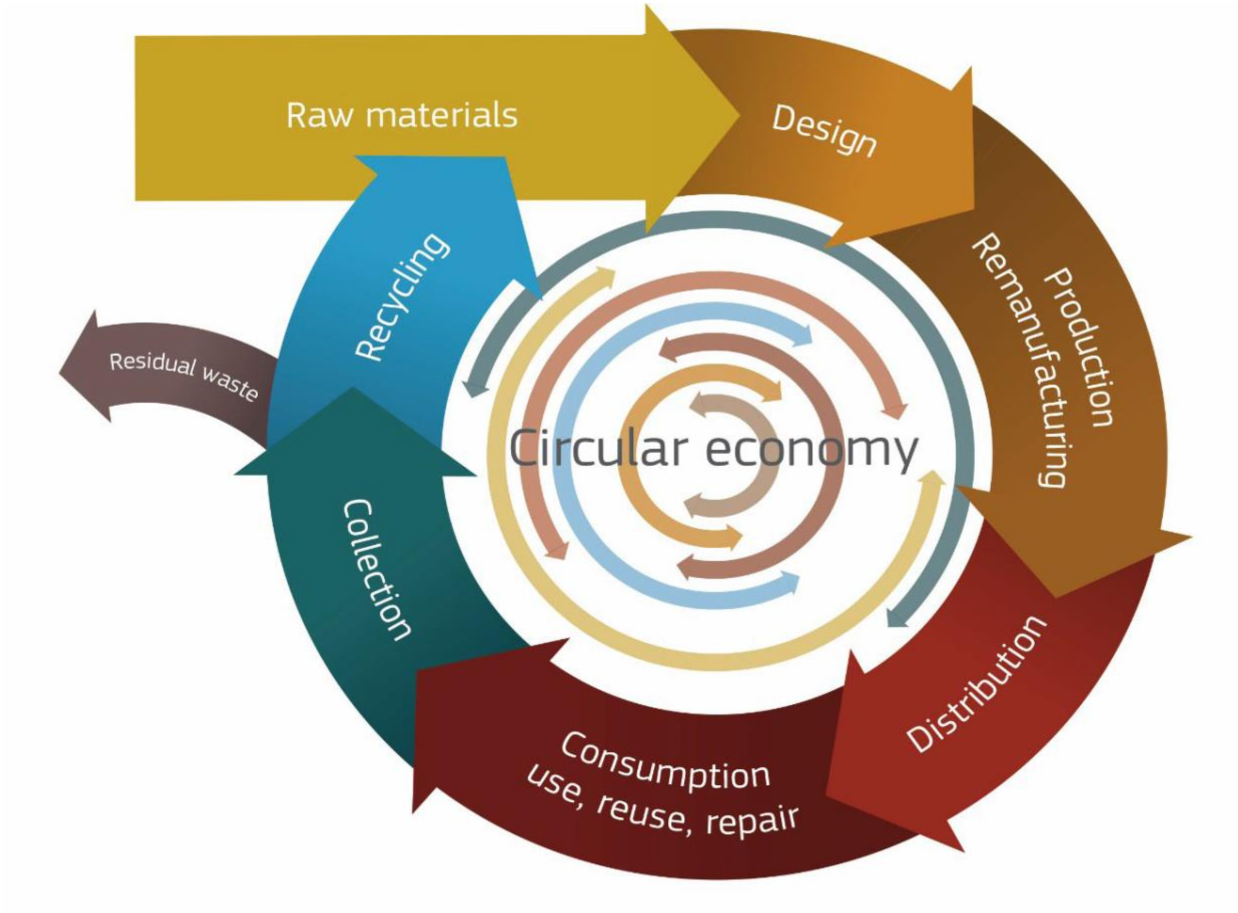

Figure 2. Circular economy diagram. (EC, 2018)

A number of companies that are restructuring themselves towards the CE is growing because this business model is needed for finding the most optimal solutions for current problems such as growing resource scarcity, volatile price markets, societal unrest, and emerging environmental problems.

The main focus of CE is on transforming waste into resources and improving the efficiency and effectiveness of production and consumption flows. If to study CE as a concept, the definition can be formulated into three principles: preserve and enhance natural capital, optimize resource yields, foster system effectiveness. If to define the framework out of these three principles, CE consist of the following actions: regenerate, share, optimize, loop, virtualize, and exchange. (Gaustad, 2018)

2.3 Criticality assessment

The first study that can be identified as closely related to criticality is “a governmental memorandum about critical imported non-fuel commodities”, that took place in the USA in 1974 (The White House 1974). This document provides a very narrow focus that was based on general market observation with the raw materials discussion of the raw materials as “strategic”. A few decades later first direct critical materials study with clear logic and methodology has been generated by Natural Research Council, in 2008. It presented a developed “criticality matrix” that determined critical materials from potential candidates preliminary research (Natural Research Council 2008). Key drivers of this matrix were “demand emerging on increasing, dependence on imported materials, social or environmental pressure, policy measures and concentration of production (Lloyd 2012)”.

Most of the studies that have conducted later on were oriented on demand and supply analyses. These analyses are based on technical, economic, environmental, social parameters and technologic breakthroughs that are connected with the chosen range of potential critical materials. The focus of each study is individual and correlating with the future interests of the party that organizes them (Simandl 2015). For example, research can focus on the risks of supply identification and evaluation, disruptions on the economic impacts, implementing green energy programs, national security, or other topics. Each study also faces corresponding factors that affect the data collection and representations, such as regimes, political instability, market conditions, regional conflicts other risks and research environment conditions.

In 2016, the Research Centre on Environmental Studies & Sustainability in France has conducted a review of critical materials studied. The original research base consisted of studies from the period 1974-2014, in total 48 studies, 48% conducted by the USA, 44% by Europe and 6% by other international researches (Jin 2016). One of the review assessments was the comparison table of criticality methodologies or factors and included the top 15 from the original base. In order to make Table 2 more complete, two more studies have been added – EC 2017 and NSTC 2018 studies (Jin 2016, EC 2017, NSTC 2018, Fortier 2018).

Table 2. Criticality assessment factors and dimensions. [Source: Jin 2016, EC 2017, NSTC 2018, Fortier 2018, EC 2020]

Studies	Year	Keywords and factors								
		Demand	Supply	Vulnerability to supply restriction	Environmental	Importance or impact (included economic aspect)	Recycling	Materials	Innovation	Market dynamics
		Other statement forms								
		Demand risk/ growth; Total annual purchase; Raw materials demand of a specific application; production growth	Availability; supply risk; supply disruption potential; supply and price risk; import reliance (IR); net import reliance (NIR);	Exposure to supply disruption; reduce potential consequences of supply disturbance	Environmental Implications; Environmental country risk	Importance in use or impact of supply restriction; Importance to clean energy; Impact of an element restriction on the company; economic importance;	Recycling restriction; risk reducing filter	Material risk		Price volatility to capture the stability of the commodity's market
National Research Council	2008		✓			✓				
Morley and Eartherley	2008		✓					✓		
Öko-Institute	2009	✓	✓				✓			
European Commission	2010		✓		✓	✓				
Duclos et al.	2010	✓	✓			✓				
Department of Energy	2011		✓			✓				
Nassar et al.	2011		✓	✓	✓					
Graedel et al.	2012		✓	✓	✓					
Poulizac	2013	✓	✓							
OUSDATL	2013	✓	✓							
Bacher et al.	2013				✓	✓			✓	
Roelich et al.	2014		✓	✓						
Nuss et al.	2014		✓	✓	✓					
Goe and Gaustad	2014		✓		✓	✓				
European Commission	2014		✓		✓	✓				
European Commission	2017		✓	✓	✓	✓	✓			
National Science & Technology Council	2018	✓	✓							✓
European Commission	2020		✓	✓	✓	✓	✓			

Overall there are three main factors that identify the criticality of raw materials. Table 3 shows that supply was used as the main parameter in studies methodologies, that influence the criticality of materials. Second place according to the importance is taken by demand and environmental factors (Jin 2016). If economic importance can be seen as a factor with significant influence, then environmental factor started to be used more often within the last decade. Earlier it was considered as a part of the recycling materials stage but now it has its own niche. A good example of this evolvement is EC reports.

The first critical materials report by EC was realized in 2011, and later it was update in 2014 , 2017 and 2020. The methodology used in the first two studies is identical (EC 2017). The analysis consisted of two parameters – Economic Importance (EI) and Supply Risk (SR). According to EC these two concepts determines the criticality of the material for the EU. In the end, raw materials that have the biggest index are identified as critical.

Economic importance was calculated as a "proportion where each material associated with industrial mega-sectors at an EU level". Afterward this proportion was combined with the mega-sectors gross value and the EU's GDP. In the end, the total value was scaled "according to the total EU GDP, in order to measure overall economic importance for the material". Supply risk was measured and strongly connected with WGI, while it was consisting of "political stability, accountability and absence of violence, government effectiveness, regulatory quality, the rule of law, and control of corruption factors (EC 2014a)".

In 2017, the updated EC criticality assessment methodology can be described as a "snapshot of the current situation" (Blengini 2017). The methodology consisted of three main innovations that were applied in revised methodology of the supply risk and two innovations in economic importance factor. The first novelty is the integration of trade barriers and agreements into supply risk formula. The second is the adaptation of supply chain bottleneck approach. The third innovation is the addition of import dependence, which explained real supply to the EU, confirmed the critical position of recycling, and resulted in a significant increase in the accuracy and representativeness of data for the EU. (EC 2017)". The first statistical breakthrough of economic importance is a more comprehensive and straightforward distribution of raw materials uses to NACE sectors. The second innovation is the introduction of a dedicated substitution index (Blengini 2017).

In contrast to EC, NSTC was using a screening approach that consisted of two steps. The first stage is dedicated to identifying potential critical minerals from non-fuel material that could be evaluated transparently and on a continuous basis. The second stage consists of in-depth supply chain analyses of selected minerals by applying a methodology that is being updated every year by the U.S. Geological Survey (NSTC 2018). In 2018, three fundamental indicators applied in the first stage are supplied risk, production growth, and market dynamics. Supply risks aim to allocate the risk that is connected with the production concentration in countries with low governance. Production growth evaluates world production growth to allocate a commodity's growing importance. Market dynamics examines price volatility to capture the commodity's market stability. The scaling system of indicators consisted of a range from 0 to 1 in which higher values mean a relatively higher criticality degree. This scale equalizes "the weight measurement before being combined into a potential criticality score through a geometric mean" (Fortier 2018).

Overall, databases vary a lot from studies to studies and the location of raw material deposits. The country area is not a guarantee of a sustainable supply of critical materials. Despite the strong presence of Asia and USA in the global economy, raw material markets evolve in international scale and consider explicit requests from the EU industry and changing policy priorities, needs, and trade (Blengini 2017). In that matter, it is relevant to narrow the scope of EU critical raw material analysis, as well as the most of the European studies correlate with the present thesis idea.

2.4 Key industries for CRM

CRMs are widely used in a broad spectrum of products. Typically, CRMs are part of the product life depended on the part, that guarantees product application efficiency. It is a very crucial product aspect for industries such as transportation, energy, ICT where the existence of CRM increases the functionality of the product (Punkkinen 2017). The fact that makes the product strong, from the recycling point of view can make it weak. There appears the challenge because CRM is primarily used in small amounts but in complex structures, which makes them hard to extract and put into secondary use.

In 2017, the SCREEN project was financed by the EU Horizon 2020 research and innovation program and has been conducted as a study with purpose of reviewing and trends of the current use of critical raw materials in the EU. The study was based on a list of critical materials that were identified by EC in 2014 because by the time of research updated CRM lists have not been published yet (Deetman

2017). Despite the revised CRM lists that are available since 2017, data provided by the SCREEN project can provide a general overview of the main application fields and trends.

Areas of critical raw material used in Europe by 2017 are represented in Figure 3 with bar charts, are based on critical raw materials of EC 2014. It illustrates the shares of critical raw material use (Deetman 2017). Economic sectors and applications for this share evaluation are based on a precise review of European and Global available studies that provide each CRM application sector data. Rows are representing the hierarchy of groups according to corresponding or overlapping sectors and products. The columns represent the individual CRM usage in the percentage of the total European. This visualization easily highlights the ranges of CRM in each economic sector.

As a result, the top three sectors that pose the biggest shares of CRM are Information and Communication Technologies (ICT), vehicles and steels. The main materials that take the biggest share in ICT are Antimony (Sb), Beryllium (Be), Gallium (Ga), Germanium (Ge), Indium (In), Praseodymium (Pr) and Dysprosium (Dy). The biggest shares of CRM in vehicle sectors are divided between Cerium (Ce), Rhodium (Rh), Platinum (Pt), Palladium (Pd), Niobium (Nb) and Magnesium (Mg). The steel sector depends the most on Magnesite, Graphite, Coking coal, Tungsten (W) and Cobalt (Co). In the end 8 materials out of 18, which have been listed above, were defined as critical by EC in 2017 and by NSTC in 2018, despite essential differences in approaches and focuses: Antimony, Gallium, Germanium, Tungsten, Dysprosium, Cerium, Praseodymium.

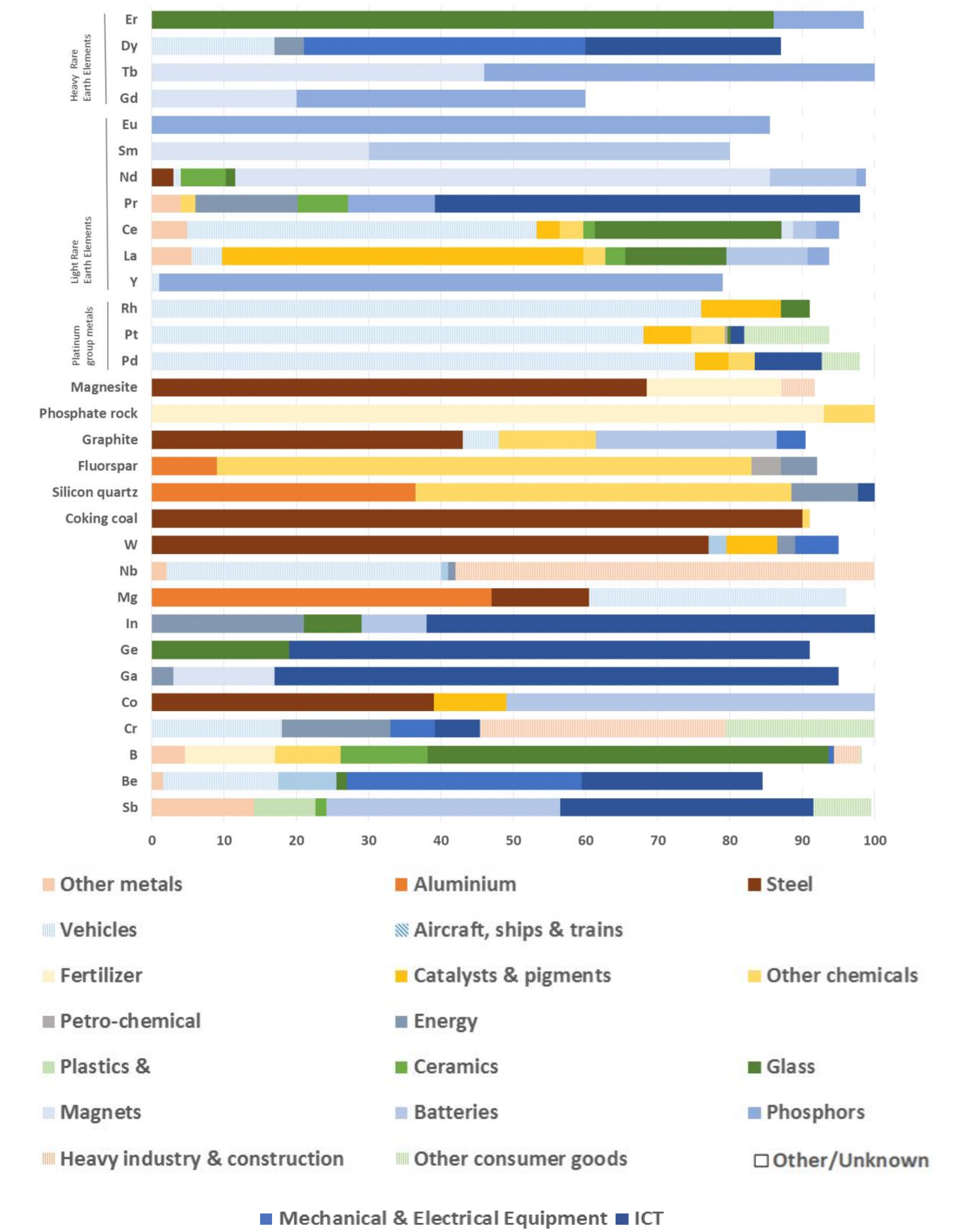

Figure 3.Shares of critical raw material use in Europe [Source: EC 2014a,b, Deetman 2017].

After identifying the application sector and it is essential to understand what actual products are and their lifetime. Studying this side of CRM use provides more profound knowledge of the criticality level of the material. Product lifetime or product lifespan is the time interval from when a product is sold to when it is discarded (Murakami 2010). Amount of companies that invest in prolonging product lifetimes continually increases. This connected with the switch in companies visions towards fundamental strategy - to work towards a circular economy.

As a result of this mindset change, in 2016, EP has published a study evaluating the potential impact of a longer life for products in Europe on the economy, society, and the environment (EP 2016). Table 4 shows a general overview of AEPL reported by household consumption data. Despite the stochastic way of representation, it illustrated the scratch of AEPL distribution beyond most commonly used products.

Table 3. Average expected product lifetimes. [Source: EP 2016]

1–2 years	3–4 years	5-6 years	7–10 years	> 10 years
○ small electrical appliances (toothbrush, ect.) ○ mobile/smart phones ○ general clothing ○ shoes	○ portable devices ○ personal computers ○ bed items ○ specific clothing (sports, ect.) ○ bicycles ○ coats	○ cameras ○ general kitchenware ○ lighting ○ power tools ○ vacuum ○ cleaners ○ washing machines ○ curtains	○ automotive ○ TVs ○ kitchen appliances ○ general furniture ○ carpets ○ beds ○ refrigerators	○ appliances attached to house (boiler, sunroof, etc.) ○ kitchen and bathroom specific furnishings

At the end of the report, EP stated that despite the clear connection between the circular economy and critical raw materials in Europe – effects of policy actions on longer product life effects and the security of the supply of critical raw materials are not clear yet (EP 2016).

In 2017, the main fields of CRM application can be identified by the report of EC about CRM in the circular economy. In this research, EC generalizes the fields that have been deeply studied in the SCREEN project: mining waste, landfills, electric and electronic equipment, batteries, automotive, renewable energy, defence, chemicals and fertilisers (EC D. 2017).

2.5 CRM related strategies based on circular economy approaches

The traditional economy can be described as “take, make, and dispose”, which refers to the activities of mining and extraction, processing and manufacturing, and waste management and disposal. Nowadays, it is possible to formulate five CE strategies that help the business to evolve its’ business stages sequence into the loop: 3R (recycling, remanufacturing, reuse), collection, lean principles, dematerialization, diversity. (Gaustad, 2018)

In terms of CRM, these 5 CE strategies are strongly connected with criticality risks that are based on EC and SR. 3R strategy unites recycling, remanufacturing, and reuse activities that are based on specific technologies for each CRM. This type of strategy is more commonly combined with another strategy due to the difficulty level of implementation, for example, lack of infrastructure, unfavourable economics compared to ore extraction, and dissipative use. Nevertheless, in case of successful implementation, this strategy provides the advantage of reducing potential socio-political supply risk by providing a domestic supply of raw materials, parts, and products.

Collection CE strategies go together with the previous strategy as if 3R is followed, collection systems become necessary to provide an adequate supply of products for recovery. Take-back services, in which stores or other collection centers allow end-of-life items that shoppers carry in, or collection programs that include agents going directly to points of use to collect the products, are also common.

CE strategy that is formed from lean principles bases on just-in-time manufacturing, time, and cost-saving advantages. This method offers significant environmental and financial advantages over the resource life cycle, from mining and manufacturing to disposal. Idle time, surplus inventory, commodity waste, emissions and water use, manufacturing costs, and material pressure can be reduced by implementing lean standards.

The CE's resource management priorities are supported by the dematerialization plan, which relates to the elimination in resources used to deliver a desired economic service. Mostly this strategy is connected with the switch from a product into a service company provider model. It is a more rare approach as there is always a limit to service providers' opportunities.

Diversity strategy is based on developing a range of active suppliers and creating an innovative sourcing system with several channels. In this way company with a flexible supply system can secure the supply disruptions of CRM and expand networks with additional circularity pathways.

2.6 Challenges and barriers in circular economy for CRM

CE is also strongly supported by the EU as well as by a number of national governments and corporate organisations all around the world. The definition was mostly developed by physicians, corporate leaders, and policymakers. During the last decade, CE became a promising concept that attracts business communities from various industries to move towards sustainable business operations. (Korhonen, 2018)

In terms of CRM, recycling, waste reduction, and end-of-life recycling input rate (EOL-RIR) are the key measures that reflect with CE model. CRM input and upgrade production systems with recycling strategies. Criticality risks and materials characteristics cause key challenges of CE for CRM related companies. The biggest and the most difficult one is recycling methods and systems for CRM. Despite the fact that CRMs have a strong recycling capacity and government support to shift toward a circular economy, CRMs have a low EOL-RIR. (EC, 2019)

Several factors are laying at the base of this challenge. Sorting and recycling solutions are not yet attainable for many CRMs. This issue automatically limits the number of companies that would be able to adapt to these technologies despite accepting the philosophy of CE. Another factor is formed from the CRM recovery rates. Unfortunately, not all CRMs are easily extracted from the manufactured products due to their chemical properties or original manufacturing design of the final product. Another important problem that disrupts recycling processes is that many CRMs are actually held up in long-life assets, causing gaps between manufacturing and scrapping, and thereby directly impacting the recycling input rate. Last but not least, demand for many CRMs is increasing in different industries, and recycling contributions are typically inadequate to satisfy demand. (Deetman, 2017)

Even though the technological aspect strikes as the most obvious and the most commonly discussed reason why CE has limited implementation progress. Figure 2 represents the survey, where the main question to 208 respondents and 47 experts was what are the most common CE barriers in the EU. The cumulative list of CE barriers was divided into four main barriers with 3-4 aspects each: cultural as a lack of awareness and consumer interest; regulatory as a lack of policies in support of a CE transition; market as economic viability of circular business models; technological that represents the CE technology implementation. (Kirchherr, 2018)

The outcome of the survey states that cultural barriers are the most essential for CE adaptation, mostly due to hesitant company culture, are considered the main circular economy barriers by businesses and policy-makers. Second, the most common barrier was a market barrier that represents mostly the financial aspect, which include low virgin material prices and high upfront investment costs (Figure 4).

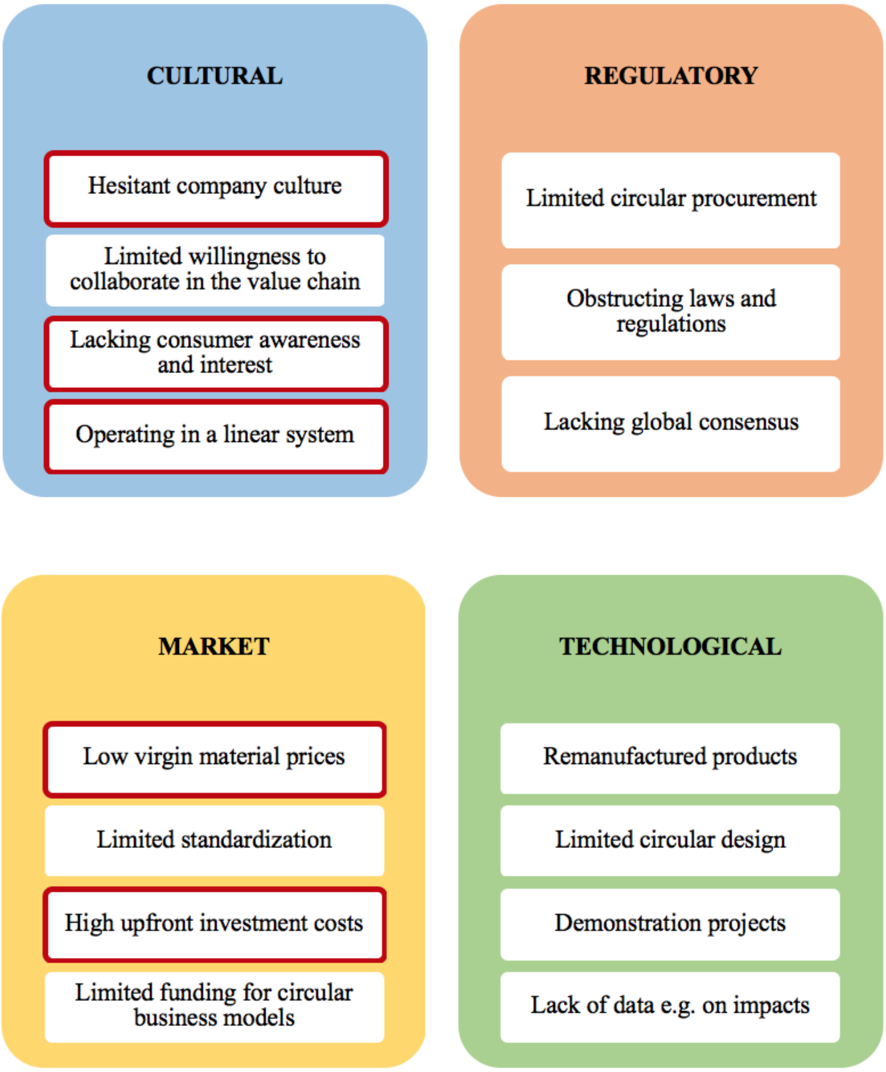

Figure 4. Key CE barriers (Kirchherr, 2018).

3. METHODOLOGY

The thesis main research question is based on three main concepts – criticality, APL of the CRM and CE strategies. The research methodology is structured according to the research framework (Figure 1) and the sub-research questions illustrated in Table 1.

The first research direction starts from theoretical and quantitative data about the criticality from the cumulative results from the previous researches about a similar subject. The exception is average product lifetime numbers because this data is based on multiple thematics open-sources. The second research direction starts from studying the CE basic principles and the most common strategies that are related to the CRM. For these concepts, data was gathered from theoretical literature as well as from the case studies.

Table 4. Objectives, sub-questions and methods of research.

Research sub-questions		Research objectives	Concepts	Research method
Sub-Q1	***What are critical raw materials (CRM)?***	• To study criticality and critical raw materials as a concept	○ Critical raw materials and their groups ○ Critical metals	○ Quantitative data screening of the secondary data
Sub-Q2	***How criticality factors can be formed into Criticality Index (CI) and is there a possible correlation with APL?***	• To analyze criticality components and assessment tools • To define the main industries of CRM application and trends of product lifetime where CRM is used the most • To conduct a possible Criticality Index (CI) that will allow to rank a list of CRM	○ Criticality assessment ○ Economic importance ○ Supply risk ○ Environmental factor ○ Average product lifetime (APL) ○ Criticality index (CI)	○ Quantitative data screening of the secondary data ○ Quantitative experiment on optimizing the criticality into CI formula
Sub-Q3	***What CE related strategies are applied in main CRM fields of application?".***	• To define the key principles of circular economy and most common strategies in companies that help hand CRM related risks. • To compare theoretical approaches with a practice based on the business cases	○ Circular economy (CE) ○ Recycling, remanufacturing, and reuse ○ Collection ○ Lean principles ○ Dematerialization ○ Diversity	○ Quantitative data screening of the secondary data ○ Qualitative document analysis of the corporate reports as business cases
Sub-Q4	***How can APL and CI of CRM can supplement the CE strategies in top CRM fields of application?***	• To identify possible implementation of APL and CI indexes in CE strategies.	○ Sorting and recycling technologies ○ Material recovery rate ○ Manufacturing and scrapping delays ○ Growing demand ○ CE corporate internal barriers	○ Qualitative observations based on analysis of previous parts of the research

3.1 Criticality Index (CI)

Three main aspects were considered for the formula creation: a selection of indicators, aggregation, uncertainties of the formula. Literature review analytics allowed to identify main criticality factors that more commonly chosen for the criticality identification. As a result of this observation CI formula was developed as follows:

$$\boldsymbol{Criticality\ Index}\ (\boldsymbol{CI}) = \boldsymbol{Economic\ Importance}\ (\boldsymbol{EI}) + \boldsymbol{Supply\ Risk}\ (\boldsymbol{SR}) + \boldsymbol{Environmental\ Impact}\ (\boldsymbol{ENV\ IM})$$

EI, SR and ENV IM can be identified as the main equal milestones of the most critical material studies. All three factors can be evaluated equally and can be united by the same measurement unit (index/coefficient). As a result, CI can be presented as the hypothetical sum of mentioned above main critical material factors.

The aggregation of these components also can be proven by looking into the formulas of each component in CM studies that are described in Table 5. Economic, social and environmental sectors are interconnected between each other and represented in each critical factor used in the formula.

No doubts, for each mathematical formula, there is a room for technical error. In this case, there are two aspects that can affect the result of formula application. The first aspect is the relativeness of the components. Despite the strong connection of the variables, there is no mathematical guarantee that this configuration works the best in the chosen case. The second aspect is data relevance. Indicators that are involved in the factors calculations are dynamic. In this case, the data has been chosen by the availability extent and the latest dated.

Table 5. CI formula elements. [Source: EC 2017, Graedel 2015.]

Indicator	Indicator description	Unit	Min (year)	Max (year)	Calculation
Economic Importance (EI)	Indicator of importance of the raw materials for the EU economy.	score / index	2010	2017	$EI = \Sigma_s(A_s * Q_s) * SI_{EI}$ A_s − the share of a certain RM used in a NACE Rev. 2 2-digit level sector Q_s − the Value Added of the 2-digit-level NACE Rev. 2 sector SI_{EI} − Substitution Index of a RM to be used in economic importance (defined in section 3.2) s − denotes the corresponding NACE Rev. 2 sector.
Supply Risk (SR)	Indicator that accounts for concentration of primary supply from countries exhibiting poor governance.	score / index	2010	2017	$SR = \left[(HHI_{WGI-t})_{GS} * \frac{IR}{2} + (HHI_{WGI-t})_{EUsourcing}\left(1 - \frac{IR}{2}\right)\right] * (1 - EoL_{RIR}) * SI_{SR}$ HHI − Herfindahl Hirschman Index (used as a proxy for country concentration) WGI − World Governance Index (used as a proxy for country governance) t − trade adjustment (of WGI) IR − Import Reliance GS − global supply $EUsourcing$ − actual suppliers EoL_{RIR} − End-of-Life Recycling Input Rate SI_{SR} − Substitution Index (in supply risk)
Environmental Impact (ENV IM)	Indicator for the environmental implications (EI) portion of our analysis consisted of potential damages to human health and ecosystems per kilogram of metal mix at the factory gate.	score	2010	2015	$Environmental\ Impact = Human\ Health + Ecosystem$ $Human\ Health = CCH + ODP + HT + POF + PM + IR$ ***CCH*** – climate change human health ***ODP*** – ozone depletion potential ***HT*** – human toxicity ***POF*** – photochemical oxidant formation ***PM*** – particulate matter formation ***IR*** – ionizing radiation $Ecosystem = CCE + TA + FE + TET + MET + ALO + ULO + NLT$ ***CCE*** – climate change ecosystems ***TA*** – terrestrial acidification ***FE*** – freshwater eutrophication ***TET*** – terrestrial ecotoxicity ***FET*** – freshwater ecotoxicity ***MET*** – marine ecotoxicity ***ALO*** – agricultural land occupation ***ULO*** – urban land occupation ***NLT*** – natural land transformation Environmental impacts per kilogram of material (cradle-to-gate) using the ReCiPe 1.10 (World) H/H method (10). Human health damage and ecosystem damage refers to results from the ReCiPe impact assessment method prior to normalization and weighting. Damages to human health and ecosystems refer to results after normalization and weighting using the hierarchical perspective and weighting set. The cradle-to-gate environmental impacts of metal production were captured using life-cycle assessment (LCA). The criticality environmental implications (EI) score is given in the last column on a 0 to 100 scale.

Data collected from mentioned above sources allows to complete the description for each critical metal that is rated as critical by EC in 2017. EI, SR and ENV IM data is represented in the same measurement unit, scores, indexes, which allows to imply the final manipulation and calculate the CI (Table 6).

Two elements were excluded from further analysis during the critical metal scanning: Fi (Fluorspar) and Si (Silicon metal). Data on Environmental Impact did not exist in the base data source. Overall the average of CI is 31,6, from the smallest and biggest CI with 11,1 and 89,5 correspondingly.

Table 6. CI calculation [Source: EC 2017, Graedel 2015.].

Element		Supply Risk	Economic Impact	Environmental Impact			Criticality Index
				Human Health	Ecosystem	Total	
Sb	**Antimony**	4,30	4,30	8.0E+00	6.7E-02	19,10	**27,70**
Be	**Beryllium**	2,40	3,90	5.1E+00	4.5E-01	16,30	**22,60**
Bi	**Bismuth**	3,80	3,60	2.7E+00	2.2E-01	11,80	**19,20**
Ce	**Cerium**	5,70	3,20	6.6E-01	8.0E-02	4,80	**13,70**
Co	**Cobalt**	1,60	5,70	6.0E-01	4.2E-02	4,30	**11,60**
Dy	**Dysprosium**	5,20	6,30	3.1E+00	3.7E-01	12,90	**24,40**
Er	**Erbium**	5,20	2,70	2.5E+00	3.0E-01	11,60	**19,50**
Eu	**Europium**	3,40	3,70	2.0E+01	2.5E+00	27,50	**34,60**
Gd	**Gadolinium**	5,10	4,10	2.4E+00	2.9E-01	11,30	**20,50**
Ga	**Gallium**	1,40	3,20	8.0E+00	7.5E-01	19,80	**24,40**
Ge	**Germanium**	1,90	3,50	1.9E+01	6.7E-01	26,10	**31,50**
Hf	**Hafnium**	1,30	4,20	5.8E+00	4.6E-01	17,20	**22,70**
Ho	**Holmium**	5,40	3,30	1.2E+01	1.4E+00	22,90	**31,60**
In	**Indium**	2,40	3,10	1.1E+01	4.0E-01	21,90	**27,40**
Ir	**Iridium**	2,80	4,30	2.0E+03	3.6E+01	66,30	**73,40**
La	**Lanthanum**	5,40	1,40	5.6E-01	6.8E-02	4,30	**11,10**
Lu	**Lutetium**	5,40	3,30	4.6E+01	5.6E+00	34,40	**43,10**
Mg	**Magnesium**	4,00	7,10	1.9E-01	1.9E-02	1,70	**12,80**
Nd	**Neodymium**	4,80	4,20	9.0E-01	1.1E-01	6,10	**15,10**
Nb	**Niobium**	3,10	4,80	6.2E-01	4.8E-02	4,40	**12,30**
Pd	**Palladium**	1,70	5,60	2.6E+03	2.0E+01	68,50	**75,80**
Pt	**Platinum**	2,10	4,90	4.3E+03	5.9E+01	72,70	**79,70**
Pr	**Praseodymium**	4,60	3,80	9.8E-01	1.2E-01	6,50	**14,90**
Rh	**Rhodium**	2,50	6,60	1.0E+04	1.5E+02	80,40	**89,50**
Ru	**Ruthenium**	3,40	3,50	5.0E+02	8.9E+00	54,20	**61,10**
Sm	**Samarium**	4,50	5,50	3.0E+00	3.7E-01	12,90	**22,90**
Sc	**Scandium**	2,90	3,70	2.6E+02	2.1E+01	48,80	**55,40**

Ta	**Tantalum**	1,00	3,90	1.7E+01	1.8E+00	25,80	**30,70**
Tb	**Terbium**	4,80	3,90	1.5E+01	1.8E+00	25,10	**33,80**
Tm	**Thulium**	5,40	3,30	3.3E+01	4.0E+00	31,70	**40,40**
W	**Tungsten**	1,80	7,30	1.6E+00	6.2E-02	8,60	**17,70**
V	**Vanadium**	1,60	3,70	1.2E+00	1.2E-01	7,40	**12,70**
Yb	**Ytterbium**	5,40	3,30	6.4E+00	7.7E-01	18,20	**26,90**
Y	**Yttrium**	3,80	3,20	7.7E-01	9.3E-02	5,40	**12,40**

3.2 Average product lifetime (APL)

Product lifetime – is the time of product usage until disposal. In order to calculate the average of product lifetime data, it is important to list the areas of CM application and identify main products (n), that consists at least 80% of this CM, with its average lifetime. From this logic APL formula is following:

$$\boldsymbol{Total\ Average\ Product\ Lifetime\ (APL)} = \frac{\sum_{i=1}^{n} \boldsymbol{Average\ Product\ Lifetime_n}}{\boldsymbol{n}}$$

Aggregation as a logic of this formula is quite simple and consists of logical statistical manipulation. It consists of collecting all the data relevant to the sampling and then calculating the mean of the data. The uncertainty aspect can be noticed from the same area as for the CI formula – data relevance. Each CM has its unique characteristics and application specifics, in this way possibility of missing relevant professional data due to its manufacturing confidentiality.

From EC 2014a,b and Deetman 2017 reports, it is possible to complete the data for each critical metal main fields and product application data collected from the data mentioned above (Appendix 1). Data were collected by following the principal – industry, most common products, average product lifetime either lifespan or the average age of the products. (Figure 2)

Lists of element industry application were analyzed and summarized from two main sources – CRM factsheet (EC 2017) and SCREEN project data (Deetman 2017). Lists of industries listed were not similar in each element cause. In order to keep the objectiveness of analysis, industries were unified.

Criteria for the element product choice had to be modified from the original scope. The element product list represents the list of element composition or end product that is most commonly used in the main industries of the chosen element. This decision was made due to the unavailability of each product's chemical content data or properties that would allow applying the criteria of 80% element content of the product.

The product lifetime data was correspondingly based on the element composition type or end product lifetime according to the available data. Product lifetime was indicated by screening the available data about the average product lifetime, lifespan, average product age or product disposal by end-customer. In addition, some element compositions or products have a lifetime guarantee or an unlimited product lifetime. In order to keep product lifetime calculation in the real lifetime gap, this type of products got the average product lifetime as 100 years by default (Appendix 1).

After data was collected, APL was calculated as an average from all listed products' lifetime. Plus, maximum and minimum APL were allocated from products APL to better represent the final results. The overall average of TOTAL APL is 27,5 years, from MIN APL with 2 years and MAX APL with 52 years.

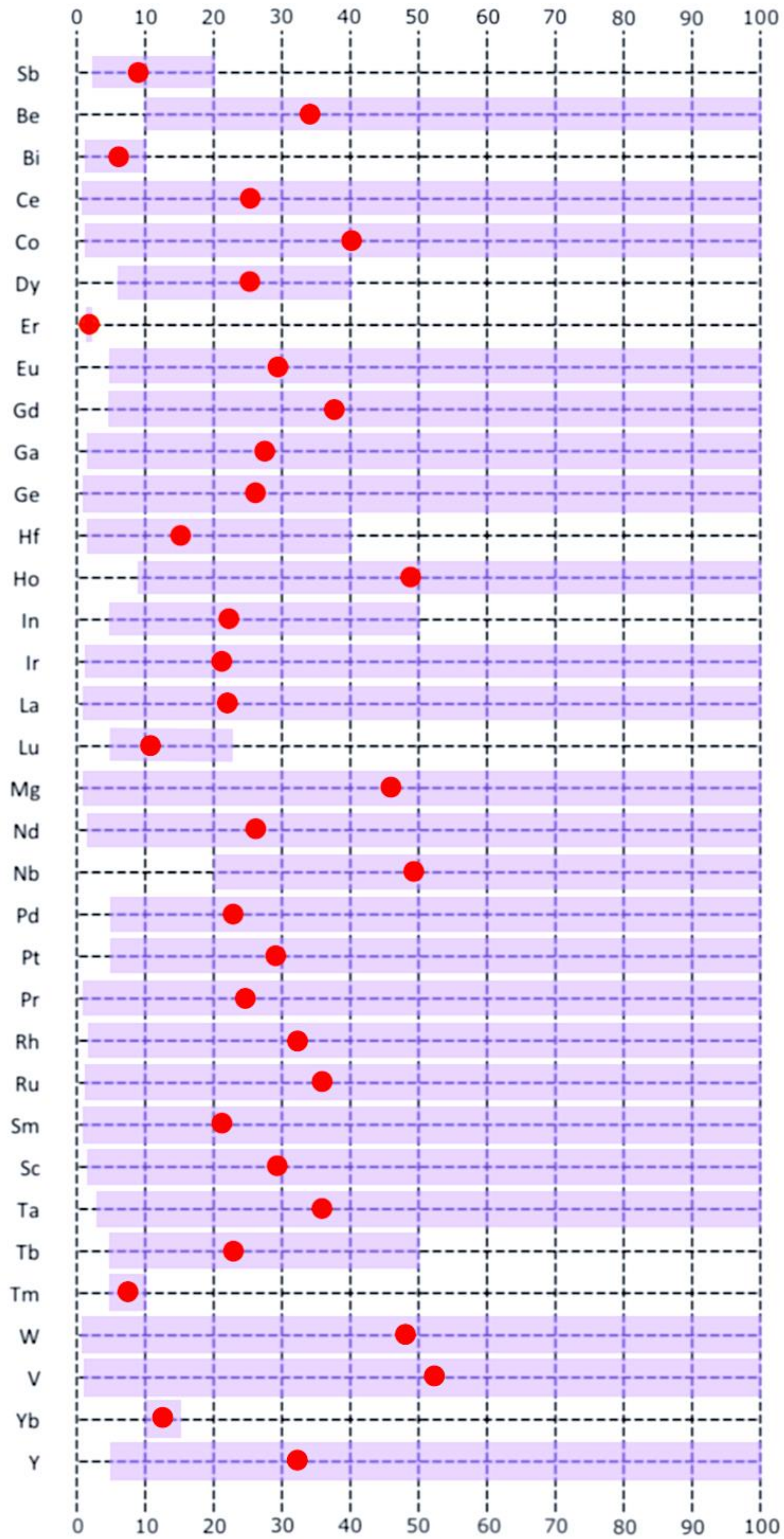

Figure 5. APL analysis of critical metals [Source: Deetman 2017, factsheet (EC 2017)].

3.3 Final data

Correlation is a statistical association between data variables. In the case of this project, variables that will be checked for the correlation existence are: supply risk (SR), economic importance (EI), environmental impact (ENV IM), criticality index (CI), minimum year of the average product lifetime (MIN APL), maximum year of the average product lifetime (MAX APL), total average product lifetime (TOTAL APL). Chosen variables are the main formula components of CI and TOTAL APL, that can characterize each CM and conclude the final data for correlation. (Table 7).

Table 7. Final data for correlation. [Source: EC 2017, Appendix 1]

Element		Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Sb	Antimony	4,30	4,30	19,10	27,70	3,0	20,0	9,3
Be	Beryllium	2,40	3,90	16,30	22,60	10,0	100,0	34,1
Bi	Bismuth	3,80	3,60	11,80	19,20	1,0	10,0	5,5
Ce	Cerium	5,70	3,20	4,80	13,70	0,5	100,0	25,3
Co	Cobalt	1,60	5,70	4,30	11,60	1,0	100,0	40,0
Dy	Dysprosium	5,20	6,30	12,90	24,40	7,5	40,0	25,6
Er	Erbium	5,20	2,70	11,60	19,50	2,0	2,0	2,0
Eu	Europium	3,40	3,70	27,50	34,60	5,0	100,0	29,2
Gd	Gadolinium	5,10	4,10	11,30	20,50	5,0	100,0	37,9
Ga	Gallium	1,40	3,20	19,80	24,40	2,0	100,0	28,4
Ge	Germanium	1,90	3,50	26,10	31,50	1,0	100,0	26,3
Hf	Hafnium	1,30	4,20	17,20	22,70	2,0	40,0	15,2
Ho	Holmium	5,40	3,30	22,90	31,60	9,0	100,0	49,8
In	Indium	2,40	3,10	21,90	27,40	5,0	50,0	22,3
Ir	Iridium	2,80	4,30	66,30	73,40	1,0	100,0	21,5
La	Lanthanum	5,40	1,40	4,30	11,10	0,5	100,0	21,8
Lu	Lutetium	5,40	3,30	34,40	43,10	5,0	22,5	11,2
Mg	Magnesium	4,00	7,10	1,70	12,80	0,5	100,0	45,7
Nd	Neodymium	4,80	4,20	6,10	15,10	2,0	100,0	27,2
Nb	Niobium	3,10	4,80	4,40	12,30	20,0	100,0	49,0
Pd	Palladium	1,70	5,60	68,50	75,80	3,0	100,0	23,4
Pt	Platinum	2,10	4,90	72,70	79,70	3,0	100,0	29,4
Pr	Praseodymium	4,60	3,80	6,50	14,90	0,5	100,0	24,6
Rh	Rhodium	2,50	6,60	80,40	89,50	2,0	100,0	32,1
Ru	Ruthenium	3,40	3,50	54,20	61,10	1,0	100,0	35,8
Sm	Samarium	4,50	5,50	12,90	22,90	0,5	100,0	21,6
Sc	Scandium	2,90	3,70	48,80	55,40	2,0	100,0	29,6

Ta	**Tantalum**	1,00	3,90	25,80	**30,70**	3,0	100,0	**36,2**
Tb	**Terbium**	4,80	3,90	25,10	**33,80**	5,0	50,0	**23,5**
Tm	**Thulium**	5,40	3,30	31,70	**40,40**	5,0	10,0	**8,0**
W	**Tungsten**	1,80	7,30	8,60	**17,70**	0,5	100,0	**48,3**
V	**Vanadium**	1,60	3,70	7,40	**12,70**	1,0	100,0	**52,0**
Yb	**Ytterbium**	5,40	3,30	18,20	**26,90**	10,0	15,0	**11,7**
Y	**Yttrium**	3,80	3,20	5,40	**12,40**	5,0	100,0	**32,6**

Secondary data for this research is based on two business cases and analysis of the importance of the CRM in the automotive industry. The main objective of this review is to have a deeper look at how companies from this industry are familiar with CE and CRM, plus how these concepts influence company business. The secondary objective of this analysis is to collect information on the practical implementation of the techniques, instruments, solutions, concepts and final results of the implementation of the CE and CRM. Analysis of business cases is based on Annual Sustainability reports and its supplementary materials of two companies - Volvo Group (VOLVO) and Bayerische Motoren Werke AG (BMW). VOLVO and BMW were chosen as two business cases for this research because both enterprises are Europe based and keep their sustainability strategies available as open source. Cross-case analysis between sampled companies has been executed through annual sustainability reports and supplementary materials that are published at corporate websites for potential investors.

3.3.1. VOLVO

The Volvo Group is a Swedish multinational manufacturing company. Its main business is the manufacture, distribution and sale of vehicles, trucks, buses and construction equipment, as well as the development of maritime, industrial and financial services. Company's mission is to drive development through transport and infrastructure solutions and to be the most desirable and efficient transportation provider in the world and to be an effective provider. In VOLVO, the procurement of any product, service or solution is completed with the best possible commercial offer, it aims to ensure outstanding quality and technology. VOLVO powers the development of electric vehicles and machines, as well as automated solutions, for the benefit of consumers, the economy and the planet. (Humphrey, 2019)

VOLVO defines circular economy as a part of their strategy by increasing the resource efficiency and circularity. There are seven aspects that the business is focusing on to achieve the circular economy: suppliers, design, sourcing, production, distribution, reuse, recovery. The goal of this strategy is that sustainability can drive human and planet-centred innovation in manufacturing. VOLVO is driving a circular economy, recycling and eco-design mentality, as well as a more value-driven human rights policy. (Figure 6)

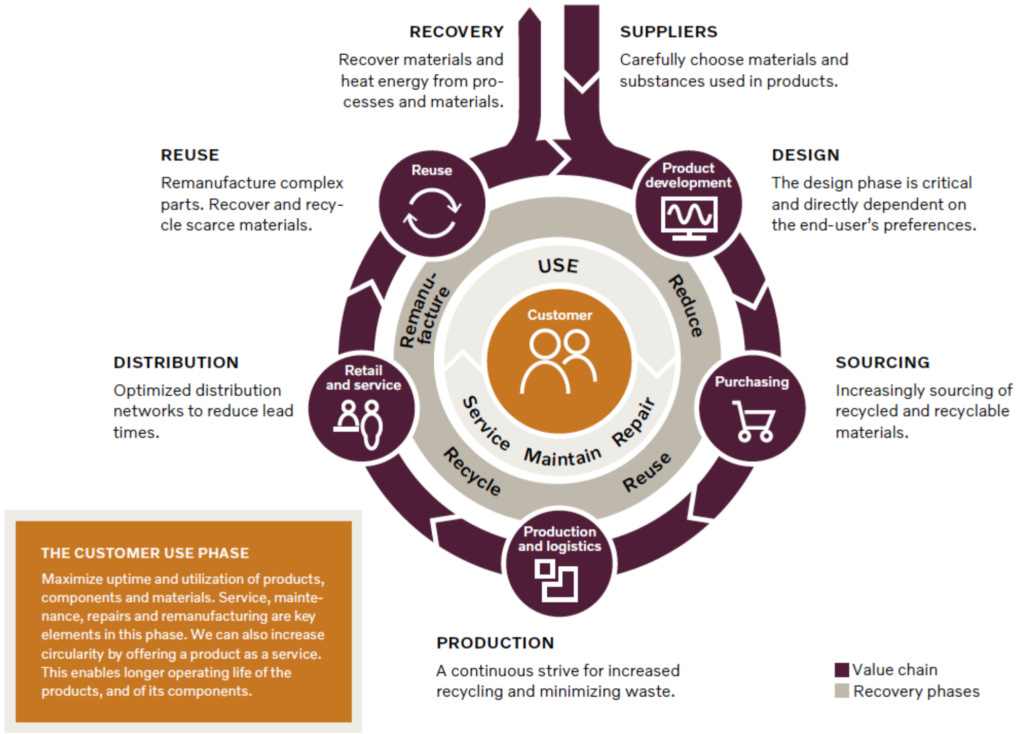

Figure 6. Circular economy scheme of VOLVO (VOLVO, Annual report 2019).

VOLVO consciously works on securing the synergies and building a long-term competitiveness by maximizing value development in every part of the value chain operations. It's efficiency, quality, and functionality are constantly optimized towards business associates, workers and the environment around it. Significantly, VOLVO's service-based business is increasing, with the primary production being uptime and availability of machines and vehicles. Plus, VOLVO incorporates remanufacturing, servicing and repairs into an extended service offer.

The availability of raw materials is the starting point of a circular economy, and VOLVO has developed a set of special programs to establish and maintain supplier relationships. One of the main tools that VOLVO uses to sustain a relationship with the suppliers and subcontractors is a Supplier Code of Conduct. It creates a right attitude and outlines the specifications of VOLVO and the goals and motivation of all suppliers. Suppliers Code of Conduct is focused on established universal norms, such as the principles of the UN Global Compact. In order to make sure that the code is followed, VOLVO created the Supplier Sustainability Evaluation Software in order to track how suppliers obey the code. It is a fundamental evaluation by a Sustainability Self-Assessment questionnaire of all supply chain stakeholders, a method built by DRIVE Sustainability. DRIVE Sustainability is a collaboration of ten major automotive firms dedicated to transforming the automotive supply chain into one that is circular and competitive. (VOLVO, Annual report 2019)

Supply Chain Mapping is another resource management technique. Mapping is conducted through special software that traces social, financial, environmental information about CRM worldwide. Sustainable Minerals Program, where VOLVO carries out supply chain mapping and human rights due-diligence of supply chains for tin, tantalum, tungsten gold, cobalt and other materials with the assistance of the RMI (Responsible Minerals Initiative) tools. RMI is a collective database of resources for the companies addressing responsible mineral solutions inside the industry. (VOLVO, GRI 2019), (VOLVO, Annual report 2019)

Design is another sector in VOLVO’s circular economy. It is important to mention that around 80% of a machine’s lifetime environmental impact is determined at the design stage. VOLVO trucks, for example, contain approximately one-third recycled material. Wrought iron is made up of half recycled metal, and cast iron is made up of 97% recycled iron. Using iron, steel and aluminium are favourable in term of recyclability, which reduces trucks environmental impact.

In addition to design optimization, VOLVO was defined and apply sustainable approaches on the manufacturing processes of automotive components. VOLVO offers remanufactured parts to its consumers all around the globe. Engines, gearboxes, rear axle transmissions, and other elements may be restored to like-new condition. VOLVO has proven that remanufacturing can increase the performance to even better conditions. Another example could be gearboxes produced through remanufacturing, which needs 80% less energy and material than producing a new component. (VOLVO, Annual report 2019)

Regarding reuse and recycling solutions VOLVO also can set up a good example for it’s competitors. Lithium-ion batteries, for example, have been given a second life in the Positive Footprint Housing project in Gothenburg, that is based in Sweden, where batteries and solar panels are used for local energy storage and processing. (Humphrey, 2020)

Despite significant innovations in production sites, management sets up the boundaries that should be followed on a constant basis as guidelines. VOLVO follows the ISO 14001 environmental management system that includes nearly 95% of its manufacturing plants and 90% of its delivery centers. VOLVO's departments and service areas use the management structure in a hierarchical manner to deploy productive environmental work. These facts ensure that all activities are accountable for their environmental performance. (VOLVO, GRI 2019)

Complex value chains make it difficult to determine the precise proportion of recycled materials, but right component decisions can also increase recyclability. From a procurement standpoint, the opportunity is straightforward. If VOLVO uses recycled or recyclable goods and parts, that keep the cost relatively stable over time and prevent commodity price fluctuations.

Another aspect of VOLVO trucks is that the impact of its products can be evaluated by five main parameters: materials and production, fuel, exhaust emissions, maintenance and end-of-life treatment (recycling). Considering possible trade-offs and incorporating the best available option for the future requires focusing on the life-cycle of the vehicles.

Reusability is not possible without extraction of the CRM, and so VOLVO together with suppliers managed to extract palladium and platinum from scrapped diesel particulate filters. Plus, trucks are largely recyclable, since 85% of the weight consists of metal – mostly iron, steel and aluminum. In addition, as previously said, VOLVO is collaborating with RMI to ensure responsible and sustainable tin, tantalum, tungsten, and gold sourcing, as well as cobalt. (VOLVO, Annual report 2018)

Each Business Area of the Volvo Group tracks and handles risks in its activities. A structured Enterprise Risk Management (ERM) framework is still used by the Volvo Group to centralize the monitoring. Three times a year, the ERM Committee evaluates, analyzes, and challenges the threats and mitigation activities that have been accumulated. Volvo Group risks are classified into four groups by the ERM: geopolitical, technical, compliance, and financial risks. All four risks are also related to CRM and being managed by tools described above. One of the particular threats on which VOLVO is currently focused is the continuing technological transition toward electrification with supportive consumer services, and the required technological innovations. This pattern could lead the industry and VOLVO to become more reliant on new suppliers with limited resources. The impact of distribution disruptions varies depending on the lead time and complexity of the items, as well as the availability of alternate vendors and transportation providers. Some components are standard throughout the industry, but there are as well other exceptional variables that VOLVO depends on.

Multiple sourcing not only satisfies the need for locally generated content while also reducing the effect of trade barriers, but it also lowers supply chain risks. Long-distance transportation reduction is becoming increasingly important, as it can lead to a major reduction in environmental effects. (VOLVO, Annual report 2019)

It is possible to conclude that the internal tools and practices VOLVO also actively collaborates with other parties in the industry. Two of the main networks where VOLVO scales its sustainable development of global supply chains are: DRIVE Sustainability focusing on supply chain sustainability of the automotive industry, and RMI, focusing on sustainable minerals sourcing. The Responsible Minerals Initiative (RMI) is a cooperative platform that works to address issues of responsible mineral procurement in global supply chains. The mix of external data and internal analytics allows VOLVO to sustain CE values in corporate strategy. (VOLVO, GRI 2019)

VOLVO has enhanced dialogue, openness, confidence with existing and future supply chain partners, as well as other stakeholders, by integrating the three aspects - people, planet, and profit. Lean methodologies are used to use less raw material but instead using more recyclable materials, reducing waste and electricity, recovering materials, and calculating a water footprint.

3.3.2 BMW

The BMW Group sees itself as a sustainability leader in the automotive industry as well as in other industries. BMW's distinct identity and economic prosperity have long been built on long-term thinking and strategic action. One of the main goals of BMW is to achieve a competitive advantage by providing forward-looking solutions. The corporate strategy "NUMBER ONE > NEXT" includes sustainability as a key component. BMW concentrates its activities on three main areas: products and services, production and value creation, and employees and society. BMW plan lays out a realistic roadmap for long-term growth and identifies strategic approaches. To bring value to market, BMW incorporates sustainability across the whole value chain and into all basic processes. (Figure 7) (BMW, Sustainable value report 2019).

Figure 7. BMW strategy ”NUMBER ONE> NEXT” (BMW, 2019).

BMW's new technologies help to address global issues such as climate change and urbanization on a continuous basis. There are three key issues on which BMW focuses special attention: the development of products and services for sustainable individual mobility; the efficient use of resources along the entire value chain; responsibility towards employees and society in general. (BMW, Annual report 2019)

Competence centres are used to coordinate global environmental conservation policies. In the fields of pollution, water, waste, teaching, and environmental management framework, BMW has five environmental competence centers. They are populated by sustainability consultants from the various plants as well as Corporate Environmental Protection experts. In terms of energy quality, the operators of participating plants and BMW's Corporate Energy Management department collaborate together. Both the competence centers and Energy Management consult with technology experts from the manufacturing plants on regulatory standards and best-practice strategies. As a result, BMW creates reference frameworks from which future planning and process changes can be developed.

In addition to designing internal initiatives, BMW also plays an active role in the field by sustaining public relations and collaborate with other parties in the numerous programs, organizations, institut ions that support and promote a circular economy. BMW is a member of the “Circular Economy Initiative Deutschland”, that drives the transformation towards a circular economy with the support of representatives from politics, science, industry and society. Among other initiatives, BMW is also involved in DRIVE Sustainability, the Responsible Business Alliance (RBA) as well as its subsidiary organisation, the Responsible Minerals Initiative (RMI). In addition, BMW wants to foster transparency in mineral supply chains through membership in the Initiative for Responsible Mining Assurance (IRMA) and other raw material-specific initiatives. Also, BMW Group has been called into the OECD stakeholder group and the “National CSR Forum” of the German Federal Government. Besides taking advantage of the networks and big data from these communities, BMW contributes by sharing the corporate experiences with various aspects of sustainability and the procurement of raw material as well as due diligence in supplier networks. (BMW, Sustainable value report 2019)

BMW monitors the resources and design materials with the aim of being certain that as many material cycles can be closed as possible. This approach drives the process of product growth. BMW completed further waste metal processes in 2019 by returning waste metal from pressing plants to steel manufacturers.

Furthermore, BMW promotes initiatives aimed at standardizing environmental standards and incorporating monitoring systems across the entire supply network, such as in extracting and processing critical raw materials. The supply network, which accounts for more than 70% of total value added, will make a substantial contribution to the company's long-term sustainability. Both manufacturers of production products and service providers are subject to BMW's sustainability standards. They are required to communicate certain specifications to their sub-suppliers. In Germany, for example, it was decided that the supplier would use a significant proportion of clean energy and secondary raw materials.

Environmental maintenance at BMW plants has a focus on resource consumption. BMW's international environmental network's steering committee oversees the procedures. The BMW Group has an ISO 14001 compliant environmental protection system, as well as a quality management system that analyses the design recycling.

BMW also has a Life Cycle Engineering department that guarantees the environmentally sustainable use of raw materials from the outset of the automotive production period. A separate BMW specification specifies the standards for recycling-optimized vehicle construction and manufacturing, as well as secondary material collection and usage. BMW creates supply chains and stock transfers in accordance with ISO 9001 certification. (BMW, Sustainable value report 2019)

Together with its sales organizations in each country, the BMW has installed recovery systems for end-of-life vehicles in 30 countries and offers environmentally friendly vehicle recycling at more than 2,800 recovery centers (BMW, Annual report 2019).

If to see for specifics regarding the metal recovery, BMW has quite impressive figures to show. Recyclables account for up to 20% of the thermoplastic components used in BMW cars. These thermoplastic materials make up about 12% of the vehicle's overall mass. BMW uses up to 50 % secondary aluminum in high-strength cast aluminum parts (BMW, Sustainable value report 2019).

Batteries that are no longer suitable for use in vehicles can be repurposed in stationary storage systems. BMW has its own energy recovery systems installed at its facilities. The BMW Group has developed a technique in cooperation with the technological university TU Bergakademie Freiberg that has dramatically improved recycling rates as opposed to traditional methods.

Another important component in the manufacturing of vehicles is cobalt. It is used in large quantities in the batteries of electric cars and plug-in hybrids. BMW interacts with battery cell producers on a regular basis and has requested the information regarding the source of this raw material.

Steel and aluminium form the most significant proportion of the components used in BMW's vehicles in terms of volume. BMW is actively seeking ways to increase supply chain productivity, accountability and at the same time to ensure that sources of materials are environmentally sustainable and socially viable way. BMW helped establish the standard for an open and safe supply chain from mine to vehicle from the start (Performance Standard, Chain of Custody) as a founding partner of the Aluminium Stewardship Initiative (ASI). BMW has also been supporting the formalization of the Responsible Steel Initiative (RSI) for a long time now and we are actively contributing towards developing a sustainability standard (BMW, Sustainable value report 2019).

Despite a comprehensive amount of internal tools and collaborations with external parties to maintain a sustainable supply chain, it is important to monitor material prices. BMW faces purchase price risks, particularly when it comes to raw materials used in vehicle design. The raw material price risk estimation is dependent on planned purchases of raw materials and products that include those raw materials. Risks related to raw materials costs may have a medium earnings effect over the two-year appraisal cycle if they materialize. If raw material prices increase in the BMW Group's advantage, significant opportunities can emerge. Price fluctuations for precious metals (platinum, palladium, rhodium), non-ferrous metals (aluminium, copper, lead, nickel) and, to some extent, for steel and steel ingredients (iron ore, coking coal) and energy (gas, electricity) are hedged using financial derivatives and production contracts with fixed price deals (BMW, Sustainable value report 2019).

4. RESULTS

4.1 Correlation between CI and APL

The first correlation approach was chosen as a general correlation analysis of all element variables. Correlation analysis as a tool can provide information about the relation that exists or does not between chosen components. The heat map that is shown in Figure 6, illustrates the results of the correlation of CM final data variables from Table 7. Each slot on the map visualizes the power of the correlation, between the variables within the page -1 and 1, by increasing the intensity of colour (Figure 6).

The two strongest correlation is shown between the ENV IM with CI and MAX APL with TOTAL APL. It means that if the first variable grows, then the second one grows as well. This correlation does not present any interest for this research because it is a clear connection between the variables comes from the CI and TOTAL APL formulas.

Unfortunately, there is no other strong correlation existing between CM variables that could be discussed further. Nevertheless, the heat map shows us the slight possibility of the positive correlation between TOTAL APL with EI and the negative correlation between TOTAL APL with SR. The first slight correlation means that if TOTAL APL increase, then EI will slightly rise. This weak trend could mean that the CM value on the market could increase in case of prolonging the APL. The second slight correlation means that if TOTAL APL decreases, then SR will slightly rise. This relation is confusing but has some ground to be true. It means that if CM APL will become shorter, it will create a shortage of CM on the market. Both hypotheses have logic that could have the potential for unexpected further research outcomes.

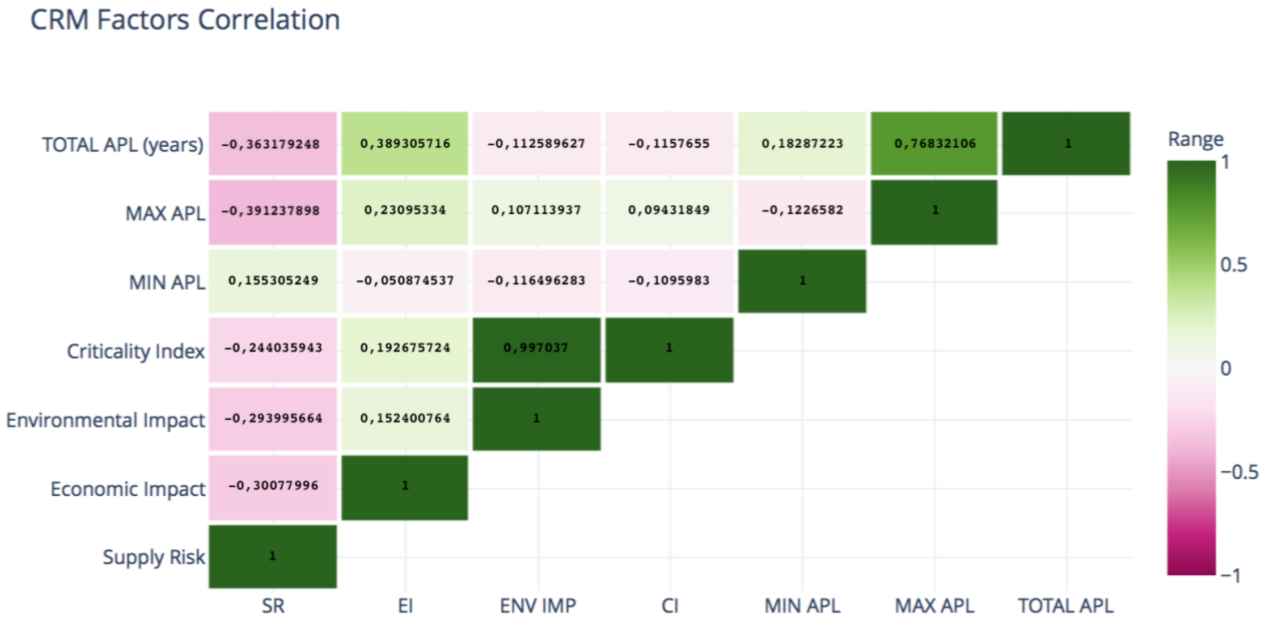

Figure 8. Correlation heat map for criticality factors.

The second method for deeper correlation analysis of the correlation data variables is histogram clustering. This approach allows structuring the analysis of the index distribution in each cluster. According to the histogram from Figure 9, the most optimal number of element clusters is either two or five. The most optimal amount of material groups for this analysis is five. This setting might increase the probability of finding the correlations in these raw material groups. Hierarchical clustering was completed with the Euclidean distance and the single linkage. Each cluster concludes certain CM that the machine learning approach has identified as the closest variables. Data that was used for clustering is the final data from Table 7. Histogram clustering results are illustrated in Figure 7, with the scale of differentiation between clusters scores - from the lowest (blue) to highest (yellow). In addition to each cluster's heat map representation, correlation analysis has also been conducted within each cluster. Correlation analysis might reveal a possible patterns between CM variables that might define the criticality of the raw materials from a different perspective (Appendix 2, 3).

The first cluster consists of elements such as Iridium, Palladium, Platinum, Rhodium, Ruthenium, Scandium. All metals are part of the PGMs group besides one abiotic material Sc. Elements from this cluster have the highest CI and lowest MIN APL beyond all researched CM. Plus, these elements all have 100 years as a MAX APL. CM variables have a very strong positive correlation between ENV IM with CI and EI. In the case of a rise of ENV IM and CI, EI starts to rise as well. The assumption from that results could be that increasing ENV IM, that affects the CI due to the formula composition, can increase the CM EI on the market. It is reasonable to assume that it can be connected with the hazard level and area of exploitation of the CM. There are two more positive correlations within the first cluster, but they do not have that big weight as the first one. There is a slight positive correlation that the increase in TOTAL APL can slightly raise SR, and that increase in MIN APL can slightly raise the EI. Probably logic beyond these statements is that customer demand on the market can grow if the product with CM has longer durability.

The strongest negative correlation in the first cluster is between MIN APL and SR. It means that if MIN APL decreases, SR will rise. The possible reason how that connection could be explained is that decreased MIN APL of the CM product can provoke the increase in consumption due to the value of the product in the market. Other negative slight correlations that stand for the relation that decrease in EI, ENV IM, CI will increase SR. A possible explanation for this connection could be the assumption that if EI, ENV IM and CI of the CM decrease, it makes the CM more affordable for product manufacturers that create a supplier competition and increase SR.

The second cluster consists of Antimony, Bismuth, Dysprosium, Erbium, Lutetium, Terbium, Thulium, Ytterbium. Most of the elements in this cluster are HREEs besides Sb and Bi. Elements from this cluster have the highest SR indices. This cluster of elements has one strong positive correlation between TOTAL APL and EI. Hypothetically the reason for this connection could be that prolonged CM product APL, increases the value of the product in the market. In addition, there is a slight positive correlation, where growing MIN APL slightly increases SR and growing MAX APL slightly increases EI. These correlations could be discussed as a complex where an increase in the MIN AND MAX APL affect the value of the CM product as for consumers as well for suppliers.

The third cluster has been identified as only one abiotic element – Niobium. This element has MAX APL with 100 years, and one of the highest TOTAL APL but one of the smallest CI. Plus, Nb has the highest indices for MIN APL beyond all CM with 20 years. It appears that this element was chosen by the machined learning approach as an element that contradicts by it’s variables.

The fourth cluster concludes elements such as Cerium, Gadolinium, Holmium, Lanthanum, Neodymium, Praseodymium, Samarium, Yttrium. This cluster consists of five LREEs and three HREEs that are Ga, Ho, Y. All elements from these clusters have MAX APL with 100 years and relatively high SR indices. First visible strong positive correlation MIN APL, TOTAL APL and ENV IM. It means that increasing MIN APL and TOTAL APM drive the growth in ENV IM. This connection is clearly referred to as CM characteristics and their effect on the environment. Another strong correlation can be seen between TOTAL APL and CI. This connection stands for the assumption that by increasing TOTAL APL, CI will be increased as well. This issue could be referred to as CM product APL and its effect on the environment. In addition to the last strong correlation, there is also a slight correlation between MIN APL and CI. This connection could be seen as a supplement to the previous one, by confirming the assumption mentioned above.

The fifth cluster units are the biggest cluster that consists of Beryllium, Cobalt, Europium, Gallium, Germanium, Hafnium, Indium, Magnesium, Tantalum, Tungsten, Vanadium. This cluster consists of abiotic materials besides the Eu that belongs to HREEs. The elements of this cluster conclude two types of CM, the ones with the highest EI indices and the ones with the relatively lowest EI indices. In addition, the majority of the elements have MAX APL with 100 years besides two elements – Hf and In with 40 and 50 years correspondingly. This cluster has a slight positive correlation where rising TOTAL APL increases EI. This connection is quite possibly connected with the CM product value on the market as it was in previous clusters. The strongest negative correlation in this cluster is between ENV IM and EI. The decrease in ENV IM can drive the increase in EI. There are small negative correlations where a decrease reduction in TOTAL APL increases ENV IM and CI, which is connected with the ecological impact after disposal and exploitation durability of the CM product.

The last method for correlation data analysis is the 2D Scatter method. This method provides a visual representation of the data distribution for recognition and allows to visualize the position of elements according to the clustering method applied in the heat map above. As well as for the clustering, for this method base data was the final data Table 7. The main research question of this work was to study the possible correlation between two main indices from this research – CI and TOTAL APL. In this way, Figure 8 represents elements positioning within clusters on the two-dimensional matrix with indices of main interest (Figure 8).

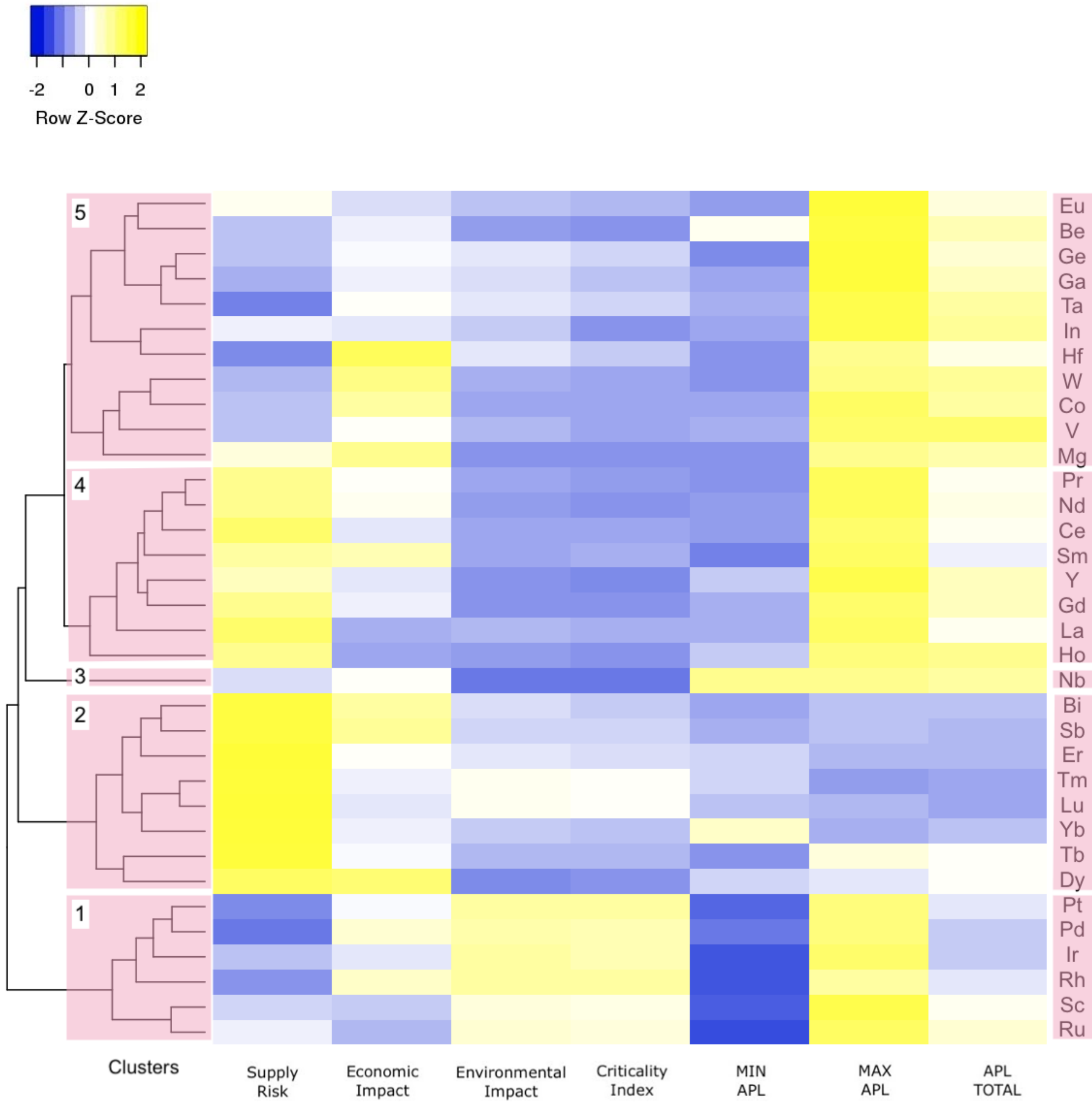

Figure 9. Clustering heat map for critical materials.

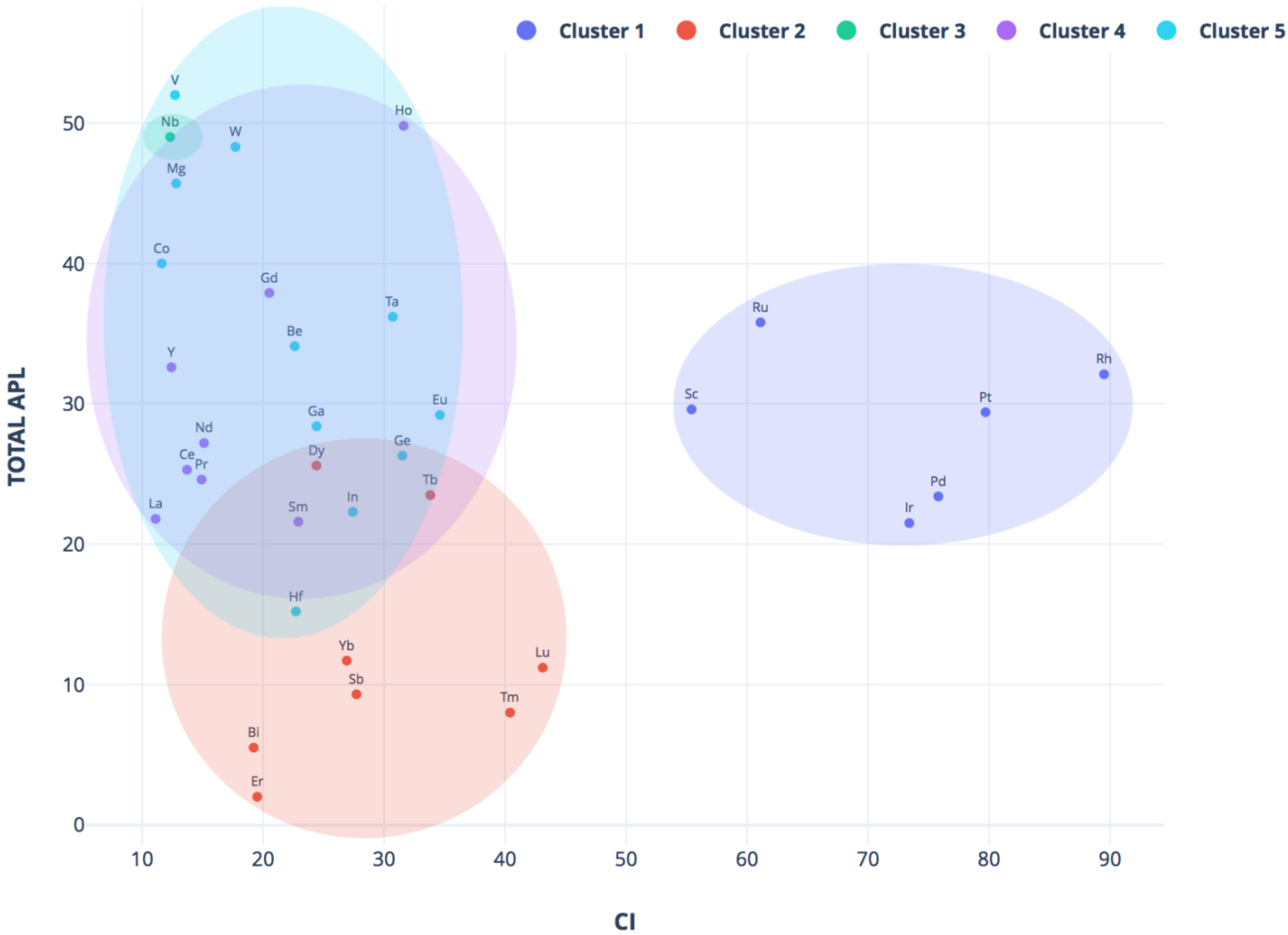

Figure 10. Critical metals 2D matrix.

As it has been described above, the cluster that differs the most from the other clusters, is the first cluster with the highest CI and TOTAL APL indices. The second cluster concludes elements with the smallest TOTAL APL. The third, fourth and fifth cluster has similar CI and TOTAL APL indices. Overall it is possible to make an observation that there is a direct correlation between indices beyond 14 CM where the majority of them are PGMs and HREEs – higher the CI, higher TOTAL APL and lower the CI, lower TOTAL APL. In the case of the rest 20 CM, low CI and high TOTAL APL appear to be a pattern that can be studied further by specific sampling (Appendix 2,3).

At first glance, if to review the clustering from a theoretical point of view, the number of elements that will ensure the reliability of the results might not be the most optimal. This research focuses on metals, the largest group of CRMs which number is relatively fixed. The number of elements could have been extended with metal compositions and variations, but this approach can be considered for future studies. If to sum up the review of the clusters, it is possible to define the following highlights:

- In cluster 1 (Pt, Pd, Ir, Rh, Sc, Ru) criticality depends on EI and SR, and rises when the MIN APL increases.
- In cluster 2 (Bi, Sb, Er, Tm, Lu, Yb, Tb, Dy) criticality depends on EI, and SR and rises when the MAX APL increases.
- In cluster 4 (Pr, Nd, Ce, Sm, Y, Gd, La, Ho) criticality depends on ENV IM and rises when the MI APL increases.
- In cluster 5 (Eu, Be, Ge, Ga, Ta, In, Hf, W, Co, V, Mg) criticality depends on ENV IM and rises when the MIN APL decreases.

The last highlight is represented through the visualization shown in Figure 11. CM was originally reviewed as a list of elements, even-though each metal has its class based on chemical characteristics and properties (group blue, yellow, orange). The clustering method that was based on CI and APL variables has defined new groups of metals and patterns through the correlation analysis. The finding is that new metal groups consist of metals from similar metal classes (REEs, LEEs, PGMs). The result of this observation is that criticality correlates with the chemical properties of the metals and it can be studied further within the metal classes.

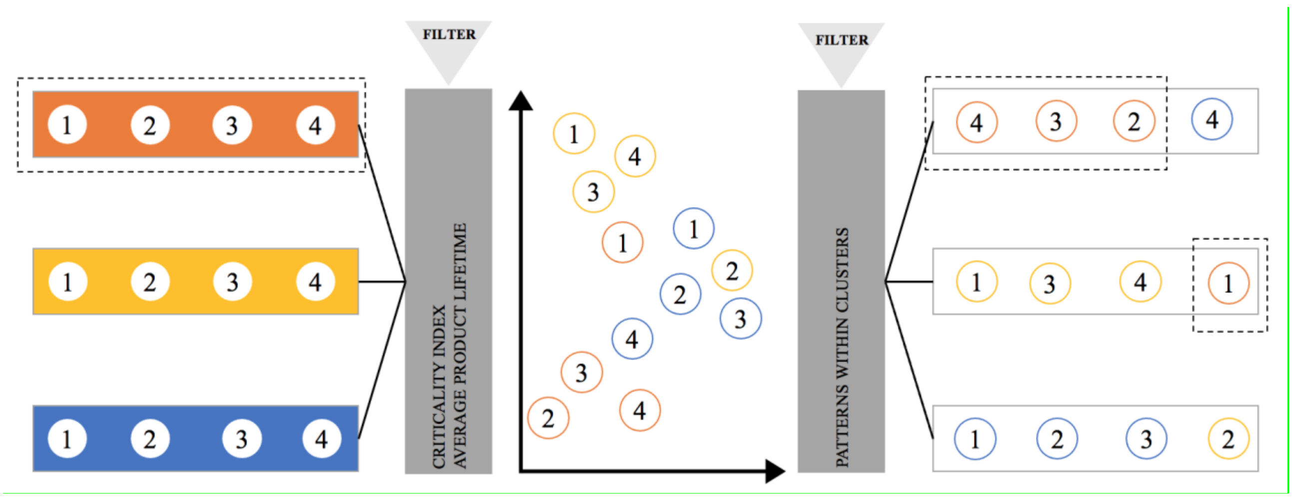

Figure 11. Cluster patterns visualization.

4.2 Cross-case analysis

VOLVO and BMW identify raw materials and other materials that are particularly critical in terms of sustainability for the environment and maintain the circular economy principles inside the companies. These businesses examine the effect of these materials on the environment and community in the supply chain, implement raw material-specific hedging plans, and conduct pilot projects to improve sustainability.

Both organizations are committed to foster the integration of sustainability requirements. In addition to internal efforts supplemented by cooperation with other businesses that pushes meaningful improvements more efficiently. In order to summarize the comparison, both companies can be compared by the following aspect: corporate strategy structure, unions and other organizations, set of lean methods and tools, recycling and reusability of the raw materials, critical metals, risk management (Table 8).

VOLVO strategy emphasises the circular economy as a core while BMW has a competition-driven strategy where sustainability and circularity of raw materials is an additional element of the corporate strategy. There are three main unions and associations where both companies are members: DRIVE Sustainability (DRIVE), Responsible Business Alliance (RBA), Responsible Minerals Initiative (RMI). Those associations can be evaluated as the obligatory unions that each corporation in automotive industry that supports the circularity principles should be part of. Suppose to analyses the way how companies describe their union memberships, they could be evaluated as a political investment into the company image and position in the market, which makes company more prestige how companies describe their union memberships. In that case, they could be evaluated as a political investment into the company image and position in the market, which makes the company more prestigious.

An interesting observation can be mentioned regarding the lean tools, software's and data analytics that VOLVO and BMW use. CRM and supplier-related information in most cases are open sources for union members in each association. This aspect makes corporations more competitive and innovative in the area of internal tool development for raw material management. The high level internal system for CRM management can be divided into supplier evaluation, recycling, and remanufacturing planning. Code of Conduct, Sustainability Self-Assessment Questionnaire, Supply Chain Mapping and other programs are directed on scanning and evaluating potential supply risks from a sourcing point of view. At the same time, the development of collection centers, sustainably product design, and Environmental Management Systems are forming the internal ecosystem of CRM management.

In addition to developing internal circular operations, both corporations share their vision and position in the market by promoting and upgrading their public image. One of the most professional tools in that business is to be a member or be certified by various unions and associations. Even though CRM-related unions provide a certain level of prestige to the companies, in return, each member should fulfill a list of specific requirements and pass detailed assessments. Nevertheless, besides the strict conditions, various associations provide industry-specific software and database accesses. These valuable tools make resource management more sustainable as each player in the market has an access, which creates a forced community that can work together towards long-term goals. One of the examples is a DRIVE Sustainability. This union is a partnership of 10 leading automotive companies that work together to improve sustainability in the supply chain. Starting with 2012, its members have assessed over 20,000 suppliers in more than 100 countries and engaged over 1500 suppliers in capacity building initiatives (DRIVE. 2017).

If to review the core of the vehicle production and the need CRM in product design, both companies have similar demands. VOLVO and BMW emphasize the importance of the metals that are related to the batteries like lithium or the core of the vehicle structure like steel and cobalt. Despite these key elements, both companies mention other RRE, HREEs, LREEs and PGMs as CM.

As it was mentioned above, both corporations are actively integration CE strategies and practices into their busines operations. One of the solutions for VOLVO and BMW was to give second life in lithium-ion batteries in various building projects. Another remarkable example is that VOLVO trucks are made up of about one-third from recycled material, and half the wrought iron comes from recycled metal and 97% of the cast iron is made from recycled iron. Simultaneously, BMW has recovery systems for end-of-life vehicles in 30 countries and offers environmentally friendly vehicle recycling at more than 2,800 recovery centers. In the end, up to 20 % of the thermoplastic materials in BMW vehicles are made from recyclables and up to 50 % secondary aluminium in high-strength cast aluminium parts (Table 8).

In terms of CRM, VOLVO and BMW emphasize the importance of the metals that are related to the batteries like lithium or the core of the vehicle structure like steel and cobalt. Despite these key elements, both companies mention other RRE, HREEs, LREEs and PGMs as CM.

Last but not least, the especial association that both companies are in is the Responsible Business Alliance (RBA) with Responsible Minerals Initiative (RMI). Using direct and indirect collaborations within international norms, the RMI strives to foster the shared purpose of identifying and contributing to mitigating the major social and environmental impacts of raw material production and manufacturing in supply chains. One of the last RBA’s innovations is a useful tool that both corporations use is the RBA’s Risk Assessment Platform. It's a new rating model that uses a complex scoring system to include a high-quality risk assessment and a confidence score for each supplier's location that's been assessed. (RBA, 2020)

Overall, VOLVO and BMW have an extensive spectrum of similarities in approaches, tools, performance criteria. Nevertheless, it is remarkable how different both companies position themselves in terms of sustainability and circularity of business operations as well as resource management achievements.

Table 8. Comparison analysis of VOLVO and BMW (VOLVO 2018, 2019, Chemical substances 2019; BMW, 2019; BMW Guidance 2019).

COMPANY / ASPECT	VOLVO	BMW
CORPORATE STRATEGY STRUCTURE	Vision of company operations with a mindset towards circular economy, recycling and eco-design, and as well a more value driven approach for human rights.	Sustainability is an integral part of our corporate Strategy NUMBER ONE > NEXT. BMW focuses on three key areas of operations: products and services; reduction and value creation; employees and society. economical use of resources and design products
UNIONS AND ASSOCIATIONS	• DRIVE Sustainability (DRIVE) • Responsible Business Alliance (RBA) • Responsible Minerals Initiative (RMI)	• DRIVE Sustainability (DRIVE) • Responsible Business Alliance (RBA) • Responsible Minerals Initiative (RMI) • Responsible Steel Initiative (RSI) • Aluminum Stewardship Initiative (ASI) • Responsible Mining Assurance (IRMA) • Carbon Disclosure Project's (CDP) • Supply Chain Programme • National CSR Forum (of the German Federal Government) • Circular Economy Initiative Deutschland
CIRCULAR ECONOMY STRATEGIES	• Supplier Code of Conduct • Supplier Sustainability Assessment Program • Sustainability Self-Assessment questionnaire from DRIVE • Supply Chain Mapping • Sustainable Minerals Program developed with tools of the RMI • ISO 14001 Environmental management system	• Five environmental centers of competence in the areas of emissions, water, waste • Training and environmental management system. • Sustainability Self-Assessment questionnaire from DRIVE • Methods of the WPS-Lernwerkstatt (learning workshop for a value creation-focused production system) • ISO 14001 Environmental management system • ISO 9001 certified

RECYCLING AND REUSABILITY OF THE RAW MATERIALS	• Lithium-ion batteries got second life in building project Posisitive Footprint Housing • Volvo Trucks is made up of about one-third from recycled material. Half the wrought iron comes from recycled metal and 97% of the cast iron is made from recycled iron. • Remanufactured components are offered to Volvo Group's customers worldwide (Engines, gearboxes, rear axle transmissions and other parts) • Together with suppliers managed to extract palladium and platinum from scrapped diesel particulate filters	• Recovery systems for end-of-life vehicles in 30 countries and offers environmentally friendly vehicle recycling at more than 2,800 recovery centers • Up to 20 % of the thermoplastic materials in BMW vehicles are made from recyclables • Up to 50 % secondary aluminium in high-strength cast aluminium parts. • Large proportions of electricity from renewable sources in Germany and secondary raw materials must be used by the supplier.
CRITICAL METALS	• Platinum group metals: platinum, palladium, rhodium, molybdenum. • Rare earth elements: dysprosium, neodymium, praseodymium, tin, bismuth, indium, gallium, gold, antimony, silver, cobalt. copper, nickel. • Other metals: lithium, aluminium, steel, iron.	• Platinum group metals: platinum, palladium. • Rare earth elements: cobalt. • Other metals: lithium, aluminium, steel, iron.
RISK MANAGEMENT	• Centralized Enterprise Risk Management (ERM) process • Electrification • Multiple sourcing • Reduction of long-distance transports	• Corporate Energy Management department • Electrification • Multiple sourcing

5. DISCUSSION AND CONCLUSIONS

5.1 DISCUSSION

The research was conducted through hypothetical formula application and review of two busines cases, that were supported by theoretical review. The research framework (Figure 1) represents how the findings contribute to the hypothesis generated through the main research question – “how the criticality level of critical raw materials and average lifetime of products, that are manufactured from these materials, might affect or even improve the implementation of circular economy strategies?”. After completing the research according to the methodology, it is possible to discuss the findings of each direction of the framework: CI and APL concepts from the theoretical point of view; CE principals in VOLVO and BMW cross-case analysis from the practical point of view.

The criticality of raw materials is quite a flexible concept. European Commission (EC) has defined critical raw materials that have high economic importance in EU and high risk of supply to the EU. In this way, the current EU CRM is considered critical" because of its high economic and commercial value and at the same time "strategic" for the supply or defence of a nation (EC 2017). At the same time, if to move from a high level into a company point of view, critical raw materials are the substances that shall be avoided, if technically feasible, or design-for-recycling shall be considered for new or changed components. (VOLVO Chemical substance, 2020)

The criticality of raw materials can be seen as a result of the effect of certain parameters. Market imperfections in the processing or use of products are the first factor. The second factor is third-party representatives such as governments and investors. The third factor is the disruptions in the resource supply chain from operational dislocations, spontaneous, structural or operational disturbances. The last factor is a set of alternative technologies that effect on the functionality of different materials usage (Poulizac 2013). In addition, if to review the latest studies about criticality factors, it will be possible to define key criticality assessment factors and dimensions that more commonly used by the governments: demand, supply, vulnerability to supply restrictions, environmental, importance or impact, recycling, materials, innovation, market dynamics. (Jin 2016, EC 2017, NSTC 2018, Fortier 2018)

And again, if to go down into the corporate view, the material criticality is associated mainly with environmental impact that takes into account the possibilities of economic and supply risks in different segments of company operations. For example, company can have a set of policies, specifically defined essential risks (impact of company's value chain, environmental impact by company operations, scarce materials and minerals, etc), mitigation activities (product development and new technologies, recourse efficiency and circularity, sustainable purchasing) as well as individual KPI's (product emissions, recyclability rate, energy use, sources use efficiency, CO_2 emissions, supplier self-assessments, ISO Certifications) (VOLVO, 2019).

One of the primary components of this research methodology was to find a correlation within their products between critical metal criticality and average lifetime. It was translated into a series of sub-questions that logically organize the research plan, in order to find a CI and its correlation with the APL. The overall result can be divided into two findings. The first result is that the criticality and APL of CM are not clearly correlated. A quite strong correlation exists only within certain cluster groups, but due to the diversity of the material origins, it could not be generalized. The data collection approach and formula composition could be further improved by either adding additional components or verifying a more complex connection between the variables. Secondly, despite the fact that there is no direct correlation between CI and APL beyond all CM, this research has revealed another solution for more profound analysis - to analyze each CM group as a separate grouping. If to narrow the CM groups by its specific chemical properties and materials characteristics, it will be possible to define a strong correlation.

The circular economy differs from the traditional economy in its sustainable solutions to environmental, economic and social problems related to the use of energy, waste generation and depletion of natural resources. (Figure 3; EC, 2018) As it is descried in the literature review chapter, it is possible to define 5 CE strategies are strongly connected with criticality risks that are based on EC and SR: 3R strategy (recycling, remanufacturing, reuse), lean principles (just-in-time manufacturing, time, and cost-saving advantages), dematerialization strategy (resource efficiency, reduction of materials needed), collection (take-back programs, collection sites), diversity strategy (range of active, innovative sourcing system with several channels) (Gaustad, 2018).

Based on the cross-case analysis, both sampled companies have integrated key elements of each of the 5 strategies into their corporate strategy (Table 8). It is important to highlight that all 5 strategies (3R, lean principles, collection, dematerialization, supplier's diversity) are mentioned in the company's sustainability reports as unique solutions aimed at improving the product footprint well as enhancing the human resource management. In most of CE tools implementation descriptions, the most common justification is found in human rights and employees well-being. For example, supplier's diversity strategy is supported by assessments programmes and audits, where reports about material sources have smaller value compared to the evaluation of human right violation. There is a possibility that the main message from sustainability reports has been formed into a highlight of human values. Unfortunately, this approach creates the impression that companies are mixing the CE and sustainability main pillars.

In theory concept of CE has three principles: preserve and enhance natural capital, optimize resource yields, foster system effectiveness. As a framework CE consists of three principles that require corporations to do the following actions: regenerate, share, optimize, loop, virtualize, and exchange. (Gaustad, 2018) If to review this concept in the automotive field, it will be possible to define 3 sections that circular corporate strategy consists (Figure 9, (VOLVO, Annual report 2019)).

The first section includes suppliers, product design and purchasing of the resources. At start, the company has to manage its suppliers and develop transparent relations that guarantee sustainable supply and cooperation. After ensuring that the supplier answers all the sustainability-related criteria, the company should make sure the product development is in sync with product design because the lifecycle of the product depends on the design stage. Plus, high APL rates, recyclability, and reusability will be only possible if they are the fundamental of the product design. All mentioned above won't be possible without raw materials purchased through “smart” sourcing, including multiple sourcing, stock management, demand predictions, etc.

The second section unites recycle and distribution elements of company operations. The way how production and logistics flows affects the distribution strategy of the company. The third section that flows into the first one is reuse and recovery. After collecting the products from the collection points, company can process and recover CRM and energy for secondary use. Sorting and recycling technologies depend on the industry. As the case studies show, in automotive industry, lithium batteries are given second life in constructions requiring lower energy consumption than vehicles, such as warehouses. Besides, metal scrap is being collected at unique collection points and remanufactured by the company into new parts or redirected to the company supplier who is obliged to use it for the next delivery.

Material recovery rate depends on the material but each company drives to reach a high recycling rate, and as a result half the wrought iron comes from recycled metal and 97% of the cast iron is made from recycled iron; or up to 20 % of the thermoplastic materials in vehicles are made from recycles;

or 50 % secondary aluminum exists in high-strength cast aluminum parts. (VOLVO 2018, 2019) Risks that are related to manufacturing and supply delays are being managed by multiple-sourcing and sustaining the supplier programs and assessments. (BMW Guidance 2019) Plus, companies that are in one industry tend to be part of global unions and cooperation's that assist to companies to maintain their position in the market by sharing the raw materials, suppliers, mining centers data.

5.2 CONCLUSION

The main question of this research was - how can APL and CI of CRM supplement the CE strategies in top CRM fields of application?". APL is a commonly used indicator of product development efficiency through life-cycle assessment and the statistics from corporate collection points. CI can include individualistic characteristics that can be adapted for a specific environment and target. Application of CE strategies actively expands beyond the industrial as well as in consumption sectors.

Based on theoretical research and cross-case analysis in the automotive industry, the answer is that integrations of these concepts could help a corporation to develop an individualistic long-term strategy based on business specifics. By applying CE principles, each corporation could have a deeper analysis of future perspectives and more efficient optimization of the resources with innovations in product design solutions. This analysis should be seen as proof that the generalization of criticality studies is exceedingly difficult. A specific scope of criticality study is likely to be more advantageous nowadays because it will be supported by more focused data and offer greater potential interested parties. A concluding statement could be formulated to say that the answer is at the origin of the link if you want to find the connection.

This study has limited scope due to the broad characteristics of the raw materials. More comprehensive CI and deeper analysis of criticality factors could be implemented within each metal group according to elements chemical properties. Also, the outcomes of this work could have more depth, if information about the CE practices would have been collected through the face-to-face interview with the representative of the company management from the procurement or sustainability departments. The main obstacle in acquiring the primary data was the limited access to high-level information of the middle-level workers of the companies that also varies a lot depending on the office locations.

The criticality of metals assessment is not a static measure, because it is a value that evolves over time as new ore deposits are located, political circumstances change, and technologies undergo a transformation. The scope of this research was the high-level view of CE practices applied for CRM in order to evaluate and manage the criticality. There are other factors that can be studied deeper, such as product emissions, energy use rate and ISO certifications. Energy and CO2 emission play a significant role in sustainability evaluation of company performance, that has an influence on the overall value of the materials at each stage of the production chain. For future research on this topic could cover more practical aspects related to the circularity of the resources and their evaluations in the companies. Therefore further studies of raw materials criticality can be analyzed further from the perspective of each factor in depth.

To sum up, the criticality of CRM is a flexible concept that depends on the evaluation sample and scope. The importance of the CRM depend on the research party that conducts the analysis, either it is a country, government, association, union or global corporation from industrial, service, or any other sector. As a result, estimation of future criticality of materials will become more visible and transparent in a broader range of industries.

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APPENDICES

Appendix 1. Data collection or APL of CRM with references and explanations.

Element		Main field of application according SCREEN 2014	Main product or element of application	APL PER PRODUCT (years)	Remark	MIN APL (years)	MAX APL (years)	TOTAL APL (years)
Sb	**Antimony**	ICT Batteries Catalysts and stabilisers Plastics and Ceramics Batteries Catalysts and stabilisers Plastics and Ceramics	antimony trioxide as a flame retardant	20	r	**3,0**	**20,0**	**9,3**
			lead antimony battery	3	b			
			semiconductor in diodes, infrared detectors, and Hall-effect devices	5	i			
Be	**Beryllium**	ICT or telecommunication equipment Mechanical and electrical equipment Automotive electronics Vehicles Aircraft, ship and trains Glass Energy application Metal	x-ray	10	m	**10,0**	**100,0**	**34,1**
			airbag system	11,3	c			
			anti-lock break system	11,3	c			
			fire extinguisher systems	13,5	f			
			aircraft electronics	24,8	a			
			rocket	100	e			
			satellite	100	e			
			aircraft	24,8	a			
			car body parts and seat frames	11,3	c			
Bi	**Bismuth**	Bi chemicals Cosmetics Fusible alloys Weapons Metallurgical additices and others	antibiotics	1	d	**1,0**	**10,0**	**5,5**
			Colour pigment	1	d			
			bullets	10	h			
			acrylonitrile as a colour for plastic	10	p			
Ce	**Cerium**	Vehicles as auocatalysts Glass and ceramics Polishing powders Fluid cracking catalysts and pigments Phosphors as lighting Batteries	carbon electrodes in steel	25	t	**0,5**	**100,0**	**25,3**
			arc lamps	0,5	ga			
			permanent magnets	100	e			
			cerium oxide (catalyst to clean up exhaust vehicles)	11,3	c			

		Magnets Metal	cerium sulphide (pigment)	10	v, o, c, l			
			flat-screen television	15	l			
			low-energy light bulbs	25	k			
			magnetic-optic compact discs	30	j			
			chromium plating	11,3	c			
Co	**Cobalt**	Steel Batteries Catalysts and pigments Supperalloys Magnets Tyre adhesives and paint dryers Others	alloy for gas turbine aircraft engines	24,8	a	**1,0**	**100,0**	**40,0**
			magnetic recording media	30	j			
			catalysts for the petroleum	22,5	q			
			cobalt blue pigment	100	e			
			enamel jewellery	100	e			
			stained glass	2	v, g			
			radioactive isotopes cobalt-60 (for medical treatment and preserve food)	1	d			
Dy	**Dysprosium**	Mechanical and electrical equipment ICT Vehicles Petrol-chemical Magnets	cerement in nuclear reactors	40	n	**7,5**	**40,0**	**25,6**
			nuclear reactor control rods	40	n			
			laser materials	15	v, l			
			dosimeters for monitoring exposure to ionizing radiation	7,5	z			
Er	**Erbium**	Glass as optical application Phosphors as lighting	glass of special safety spectacles for workers	2	v, g	**2,0**	**2,0**	**2,0**
			photographic filter	2	v, g			
			porcelain enamel glaze colorant	2	v, g			
Eu	**Europium**	Phosphors as lighting	neutron absorber in nuclear reactors control rods	40	n	**5,0**	**100,0**	**29,2**
			europium phosphors as an activator in television tubes	15	l			
			mercury vapour lamps	5	be			
			europium salt for newer phosphorescent powder and paints	100	e			
			europium metal for screening the diseases	10	v, m			
			europium metal as doping for glass and lasers	5	z			
Gd	**Gadolinium**	Phosphors Magnets Medical and optical application	gadolinium yttrium garnets for microwave	9	w	**5,0**	**100,0**	**37,9**
			TV tubes	15	l			
			compact discs	30	j			
			computer memory cards	5	u			

			burnable poison for nuclear marine propulsion systems	40	n			
			Metallic gadolinium alloy for recording heads and video recorders	30	j			
			control rods for nuclear reactors and nuclear power plants	40	n			
			crystal of gadolinium oxyorthosilicate (GSO) as a scintillator in medical imaging equipment (PET)	10	m			
			gadolinium ethyl sulfate in maser	100	e			
			thermometer	100	e			
Ga	**Gallium**	ICT Magnets Energy Lighting	liquid gallium wets porcelain and glass surfaces	2	v, g	**2,0**	**100,0**	**28,4**
			reflection surface in mirrors	20	v			
			Infrared Emitting Diodes (IREDs), Laser Diodes (LDs) and Light Emitting Diodes (LEDs)	10	i, l			
			thermometer	100	e			
			gallium alloys as dental amalgams	10	de			
Ge	**Germanium**	ICT Glass as optical application Satelite solar cells	optical fibres	19	oi	**1,0**	**100,0**	**26,3**
			fluorescent lamps	6,7	la			
			single-crystal radiation detectors	5	v			
			chemotherapeutic agents	1	d			
			precious metal alloys	100	e			
Hf	**Hafnium**	Base metals Machinery parts Chemical products Optics General electronics	control rods in nuclear reactors and nuclear submarines	40	n	**2,0**	**40,0**	**15,2**
			gas in incandescent lamps, for scavenging oxygen and nitrogen	2	g			
			electrode in plasma cutting	3,5	ep			
Ho	**Holmium**	Optical application	magnetic flux concentrator	50	v	**9,0**	**100,0**	**49,8**
			part of lasers in microwave medical and dental equipment	9	w			
			control rods in nuclear reactor	40	n			
			holmium oxide as yellow gas colouring	100	e			
In	**Indium**	ICT and flat panel displays Energy Glass Batteries Semiconductors Alloys and compounds PV cells Solders	protective plate for bearings and other metal surfaces	11,3	v, c	**5,0**	**50,0**	**22,3**
			corrosion-resistant mirror surface	20	v			
			indium foils for nuclear reactors	40	n			
			light filter in low pressure sodium vapor lamps	5	v, be			
			semiconductor compounds in LEDs, laser diodes	15	l			
			indium antimonide in infrared detectors	15	l			

			indium oxide in electroluminescent panels	50	v			
Ir	**Iridium**	Electrical Electrochemical Chemical	coat the electrodes	3,5	ep	**1,0**	**100,0**	**21,5**
			pivot bearings	11,3	v, c			
			osmium/iridium alloys for tipping fountain pen nibs	2	v			
			osmium/iridium alloys for compass bearings	100	e			
			platinum/iridium in spark plugs	11,3	v, c			
			radioactive isotopes of iridium in high-dose radiation therapy	1	v, m			
La	**Lanthanum**	Fluid cracking catalysts and pigments Glass and ceramics Batteries Vehicles Phosphors as lighting Metal Polishing powders	colour televisions	15	l	**0,5**	**100,0**	**21,8**
			fluorescent lamps	6,7	la			
			energy-saving lamps	25	k			
			glasses	2	v, g			
			cameras and telescop lenses	100	e			
			carbon arc electrodes	0,5	ga			
			salt as zeolite catalysts in petroleum refining	22,5	q			
			nickel metal hydride rechargeable batteries	3	b			
Lu	**Lutetium**	Optical application	catalyst in petroleum cracking in refineries	22,5	q	**5,0**	**22,5**	**11,2**
			pure beta emitter for neutron activation	6	v			
			lutetium aluminium garnet as lens material	12,5	y			
			cerium-doped lutetium oxyorthosilicate (LSO) as compound medical imaging equipment (PET)	10	m			
			dopant to gadolinium gallium garnet (GGG) for magnetic bubble memory devices	5	v, u			
Mg	**Magnesium**	Aluminium as packaging Conclustion as steel Transportation as vehicles Desulfurisation agent	beverage cans	0,5	v	**0,5**	**100,0**	**45,7**
			high-grade car wheels	11,3	c			
			mobile phones	3	o			
			laptop	5	u			
			camera	12,5	y			
			photoengraved plates	100	e			
			aircraft	24,8	a			
			missile	100	e			

			nodular graphite	100	e			
			magnesium oxide for iron production	100	e			
Nd	**Neodymium**	Magnets Batteries Glass and ceramics Steel Phosphors Vehicles Lasers Catalysts	colour televisions	15	l	**2,0**	**100,0**	**27,2**
			fluorescent lamps	6,7	la			
			energy-saving lamps	25	k			
			didymium glass	2	v, g			
			neodymium alloy for lighter flints	100	e			
			neodymium, iron and boron (NIB) alloy for permanent magnets in loudspeakers	5	v, u			
			neodymium, iron and boron (NIB) alloy for permanent magnets in vehicles	11,3	c			
			alloy for permanent magnets in computer data storage	5	u			
			neodymium salt as colorant	100	e			
			neodymium glass laser for multiple beam systems for inertial confinement fusion	2	v, g			
Nb	**Niobium**	Heavy industry and construction as steel (scturtural) Transportation as steel (automotive) Steel (pipeline) Aircraft, ship and trains Energy Supperalloys Chemical	alloy and stainless steel	25	t	**20,0**	**100,0**	**49,0**
			niobium carbide for cutting tools	50	v			
			stainless steel alloys for nuclear reactors	40	n			
			stainless steel alloys for jets	24,8	a			
			stainless steel alloys for missiles	100	e			
			stainless steel alloys for pipelines	50	v			
			stainless steel alloys for welding rods	25	t			
			alloy as wires for superconducting magnets	55	al			
			jewellery	100	e			
			alloy as surgical implants	20	v, ze			
Pd	**Palladium**	Vehicles as auocatalysts ICT Other consumer goods Catalysts and pigments Chemical Investment Jevellery Medical and Biomedical Petroleum	alloy for low voltage electrical contacts	25	v, k	**3,0**	**100,0**	**23,4**
			jewellery	100	e			
			watch bearings, springs, and balance wheels	11,3	v, c			
			mirrors in scientific instruments	20	v			
			catalytic converter for automobile	11,3	c			
			televisions screen	15	l			

			computer screen	5	u			
			mobile prone screen	3	o			
			salt as electroplating	20	v			
Pt	**Platinum**	Vehicles as auocatalysts ICT Other consumer goods Catalysts and pigments Chemical Investment Jevellery Medical and Biomedical Petroleum	jewellery	100	e	**3,0**	**100,0**	**29,4**
			surgical tools	10	v, m			
			laboratory utensils	10	v, m			
			electrical resistance wires	55	al			
			electric contacts	55	v, al			
			catalytic converter for automobile	11,3	c			
			televisions screen	15	l			
			computer screen	5	u			
			mobile prone screen	3	o			
Pr	**Praseodymium**	ICT Energy Phosphors Glass and ceramics Metal Chemical Polishing powders Magnets Batteries	pyrophoric alloy in cigarettes lighter flints	0,5	v	**0,5**	**100,0**	**24,6**
			praseodymium oxide in carbon electrodes for arc lighting	0,5	ga			
			goggles for welders	100	e			
			aircraft engines	24,8	a			
			colour televisions	15	l			
			fluorescent lamps	6,7	la			
			energy-saving lamps	25	k			
Rh	**Rhodium**	Vehicles as auocatalysts Catalysts and pigments Glass Chemical Electrical	catalytic converter for automobile	11,3	c	**2,0**	**100,0**	**32,1**
			furnace windings	15	v			
			pen nibs	2	v			
			phonograph needles	2	v			
			high-temperature thermocouple	5	v			
			resistance wires	55	al			
			electrodes for aircraft spark plugs	24,8	a			
			reflectors of searchlights	6	v, g, l			
			jewellery	100	e			
			laboratory crucibles	100	e			

Ru	**Ruthenium**	Electrical Chemical	electric contacts	55	v, al	**1,0**	**100,0**	**35,8**
			chip resistors	24,8	v, a			
			jewellery	100	e			
			pen nibs	2	v			
			instrument pivots	100	e			
			colour ceramics and glass	2	v, g			
			versatile catalyst	22,5	v, q			
			catalysts for organic and pharmaceutical chemistry	1	d			
			light absorbent in solar technologies	15	v, s			
Sm	**Samarium**	Batteries Magnets Medical and optical application	catalyst in certain organic reactions for synthetic versions of natural products	1	d	**0,5**	**100,0**	**21,6**
			infrared adsorbing glass	2	v, g			
			cores of carbon arc-lamp electrodes	0,5	ga			
			catalyst for the dehydration and dehydrogenation of ethanol	100	e			
			doping CaF2 crystals for optical masers or lasers	5	z			
			neutron absorber in nuclear reactor	40	n			
			headphones	3	o			
Sc	**Scandium**	Solid Oxide fuel cells (SOFCs) Sc-Al alloyes	colour televisions	15	l	**2,0**	**100,0**	**29,6**
			fluorescent lamps	6,7	la			
			energy-saving lamps	25	k			
			aerospace industry components	24,8	a			
			bikes	15	v			
			basketball bats	50	v			
			lacrosse sticks	2	v			
			firearms	100	e			
			high-intensity lights	2	g			
			television cameras	12,5	y			
			light bulbs	2	g			
			submarine-launched ballistic missiles	100	e			
Ta	**Tantalum**	Capacitors	aircraft engines	24,8	a	**3,0**	**100,0**	**36,2**

		Supperalloys Sputtering targets Chemicals Mill products Carbides	capacitors in phones	3	o			
			capacitors in laptop	5	u			
			surgical implants and handling corrosive chemicals	20	v, ze			
			heat exchanger in boilers	13	v			
			audio-grade resistors	20	v			
			nuclear reactors	40	n			
			missile parts	100	e			
			carbide tools for metalworking equipment	100	e			
Tb	**Terbium**	Lighting Magnets	laser materials	5	z	**5,0**	**50,0**	**23,5**
			semiconductor devices	50	v			
			phosphorous in colour television tubes	15	l			
			stabilizer of fuel cells	22,5	q			
			terbium oxide colour TV tubes	15	l			
			terbium oxide for green phosphors in fluorescent lamps	6,7	la			
			dope for solid-state devices	50	v			
Tm	**Thulium**	Optical application	laser materials	5	z	**5,0**	**10,0**	**8,0**
			radiation source in portable X-ray devices	10	m			
			ferrites in microwave equipment	9	w			
W	**Tungsten**	Mining and construction tools Mechanical and electrical equipment Catalysts and pigments Aeronautics and energy use Energy Lighting and electronic uses High speed steels applications	filaments in incandescent light bulbs	2	g	**0,5**	**100,0**	**48,3**
			electric contacts	55	v, al			
			arc-welding electrodes	0,5	ga			
			cutting tools for the machining of steel	100	e			
			emitter coil and the screen in X-ray	10	m			
			microchip technology	5	v, u			
			liquid crystals displays	10	v, l, u			
			heavy metal alloys for armaments	100	e			
			counterweights and ballast keels for yachts	100	e			
			darts	100	e			
V	**Vanadium**	HSLA	ferrovanadium or as a steel additive	100	e	**1,0**	**100,0**	**52,0**

		Special steel Supperalloys for hish-end uses Chemicals Cast Iron for rigid structures Stainless steel Energy storage	jet engines	24,8	a			
			high speed air-frames	24,8	a			
			alloy for axles	11,3	c			
			alloy for crankshafts	11,3	v, c			
			alloy for gears	11,3	c			
			alloy for nuclear reactors	40	n			
			vanadium oxide for catalyst in manufacturing sulfuric acid	100	e			
			vanadium oxide for maleic anhydride	1	v, d			
			vanadium oxide for ceramics	100	e			
			vanadium dioxide as a green pigment for glass	100	e			
			jewellery	100	e			
Yb	**Ytterbium**	Optical application	alloys for dental purposes	10	de	**10,0**	**15,0**	**11,7**
			radiation source in portable X-ray devices	10	m			
			dope for phosphors or ceramic capacitors	15	v, th			
Y	**Yttrium**	Phosphors as lighting Vehicles Glass and ceramics Alloys	yttrium oxide for red phosphors for colour television picture tubes	15	l	**5,0**	**100,0**	**32,6**
			camera lenses	12,5	y			
			yttrium oxide superconductors	50	v			
			light-emitting diodes (LEDs)	15	l			
			yttrium iron garnet for microwave filter	9	w			
			yttrium iron garnet for acoustic energy transmitter	10	v			
			yttrium iron garnet for transducer	20	v			
			jewellery	100	e			
			infrared lasers	5	z			
			superconductor	50	v			
			catalyst for ethylene polymerization	5	v, p			
			gas mantles for propane lanterns	100	e			

a	aircraft	value is based on average lifetime of passenger and cargo aircrafts [1]
b	batteries	value is based on average lifetime of batteries in condition of "normal" usage [2]
c	vehicle	value is based on average age of passenger cars, vans and heavy commercial vehicles in Europe [3]
d	medical	value is based on assumption of exploitation or consumption in the same year of production
e	no limit	product that has no product lifetime limits was assigned by the maximum value, with 100 years
f	fire extinguisher systems	value is based on average lifetime of fire extinguisher system [4]
g	average guarantee	value is based on assumption of average guarantee of the product, with 2 years
h	bullets	value is based on assumption of average bullets lifetime before deformation [5]
i	infrared detectors	value is based on average lifetime of infrared detectors [6]
j	CD and DVD	value is based on average lifetime of CD and DVD related products before deformation [7][8]
k	low energy lamps	value is based on the average lifetime of low energy lamps [9]
l	TV / LED	value is based on average lifetime of LED lamps [10]
m	MRI / X-ray / PET	value is based on average lifetime and usage cycle of x-ray equipment [11] [12]
n	nuclear	value is based on average lifetime of nuclear plants [13]
o	mobile phone	values is based on average lifetime of mobile phone [14]

[1] https://www.statista.com/statistics/622600/average-age-of-jets-when-removed-from-service-by-type/
[2] http://ec.europa.eu/environment/waste/batteries/pdf/evaluation_report_batteries_directive.pdf
[3] https://www.acea.be/statistics/tag/category/average-vehicle-age
[4] https://www.statesystemsinc.com/blog/how-long-fire-extinguisher-last/
[5] https://familyprotectionassociation.com/when-is-ammunition-too-old/
[6] http://www.intlsensor.com/pdf/infrared.pdf
[7] https://www.loc.gov/preservation/scientists/projects/cd-r_dvd-r_rw_longevity.html
[8] https://www.clir.org/pubs/reports/pub121/sec4/
[9] https://lampputieto.fi/wp-content/uploads/retailer_brochure.pdf
[10] https://www-sciencedirect-com.ezproxy.cc.lut.fi/science/article/pii/S096014811500052X?via%3Dihub
[11] https://info.blockimaging.com/what-does-end-of-life-mean-for-mri-scanners
[12] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4195838/
[13] https://www.iaea.org/newscenter/news/extending-operational-life-span-nuclear-plants
[14] https://www-sciencedirect-com.ezproxy.cc.lut.fi/science/article/pii/S096014811500052X?via%3Dihub

p	plastics	value is based on average useful life until irresistible deactivation from average plastic product shelf-life from 1 year till 15 years [15] [16]
q	petroleum	values is based on average lifetime of petroleum before deformation of the formula [17]
r	flame retardant	value is based on the average lifetime of products content the flame retardant [18]
s	solar panel	value is based on average lifetime solar panel [19]
t	stainless steel	value is based on average lifetime of stainless steel products before the deformation [20]
u	lap top / computer	value is based on average lifetime of personal computers and laptops [21]
v	authors estimations	value is based on author's own estimation and observation
w	microwave	value is based on average lifetime of microwave for personal use [22]
x	laser	value is based on average lifetime of laser LED [23]
y	camera / lenses	value is based on average lifetime of the portable cameras [24]
z	dosimeters	value is based on average usage time of dosimeters [25]
al	cables / wires	value is based on average product lifespan of average cable and wires [26]
be	mercury vapor lamps	value is based on product lifespan in hours, by average 10 hours per day lifespan, by assuming 365 days in year [27]
ga	arc lamps	values is based on average lifetime of arc lamps [28]
de	dental works	value is based on product lifespan of dental instruments [29]
ep	electrodes	value is based on average lifetime of electrodes [30]

[15] http://ec.europa.eu/environment/waste/packaging/pdf/Hazardous%20Crates.pdf
[16] https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf
[17] https://www.planete-energies.com/en/medias/close/life-cycle-oil-and-gas-fields
[18] https://www.niehs.nih.gov/health/topics/agents/flame_retardants/index.cfm
[19] https://www-sciencedirect-com.ezproxy.cc.lut.fi/science/article/pii/S096014811500052X?via%3Dihub
[20] http://www.worldstainless.org/Files/ISSF/non-image-files/PDF/Team_Stainless_Stainless_Steel_for_a_Sustainable_Future.pdf
[21] https://www.techwalla.com/articles/how-to-put-a-laptop-processor-in-a-desktop-pc
[22] https://www.hunker.com/12003628/what-is-the-average-lifetime-of-microwave-ovens
[23] https://www.newport.com/medias/sys_master/images/images/hbc/h43/8797050241054/AN33-Estimating-Laser-Diode-Lifetimes-and-Activation-Energy.pdf
[24] https://www.quora.com/There-is-any-Lifetime-for-a-DSLR-Camera-Sensors
[25] https://www.dhs.gov/sites/default/files/publications/Radiation-Dosimeters-Response-Recovery-MSR_0616-508_0.pdf
[26] https://www.elandcables.com/the-cable-lab/faqs/faq-what-is-the-life-expectancy-of-electrical-cables
[27] https://www.sciencedirect.com/topics/pharmacology-toxicology-and-pharmaceutical-science/mercury-vapor-lamp
[28] https://www.microscopyu.com/tutorials/arclamp
[29] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3011298/
[30] http://www.denverinstrument.com/denverusa/media/pdf/Shelf_life_of_pH_electrode.pdf

ze	medical implants	value is based on average lifespan of the most common medical implants [31]
th	capacitors / 15	value is based on average lifespan of the capacitors in condition of average usage [32]
io	optical cable	value is based on average lifetime guarantee of optical cable [33]
la	fluorescent lamps	value is based on product lifespan in hours, by average 10 hours per day lifespan, by assuming 365 days in year [34]

[31] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4854641/
[32] https://www.allaboutcircuits.com/news/calculating-the-lifespan-of-electrolytic-capacitors-with-de-rating/
[33] http://seeds4green.net/sites/default/files/fibre%20optique.pdf
[34] https://www.lrc.rpi.edu/programs/nlpip/lightingAnswers/t8/05-t8-lamp-life.asp

Appendix 2. Cluster profiles.

Elements from cluster 1		Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Ir	**Iridium**	0,38	0,49	0,82	0,79	0,03	1,00	0,39
Pd	**Palladium**	0,15	0,71	0,85	0,83	0,13	1,00	0,43
Pt	**Platinum**	0,23	0,59	0,90	0,88	0,13	1,00	0,55
Rh	**Rhodium**	0,32	0,88	1,00	1,00	0,08	1,00	0,60
Ru	**Ruthenium**	0,51	0,36	0,67	0,64	0,03	1,00	0,68
Sc	**Scandium**	0,40	0,39	0,60	0,57	0,08	1,00	0,55

Elements from cluster 2		Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Sb	**Antimony**	0,70	0,49	0,22	0,21	0,13	0,18	0,15
Bi	**Bismuth**	0,60	0,37	0,13	0,10	0,03	0,08	0,07
Dy	**Dysprosium**	0,89	0,83	0,14	0,17	0,36	0,39	0,47
Er	**Erbium**	0,89	0,22	0,13	0,11	0,08	0,00	0,00
Lu	**Lutetium**	0,94	0,32	0,42	0,41	0,23	0,21	0,18
Tb	**Terbium**	0,81	0,42	0,30	0,29	0,23	0,49	0,43
Tm	**Thulium**	0,94	0,32	0,38	0,37	0,23	0,08	0,12
Yb	**Ytterbium**	0,94	0,32	0,21	0,20	0,49	0,13	0,19

Elements from cluster 3		Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Nb	**Niobium**	0,45	0,58	0,03	0,02	1,00	1,00	0,94

Elements from cluster 4		Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Ce	**Cerium**	1,00	0,31	0,04	0,03	0,00	1,00	0,47
Gd	**Gadolinium**	0,87	0,46	0,12	0,12	0,23	1,00	0,72
Ho	**Holmium**	0,94	0,32	0,27	0,26	0,44	1,00	0,95
La	**Lanthanum**	0,94	0,00	0,03	0,00	0,00	1,00	0,40
Nd	**Neodymium**	0,81	0,47	0,06	0,05	0,08	1,00	0,50
Pr	**Praseodymium**	0,77	0,41	0,06	0,05	0,00	1,00	0,45
Sm	**Samarium**	0,74	0,69	0,14	0,15	0,00	1,00	0,39
Y	**Yttrium**	0,60	0,31	0,05	0,02	0,23	1,00	0,61

Elements from cluster 5		Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Be	**Beryllium**	0,30	0,42	0,19	0,15	0,49	1,00	0,64
Co	**Cobalt**	0,13	0,73	0,03	0,01	0,03	1,00	0,76
Eu	**Europium**	0,51	0,39	0,33	0,30	0,23	1,00	0,54
Ga	**Gallium**	0,09	0,31	0,23	0,17	0,08	1,00	0,53
Ge	**Germanium**	0,19	0,36	0,31	0,26	0,03	1,00	0,49
Hf	**Hafnium**	0,06	0,47	0,20	0,15	0,08	0,39	0,26
In	**Indium**	0,30	0,29	0,26	0,21	0,23	0,49	0,41
Mg	**Magnesium**	0,64	0,97	0,00	0,02	0,00	1,00	0,87
Ta	**Tantalum**	0,00	0,42	0,31	0,25	0,13	1,00	0,68
W	**Tungsten**	0,17	1,00	0,09	0,08	0,00	1,00	0,92
V	**Vanadium**	0,13	0,39	0,07	0,02	0,03	1,00	1,00

Appendix 3. Correlations of the cluster components.

Correlation between components of cluster 1	Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Supply Risk	1						
Economic Impact	-0,675785403	1					
Environmental Impact	-0,611819591	0,89803376	1				
Criticality Index	-0,592791656	0,909398029	0,998966537	1			
MIN APL	-0,886258735	0,509041474	0,394207774	0,37719344	1		
MAX APL	-	-	-	-	-	1	
TOTAL APL (years)	0,530934786	-0,147322756	-0,195152904	-0,172273	-0,1906545	-	1

Correlation between components of cluster 2	Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Supply Risk	1						
Economic Impact	-0,093581538	1					
Environmental Impact	0,437756801	-0,277530062	1				
Criticality Index	0,491032931	-0,159896203	0,990990376	1			
MIN APL	0,654041409	0,305916055	0,185320262	0,2656337	1		
MAX APL	0,029371932	0,644593012	0,163901559	0,24429775	0,36321205	1	
TOTAL APL (years)	0,175477237	0,760348437	0,083105225	0,18776057	0,55162447	0,95366299	1

Correlation between components of cluster 4	Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Supply Risk	1						
Economic Impact	-0,380335488	1					
Environmental Impact	0,187577716	0,30281265	1				
Criticality Index	0,197865437	0,414645244	0,989645339	1			
MIN APL	-0,013782242	-0,037340327	0,733810034	0,668613161	1		
MAX APL	-	-	-	-	-	1	
TOTAL APL (years)	0,143686358	-0,023124693	0,770162496	0,718624255	0,976787441	-	1

Correlation between components of cluster 5	Supply Risk	Economic Impact	Environmental Impact	Criticality Index	MIN APL	MAX APL	TOTAL APL (years)
Supply Risk	1						
Economic Impact	0,307547752	1					
Environmental Impact	-0,169804882	-0,746723289	1				
Criticality Index	-0,02270504	-0,630228827	0,982039452	1			
MIN APL	0,194227284	-0,44436219	0,40095904	0,39650786	1		
MAX APL	0,146021988	0,254842147	-0,174992664	-0,1354678	-0,0930616	1	
TOTAL APL (years)	0,136752352	0,594202745	-0,684738996	-0,654647	-0,3177474	0,68420706	1