VIENNA UNIVERSITY OF TECHNOLOGY

# MASTER THESIS

# Assessment methods and design guidelines for criticality and circularity of electronic products and components

for the attainment of the academic degree

## Diplom-Ingenieur

submitted at the Vienna University of Technology

**Faculty of Mechanical and Industrial Engineering**

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Vienna, September 2023

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I declare in lieu of oath, that I wrote this thesis and carried out the associated research myself, using only the literature cited in this volume. If text passages from sources are used literally, they are marked as such.

I confirm that this work is original and has not been submitted for examination elsewhere, nor is it currently under consideration for a thesis elsewhere.
I acknowledge that the submitted work will be checked electronically-technically using suitable and state-of-the-art means (plagiarism detection software). On the one hand, this ensures that the submitted work was prepared according to the high-quality standards within the applicable rules to ensure good scientific practice "Code of Conduct" at the TU Wien. On the other hand, a comparison with other student theses avoids violations of my personal copyright.

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Vienna, September 2023

**Thomas Mandl**

# Acknowledgements

This Master's thesis was written during my employment as a student assistant at the Vienna University of Technology at the Institute of Engineering Design and Product Development within the Research Group for Ecodesign.

I would like to express my special thanks to my supervisor Ao. Univ. Prof. Dipl.-Ing. Dr. Wolfgang Wimmer. He made this thesis possible in the first place and was always available to answer questions throughout the development process. In numerous discussions I was able to gain valuable topic specific knowledge and helpful feedback for the preparation of the thesis.

Furthermore I want to express my gratitude to the rest of the colleagues in the Research Unit for their humorous and personal approach. These are also Dr. Rainer Pamminger, DI Philipp Feuchter, MSc. and DI Sebastian Glaser. The active exchange of ideas and insights related to environmental assessment methods played a key role in the progress of this work.

Special thanks are also due to my girlfriend who has always provided me with motivation, support and encouragement throughout the research and writing process.

Finally I would like to thank my family who has always provided me with unwavering support and a place of refuge whenever needed throughout my academic journey. Regardless of their understanding of the subject matter they have always tried to help me and have always had an open ear demonstrating their unconditional support.

# Abstract

There is currently a great hype concerning the topic of circular economy. Numerous papers are being published that describe the concept of circular economy and propose solutions for making products more circular. These solutions are often called circular strategies.

The objective of this study is to evaluate two of these circular strategies. Assessment methods are developed for evaluating the raw material criticality and circularity of products. Requirements for these methods are specified. The aim is to identify the most relevant areas of a product which could benefit from circular strategies. The areas could include critical raw materials or product parts with non-circular designs.

The existing array of established evaluation methods for criticality and circularity was identified in a literature review. No established method was found to fulfil all the requirements satisfactorily. Therefore, the evaluation methods used in this thesis are based on established methods but have been newly developed to meet the identified needs.

The methods were applied to a product to demonstrate the useful results of this study. The product being analysed is the Fairphone 4. The raw material criticality and circularity of the smartphone were assessed. The objective was to identify and analyse the most valuable areas of the Fairphone 4 for product design improvements. Product design improvements were defined based established circular strategies.

The potential of future evaluation methods for circular economy strategies is evident. Substantial changes of the evaluation methods are essential for informing legislative decisions. By having a robust methodology as a basis for decision-making it is hoped that future binding guidelines will lead in the direction of circular designed products.

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2. Adapted from European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report* (Publications Office, 2023), p.11, https://doi.org/doi/10.2873/725585.

# List of Abbreviations

| Abbreviation | Definition |
|---|---|
| BOM | Bill of Materials |
| BPR | By-Product Risk |
| CAD | Computer Aided Design |
| CE | Circular Economy |
| CEAP | Circular Economy Action Plan |
| CMF | Companion Metal Fraction |
| CML | Critical Minerals List |
| CR | Concentration Risk |
| CRM | Critical Raw Material |
| CSR | Current Supply Risk |
| EC | European Commission |
| EI | Economic Importance |
| EoL | End-of-Life |
| EoL-RIR | End-of Life Recycling Input Rate |
| EoL-RR | End-of Life Recycling Rate |
| EPD | Environmental Product Declaration |
| ERI | Economic Risk of Importance |
| EU | European Union |
| FDR | Future Demand Risk |
| FTD | Future Technology Demand |
| GAMe | General Assessment Method |
| GAMo | General Assessment Model |
| GWP | Global Warming Potential |
| HDI | Human Development Index |
| HHI | Herfindahl-Hirschman Index |
| HREE | Heavy Rare Earth Element |
| IRTC | International Round Table on Materials Criticality |
| JRC | Joint Research Centre |
| LCA | Life Cycle Assessment |
| LREE | Light Rare Earth Element |
| MCI | Material Circularity Indicator |
| MCS | Mineral Commodity Summaries |
| NRC | National Research Council |
| PCR | Product Category Rule |
| PGM | Platinum Group Metal |
| PSR | Political Stability Risk |
| REE | Rare Earth Elements |
| RMIS | Raw Materials Information System |
| RO | Resource Value Retention Option |
| RR | Recirculation Risk |
| SDG | Sustainable Development Goal |
| SR | Supply Risk |
| SRM | Strategic Raw Materials |
| SSR | Social Stability Risk |
| USGS | United States Geological Survey |
| WGI | Worldwide Governance Index |

# 1 Introduction

The world's population continues to grow, while demand for limited resources increases. This situation poses a challenge not only to the climate, but also to growing concerns about escalating commodity prices and resource scarcity. In the current economic system, approximately 75% of the material resources used in products and manufacturing processes become waste within a year. If this trend is not reversed within the next five decades, resource demand and waste production could increase tenfold. This highlights the need to re-evaluate the linear economic model and consider replacing expensive primary resources with recycled waste or reusable components.[3]

The *17 Sustainable Development Goals (SDGs)*, adopted by the United Nations General Assembly in 2015, provide a globally binding framework for a sustainable societal orientation. These goals include SDG 12 - 'Responsible Consumption and Production' which aims to steer society towards more mindful sourcing and use of resources in order to reduce waste. To achieve this societal shift and measure progress control by assessment is essential to show the current state of performance.[4]

The assessment aims to provide companies with insights into the circular economy concept. By evaluating their processes and products, they can identify areas for improvement. These assessments also benefit legislation, as they serve as foundational elements for creating a regulatory framework that emphasises the production of more sustainable goods.[5]

## 1.1 Initial situation and problem definition

China supplies 100% of the EU's heavy rare earths, Turkey 98% of the EU's boron and South Africa 71% of the EU's platinum.[6] These facts illustrate a strong dependence on third countries for the import of important raw materials.
This dependency is a problem, the sustainable management of the resources we have is another. The earth's resources are finite. Figure 1.1 aims to show the availability of different elements, represented by the periodic table. Due to supply, there is a deformation in the sizes of the elements. Elements that are stretched are more abundant than those that are compressed. The colour coding indicates

3. I. H. Jaafar et al., "Product Design for Sustainability: A New Assessment Methodology and Case Studies," chap. 2 in *Environmentally Conscious Mechanical Design* (John Wiley Sons, Ltd, 2007), p.3, ISBN: 9780470168202, https://doi.org/https://doi.org/10.1002/9780470168202.ch2.

4. Gertraud Moser, Brigitte Karigl, and Silvia Benda-Kahri, *Grundlagendokument – Entwicklung einer Kreislaufwirtschaftsstrategie*, technical report (2021), p.8, https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0782.pdf.

5. Christoph Kolotzek, *Entwicklung einer nachhaltigkeitsorientierten Rohstoffbewertung zur Unterstützung von Entscheidungsprozessen in Unternehmen* (Springer-Verlag, 2018), p.2, https://doi.org/https://doi.org/10.1007/978-3-658-22392-2.

6. European Parliament; *Infographic - An EU critical raw materials act for the future of EU supply chains*;https://www.consilium.europa.eu/en/infographics/critical-raw-materials/ Accessed on 2023-07-27

how long elements will remain available. Elements in red are at serious risk of running out within the next 100 years. The message is neither comforting nor reassuring. The visual representation of scarce elements is intended to be both a warning and a call to action. The altered periodic table is intended to stimulate dialogue and introspection about redesigning our element use practices and finding ways to use abundant elements for similar functions.[7]

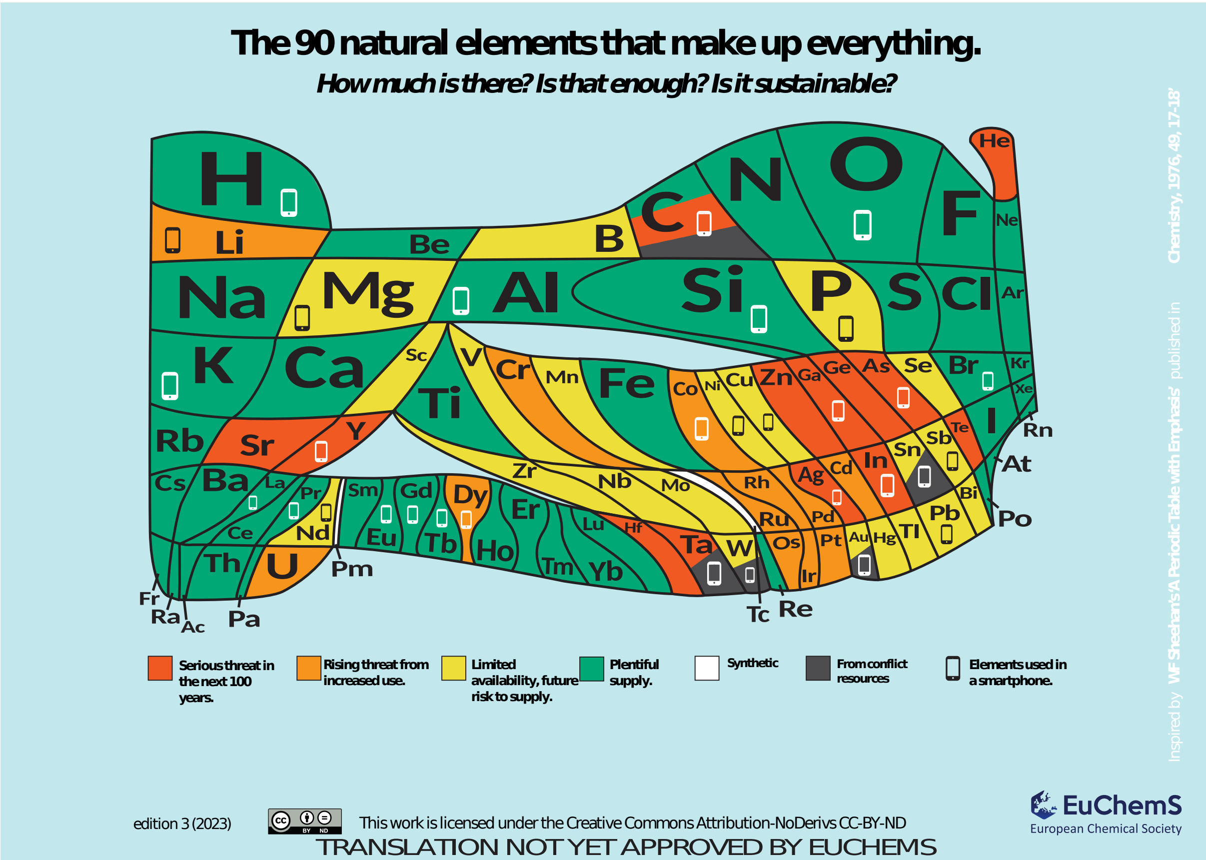



Figure 1.1: EuChemS (EU Chemical Society) periodic table[8]

Currently, 75% of the material resources used in products and manufacturing processes end up as waste within a year.[9] This statistic underlines that our current resource management practices may not be responsible. We are still predominantly operating in a linear economy. The shift to a more circular economy is imperative.

"The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum.

7. Schiphorst Alex; *The Periodic Table of Chemical Elements and us*;https://www.euroscientist.com/the-periodic-table-of-chemical-elements-and-us/ Accessed 2023-07-10
8. Source: https://www.euchems.eu/euchems-periodic-table/ Accessed on 2023-07-12
9. Jaafar et al., "Product Design for Sustainability: A New Assessment Methodology and Case Studies," p.3.
10. Source: Lempers Monique et al., *Fairphone Impact Report 2022*, technical report (April 2022), p.27, https://www.fairphone.com/wp-content/uploads/2023/05/Fairphone-Impact-Report-2022.pdf

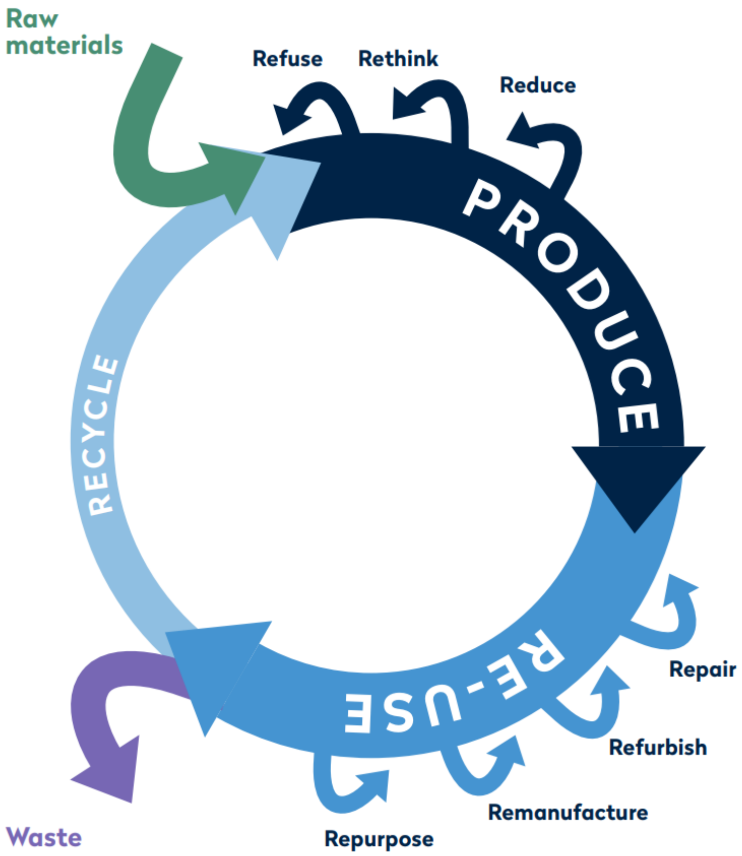



Figure 1.2: Approaches for the circular economy[10]

When a product reaches the end of its life, its materials are kept within the economy wherever possible thanks to recycling. These can be productively used again and again, thereby creating further value."[11] This presents the European Commission's definition of the circular economy.
The central aim of this approach is to maximise the life cycle of products and raw materials, based on the prevention of waste. Resources and materials from products should be kept within the economy at the end of their useful life, creating new value through reuse, repurposing or refurbishment. The circular economy thus stands in direct contrast to the traditional linear economic model, which relies on extensive resource and energy consumption. The circular economy concept is illustrated in Figure 1.2.

Assessment methods aim to measure the current performance of products. By using such methods improvements for products can be found.

11. Source: European Parliament; *Infographic - An EU critical raw materials act for the future of EU supply chains*;https://www.consilium.europa.eu/en/infographics/critical-raw-materials/ Accessed on 2023-07-10

## 1.2 Objectives of the thesis and research questions

A review of the existing literature shows that current research provides a solid foundation for environmental assessment methodologies. Nevertheless a gap in approaches that can assess the environmental performance of products and formulate recommendations for improvement was observed. Consequently, the central research question of this thesis is:

- How can the criticality of raw materials and the circularity of electronic components be assessed and recommend to guidelines for sustainable product design?

In addition, there are a number of other questions that need to be looked at in greater depth. The following sub-questions will be addressed too in this thesis:

- Which raw materials for electronic components such as smartphones are critical within the EU?
- Which factors influence the criticality of raw materials for electronic components and how can they be assessed methodically?
- What factors influence the circularity of electronic products and how can they be assessed methodically?
- What is the correlation between the criticality of raw materials and the circularity of electronic products?
- Which design parameters influence the raw material criticality of electronic products?
- What design parameters influence the circularity of electronic components?
- Which design guidelines support sustainable product design in the planning or revision phase?
- What interpretative insights can be gained by applying design guidelines to a smartphone as an illustrative example?

## 1.3 Structure and composition of the thesis

This thesis explores and merges two distinct assessment methodologies. The first method involves assessing the criticality of raw materials. The second focuses on assessing the circularity of products and components.

Although separate in their objectives, both methods follow a common structure facilitated by the development of a General Assessment Model (GAMo). This GAMo serves as a foundation, which is then tailored to the specifics of each assessment method.

To apply the assessment methods to a real product, the Fairphone 4 is chosen as subject. It is a smartphone that embodies a fair and sustainable company ethos. The results obtained demonstrate the practical application of the assessment methods and highlight how they methods can be used effectively. A comprehensive analysis of the results, as applied to the Fairphone 4, is also carried out.

Through the assessment process, opportunities for method refinement and areas of success are identified. In addition, the thesis looks at potential avenues for future improvement in the context of environmental performance assessment methodologies.

## 2 Theoretical background

Assessment methods are used to analyse and evaluate the effectiveness, quality or performance of techniques, processes, products or other entities. These methods allow to obtain objective and comparable results, which can help making informed decisions, identifying potential for improvement, and enhancing efficiency.
Before developing assessment methods, acquiring relevant background knowledge is a crucial step. It is essential to determine whether there are any established methods. If so the differences between these methods needs to be analysed. In addition, it is important to assess the potential value of introducing a new method and to understand what benefits it would provide.

The development of assessment methods is closely related to the norms and standards that reflect the current state of research. Therefore, it is necessary to consider how to apply ISO norms and standards within the specific context and how they can provide support.
If no existing ISO norms and standards are relevant to the specific evaluation method it is necessary to investigate whether such standards are currently developed or planned in the future. In that case, it is important to determine the expected publication date and whether there is any existing content that could assist in developing a new method.

This chapter explores the theoretical foundations of evaluation methods. The research intends to identify areas where similar evaluation methods already exist and whether they can be adopted or used as a basis for guidelines.

### 2.1 Criticality of raw materials

In this chapter, the concept of 'criticality' of raw materials will be precisely defined. The term is increasingly appearing in the literature and gaining importance. An overview of existing methods for assessing the criticality of raw materials is given in the further part of the chapter.

#### 2.1.1 Definition and concept of criticality

The term 'criticality' in the context of raw materials was first used by the American government in 1939. It was introduced in the *Critical Material Stockpiling Act*,[12] which defined 42 raw materials of military importance. The purpose of the act was to ensure independent access to these materials in times of military emergency. The stockpiling of critical materials mentioned in the act has continued

12. Legislative Council, *Strategic and critical materials stock piling act*, technical report (Technical Report, 1939), https://www.govinfo.gov/content/pkg/COMPS-674/pdf/COMPS-674.pdf.

till today, as evidenced by the 2015 report of the U.S. Secretary of Defense, which announced the further expansion of stockpiles of manganese, tungsten, beryllium and cobalt.[13]

The criticality of raw materials can be assessed comprehensively by considering the importance of a particular resource and the risks associated with it throughout its production, use and end-of-life stage. Such assessments are interdisciplinary in nature, encompassing various indicators to analyse supply risk, environmental impact and vulnerability to supply constraints. The area of raw material criticality examines the economic and technical dependence on specific materials and the likelihood of supply disruptions within a specified time frame. These assessments play a key role for industry and policy makers, influencing material selection, design processes, investment decisions, trade agreements, cooperation strategies, and the prioritisation of research projects and policy agendas to increase transparency within value chains.[14]

Criticality assessments are carried out at different levels: for a specific product, technology, company, country, region or even globally. The criticality of a raw material can be assessed in the short term (e.g. a few years) or in the long term (over several decades). The methods used to assess criticality cover a wide range of indicators, including geological, technological, geopolitical, social and environmental aspects. Due to the different perspectives and motivations underlying such studies, there are significant differences in the processes of identifying Critical Raw Materials (CRMs) and their outcomes.[15]

Recently, the concept of raw material criticality has also found its way into the peer-reviewed literature. Meta-studies have been carried out with the aim of organising and summarising the existing scientific work and evaluation methods on this subject (see *Helbig et al. 2016*,[16] *Schrijvers et al. 2020*,[17] *Sonnemann et al. 2015*[18] or *Tuma et al. 2014*[19]).

Figure 2.1 shows the countries with the largest shares in the production of critical raw materials. This

13. Benjamin Achzet and Christoph Helbig, "How to evaluate raw material supply risks—an overview," *Resources Policy* 38, no. 4 (2013): p.435, https://www.sciencedirect.com/science/article/pii/S0301420713000445.
14. Christoph Helbig et al., "How to evaluate raw material vulnerability-an overview," *Resources Policy* 48 (2016): p.13, https://doi.org/http://dx.doi.org/10.1016/j.resourpol.2016.02.003.
15. Dieuwertje Schrijvers et al., "A review of methods and data to determine raw material criticality," *Resources, Conservation and Recycling* 155 (2020): p.2, ISSN: 0921-3449, https://doi.org/https://doi.org/10.1016/j.resconrec.2019.104617; Berlin Beuth Verlag, *VDI 4800 Blatt 2:2018-03 Resource efficiency - Evaluation of raw material demand*, 2018, p.14, https://www.vdi.de/richtlinien/details/vdi-4800-blatt-2-ressourceneffizienz-bewertung-des-rohstoffaufwands.
16. Helbig et al., "How to evaluate raw material vulnerability-an overview."
17. Schrijvers et al., "A review of methods and data to determine raw material criticality."
18. Guido Sonnemann et al., "From a critical review to a conceptual framework for integrating the criticality of resources into Life Cycle Sustainability Assessment," *Journal of Cleaner Production* 94 (2015): 20–34, ISSN: 0959-6526, https://doi.org/https://doi.org/10.1016/j.jclepro.2015.01.082.
19. Axel Tuma et al., "Nachhaltige Ressourcenstrategien in Unternehmen: Identifikation kritischer Rohstoffe und Erarbeitung von Handlungsempfehlungen zur Umsetzung einer ressourceneffizienten Produktion," 2014, https://opus.bibliothek.uni-augsburg.de/opus4/frontdoor/deliver/index/docId/51852/file/DBU-Abschlussbericht-AZ-30438.pdf.

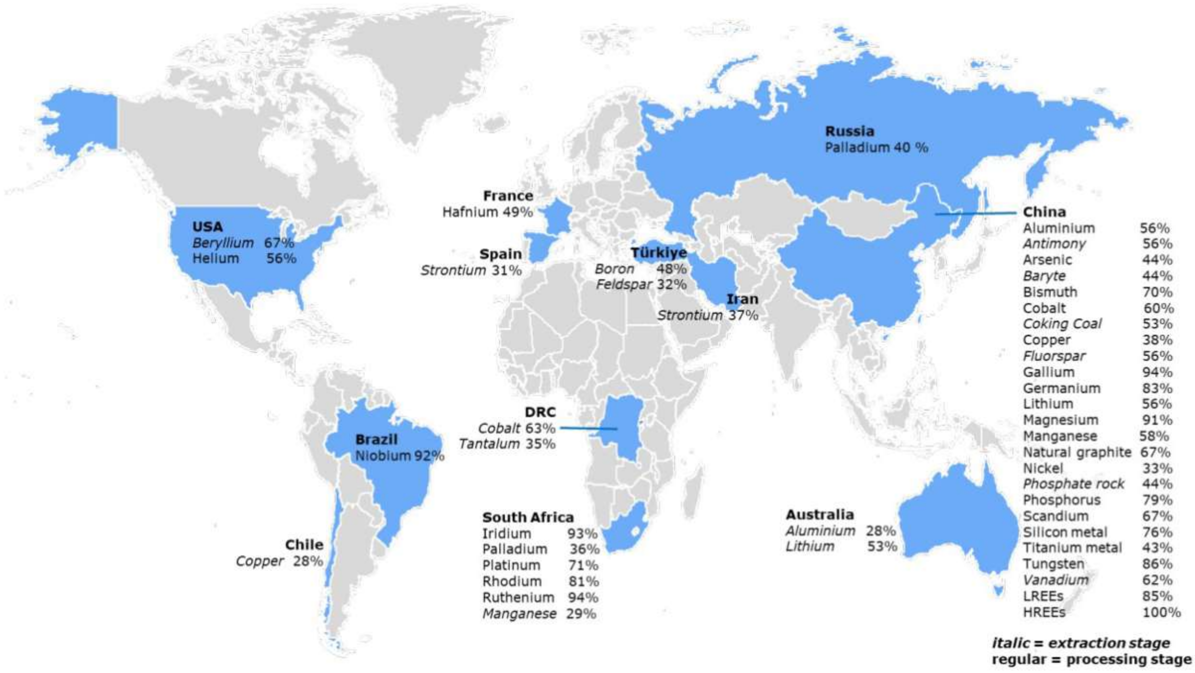



Figure 2.1: Countries with largest share of global CRM supply[20]

chart is intended to illustrate one of many aspects why the criticality of raw materials is becoming increasingly important. It shows that China has by far the largest share of these materials, while Europe has very few relevant shares. This creates dependencies on other countries. To address this problem of dependencies and to ensure the EU's access to secure, diversified, affordable and sustainable supplies of critical raw materials, the *European Critical Raw Materials (CRM) Act* was developed. The CRM Act demonstrates that policymakers are aware of the challenges related to critical raw materials and outlines the steps that are being taken. The March 2023 CRM Act report identifies a list of strategically important raw materials that are critical to Europe's green and digital ambitions, as well as defence and space applications, while being vulnerable to potential supply risks in the future. It also sets specific targets to achieve greater self-sufficiency and secure and resilient supply chains for the EU's critical raw materials by 2030. These targets include ensuring that domestic capacity covers at least 10% of the EU's annual consumption for extraction, at least 40% for processing and at least 15% for recycling, with no more than 65% of the EU's annual consumption of each strategic raw material at any relevant stage of processing coming from a single third country.[21]

To achieve these defined goals and monitor progress, the availability of data is essential. Data are mainly derived from existing evaluation methods for assessing the criticality of raw materials. The

20. Source: European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report* (Publications Office, 2023), fig.B; p.7, https://doi.org/doi/10.2873/725585
21. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661 Accessed 2023-07-14

next chapter provides an overview of relevant assessment methods and how they work.

### 2.1.2 Methods for measuring criticality

A number of raw material criticality assessment methods have been developed by governments, companies and researchers. The first institution to publish a raw material criticality assessment methodology was the U.S. National Research Council (NRC) in 2008. The NRC methodology defined a list of raw materials critical to the U.S. economy and assessed the supply risk and impact of supply restrictions. This assessment relied primarily on subjective expert judgement and was the foundation for all subsequent methodologies.[22]

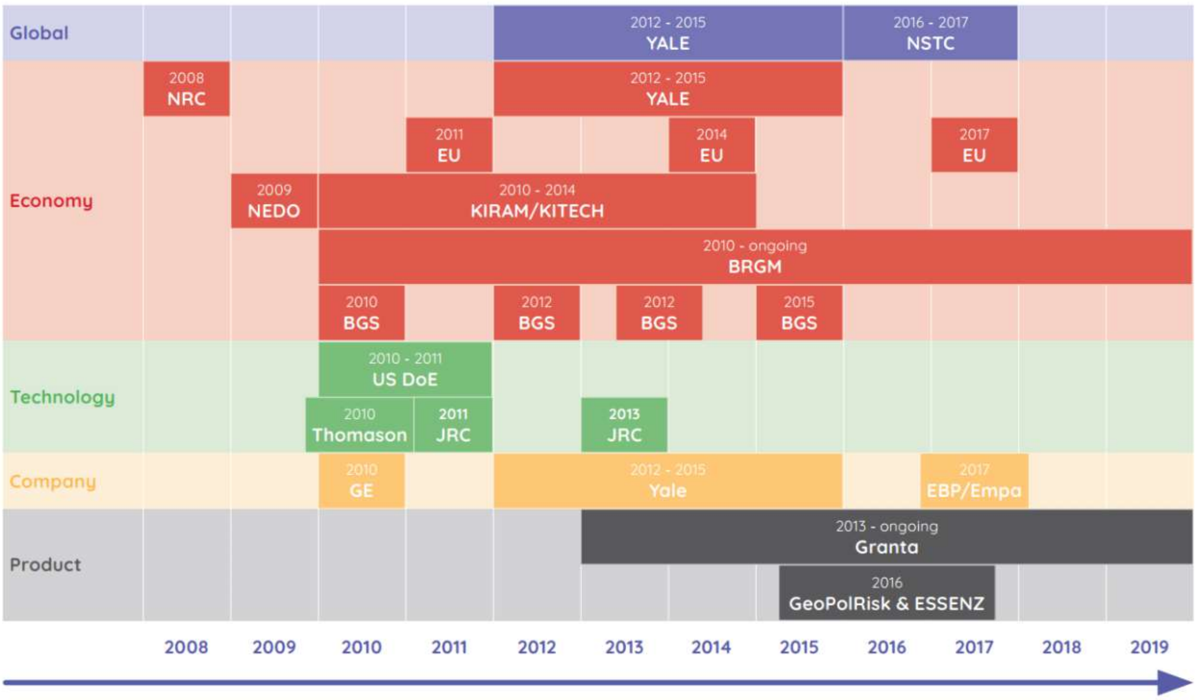



Figure 2.2: Timeline and scope of prominent criticality assessment methods[23]

Figure 2.2 provides an overview of the most prominent and frequently cited methods that have emerged in subsequent years up to 2019. Some of the most prominent methods are discussed more in detail below, including the YALE, USGS, EU CRM, Augsburg and GRANTA methods. In addition, the VDI 4800 method, which is similar to the EU method but is a guideline in the German context, is discussed. Each method focuses on a different target group and uses different assessment methods. In addition, the time frame of the data considered for the evaluation varies. The time frame indicates how many years of data are considered. Some methodologies are well established and regularly

22. D Schrijvers et al., "Material criticality: an overview for decision-makers," 2020, fig.3; p.5, https://irtc.info/wp-content/uploads/2020/05/IRTC-Brochure-1.pdf.
23. Source: Schrijvers et al., "A review of methods and data to determine raw material criticality," fig.3; p.5

updated (EU, GRANTA, USGS), while others are no longer being developed (YALE, NRC).
Assessment methods that are not regularly updated run the risk of relying on outdated data. The data acquisition for the assessment is generally one of the most crucial elements of the assessment method. Some methods rely solely on quantitative values, while others incorporate expert judgement.
The strengths and weaknesses of these methods will be discussed later. It should also be noted that *Schrijvers et al. 2020* compiled an extensive collection of additional material criticality assessment methods. The list is available in the supplementary material of the *International Round Table on Materials Criticality (IRTC)* project.[24] It is referenced in this paper as additional literature only.



**YALE Methodology**

The YALE Methodology was developed by the Center for Industrial Ecology at YALE University. The methodology was developed between 2012 and 2015 and made accessible through various publications. The initial approach of the YALE methodology was described in *Graedel et al. 2012*,[25] while the final assessment methodology was presented in the paper by *Graedel et al. 2015*.[26] There are no plans for new releases of the YALE methodology. The aim of the YALE Method was to create a consistent and defensible methodology suitable for different levels and types of users. The methodology retains the two axes of the NRC assessment methodology and adds a third axis (environmental implications) (see Figure 2.3).[27]

During the research for this thesis, it was observed that the work of *Graedel et al. 2012* and *Graedel et al. 2015* was remarkably frequently cited by subsequent assessment methods, with their data and indicators being adopted. The Augsburg Methodology is also based on the YALE method.

The YALE method assesses 62 metals and metalloids from the periodic table. The parameters are aggregated hierarchically and finally summarised in three dimensions (vulnerability to supply restrictions, supply risk, environmental implications). For each of the three axes (dimensions), the indicators are scored on a Criticality Score Scale from 0 to 100. The Criticality Score Scale per axis is determined by taking the average of the indicators. There is no weighting of the indicators, as it is the decision of the specific users to apply weighting, if desired. Consequently, there is no specific identification of critical/non-critical thresholds, as different users have different objectives, perspec-

24. Schrijvers et al., "Material criticality: an overview for decision-makers."
25. T. E. Graedel et al., "Methodology of Metal Criticality Determination," *Environmental Science & Technology* 46, no. 2 (2012): 1063–1070, https://doi.org/10.1021/es203534z.
26. T. E. Graedel et al., "Criticality of metals and metalloids," *Proceedings of the National Academy of Sciences* 112, no. 14 (2015): 4257–4262, https://doi.org/10.1073/pnas.1500415112.
27. Tom Graedel, *Yale methodology [2011-2015]*, Presented at the Resources for Future Generations 2018, Vancouver, June 2018, https://irtc.info/vancouver2018/.
28. Source: Graedel et al., "Criticality of metals and metalloids," fig.2; p.4258

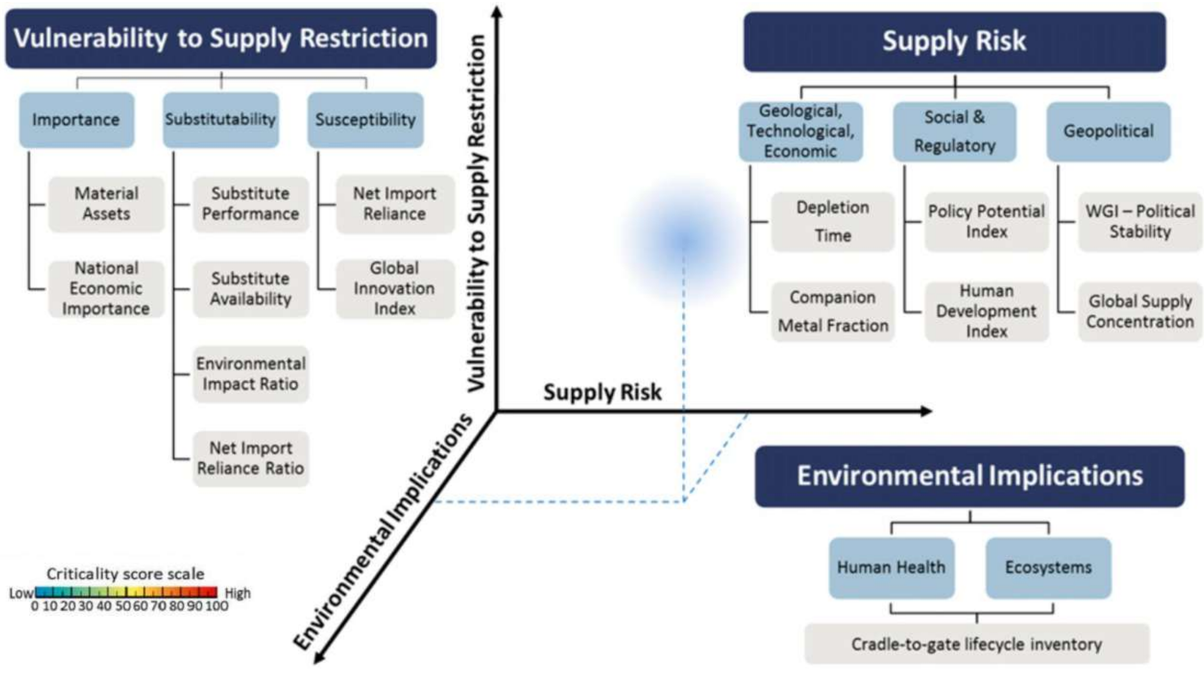



Figure 2.3: Methodology of the YALE Criticality Assessment at the national level of *Graedel et al. 2015*[28]

tives and time frames.[29]

The results of the YALE method are limited by a lack of data, particularly for co-products. During the development of the method, feedback from companies was difficult to obtain, although it would have helped to develop the method further. Many companies feared disclosing sensitive data and therefore often did not provide feedback.[30]

### Critical Minerals List (CML) of the United States Geological Survey (USGS)

The U.S. Critical Minerals List (CML) was first published in 2018 and updated in 2022. It is compiled by the United States Geological Survey (USGS) on behalf of the U.S. Department of the Interior, which is required to review and revise the CML at least every three years. The primary purpose of the CML is to identify critical minerals of particular importance to the economic security and national defence of the United States. The CML specifies which data of critical materials data should be collected and compiled.[31] The latest CML for 2022 includes 50 commodities, 15 more than in 2018.
Data for commodities listed in the CML are collected and updated monthly and published on the USGS website[32]. In addition to the CML commodities, data are collected for other minerals, resulting

29. Graedel et al., "Criticality of metals and metalloids," fig.2; p.4257-4258.
30. Graedel, *Yale methodology [2011-2015]*.
31. Nedal T Nassar and Steven M Fortier, *Methodology and technical input for the 2021 review and revision of the US Critical Minerals List*, technical report (US Geological Survey, 2021), p.1, https://doi.org/https://doi.org/10.3133/ofr20211045.
32. https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals Accessed on 2023-07-15

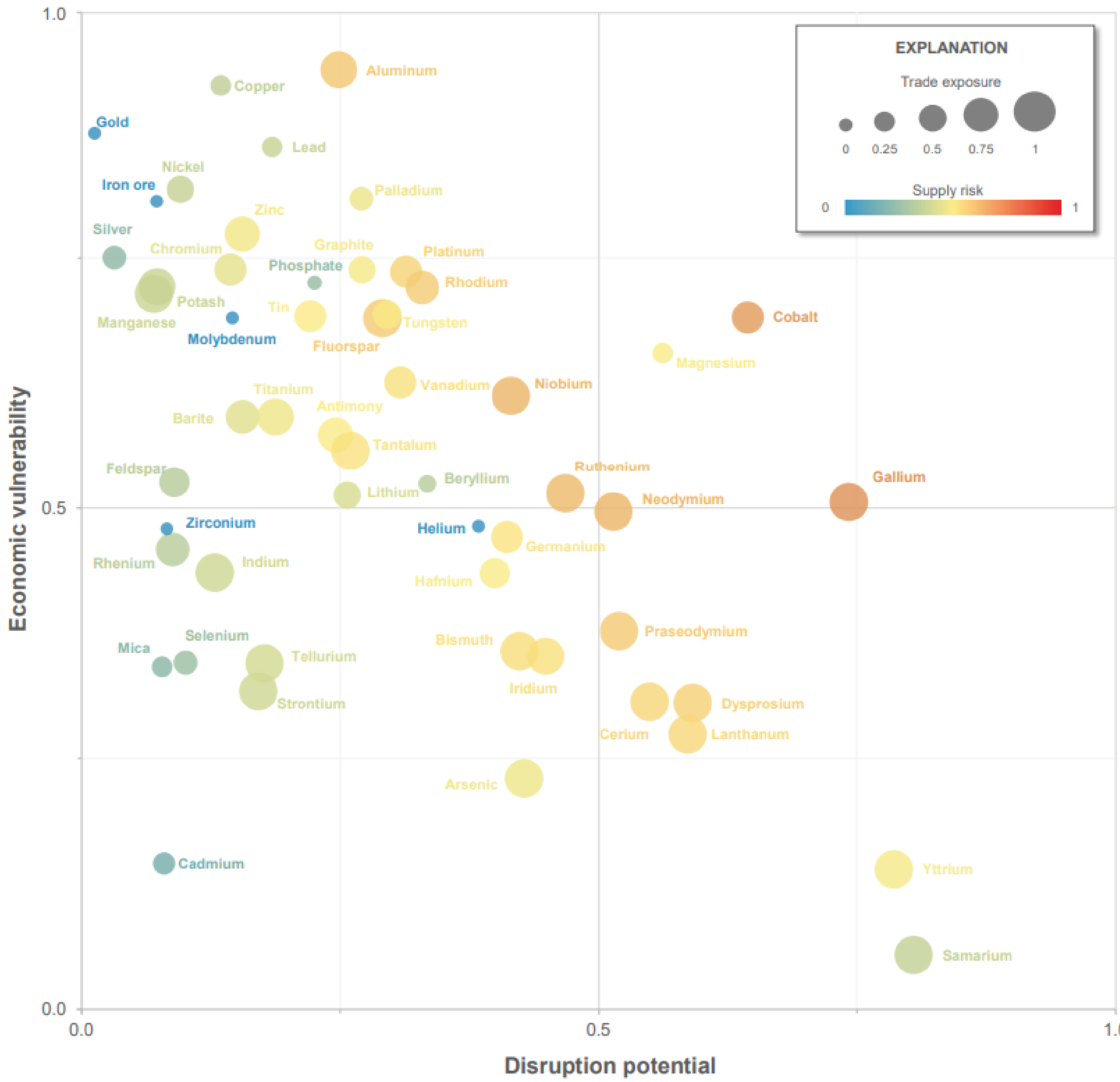



Figure 2.4: U.S. Geological Survey (USGS) assessment of mineral supply risk for materials recommended for inclusion on the Critical Minerals List[35]

in 90 individual minerals and materials covered in the *2023 Mineral Commodity Summaries (MCS)*[33] through two-page summaries. The information includes events, trends and issues for each mineral commodity, as well as discussions and tabular presentations of domestic industry structure, government programs, tariffs, 5-year salient statistics and world production, reserves and resources.[34] The underlying methodology for the CML was developed in 2021. The methodology uses Disruption Potential (DP), Economic Vulnerability (EV) and Trade Exposure (TE) to calculate an overall Supply

33. U.S. Geological Survey, *Mineral commodity summaries 2023: U.S. Geological Survey*, technical report (USGS, 1939), https://doi.org/https://doi.org/10.3133/mcs2023.
34. U.S. Geological Survey, *Mineral Commodity Summaries 2023*, technical report (2023), p.3, https://doi.org/https://doi.org/10.3133/mcs2023.
35. Source: Nassar and Fortier, *Methodology and technical input for the 2021 review and revision of the US Critical Minerals List*, fig.2; p.10

Risk (SR) for various mineral commodities. Supply risk ranges from 0 (low) to 1 (high) and is calculated as the geometric mean of the three components as follows:

$SR_{i,t} = \sqrt[3]{DP_{i,t} \cdot TE_{i,t} \cdot EV_{i,t}}$ (with commodity i and year t).

This formula calculates the SR per year. Figure 2.4 shows the three components used to calculate the SR. The two axes represent EV and DP, and the diameter of the data point for each commodity reflects the TE. The SR is indicated by colour coding.

To obtain the final risk score for a commodity, a weighted average of the SRs over the last few years is calculated. For example, the weighted average is calculated based on the following weightings for the supply risk scores for 2018, 2017, 2016 and 2015: 40%, 30%, 20% and 10%. This approach seeks to strike a balance between considering recent events and long-term trends.

Commodities with a final risk score bigger than 0.4 are recommended for inclusion in the CML.[36]

### European Union CRM Methodology

The first assessment of Critical Raw Materials (CRM) in the European Union was launched in 2011 as part of the 2008 EU Raw Materials Initiative (RMI). The list of CRM is updated every three years and the latest list available is from 2023.[37]

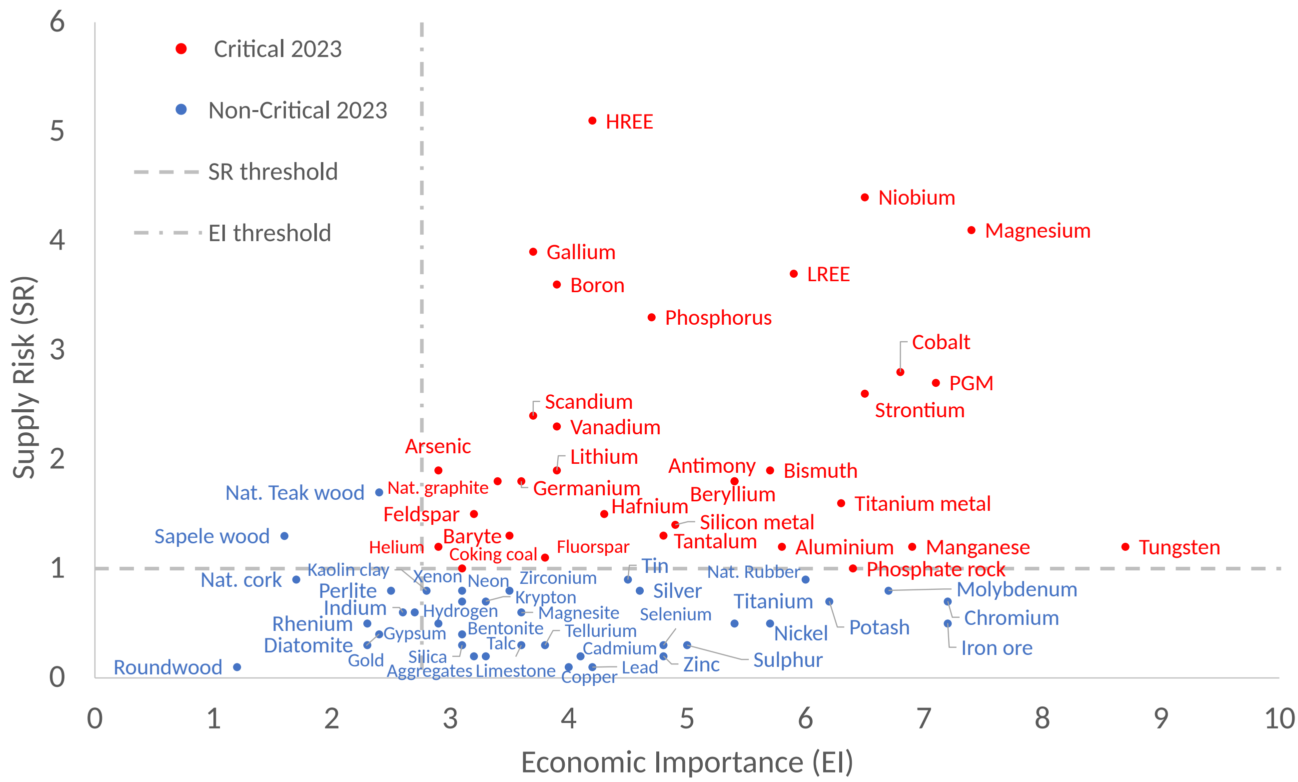



Figure 2.5: Criticality matrix of the EU CRM Report 2023[38]

36. U.S. Geological Survey, *Mineral Commodity Summaries 2023*, p.5.
37. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.1-2.
38. Adapted from: European Commission et al., fig.A; p.5

The development of the CRM list methodology was a joint effort between the European Union and the Ad hoc Working Group on Defining Critical Raw Materials (AHWG) in 2017. The methodology uses a criticality matrix, with supply risk (SR) values on the y-axis and economic importance (EI) values on the x-axis. Figure 2.5 illustrates the criticality matrix of the 2023 EU CRM report. Materials with SR values $\geq$ 1.0 and EI values $\geq$ 2.8 are classified as critical. Notably, in the 2023 EU CRM report, Nickel and Copper are considered Strategic Raw Materials (SRM) and are classified as critical despite having an SR < 1.0. Critical materials are marked with red dots in the criticality matrix, while others are marked with blue dots.[39]

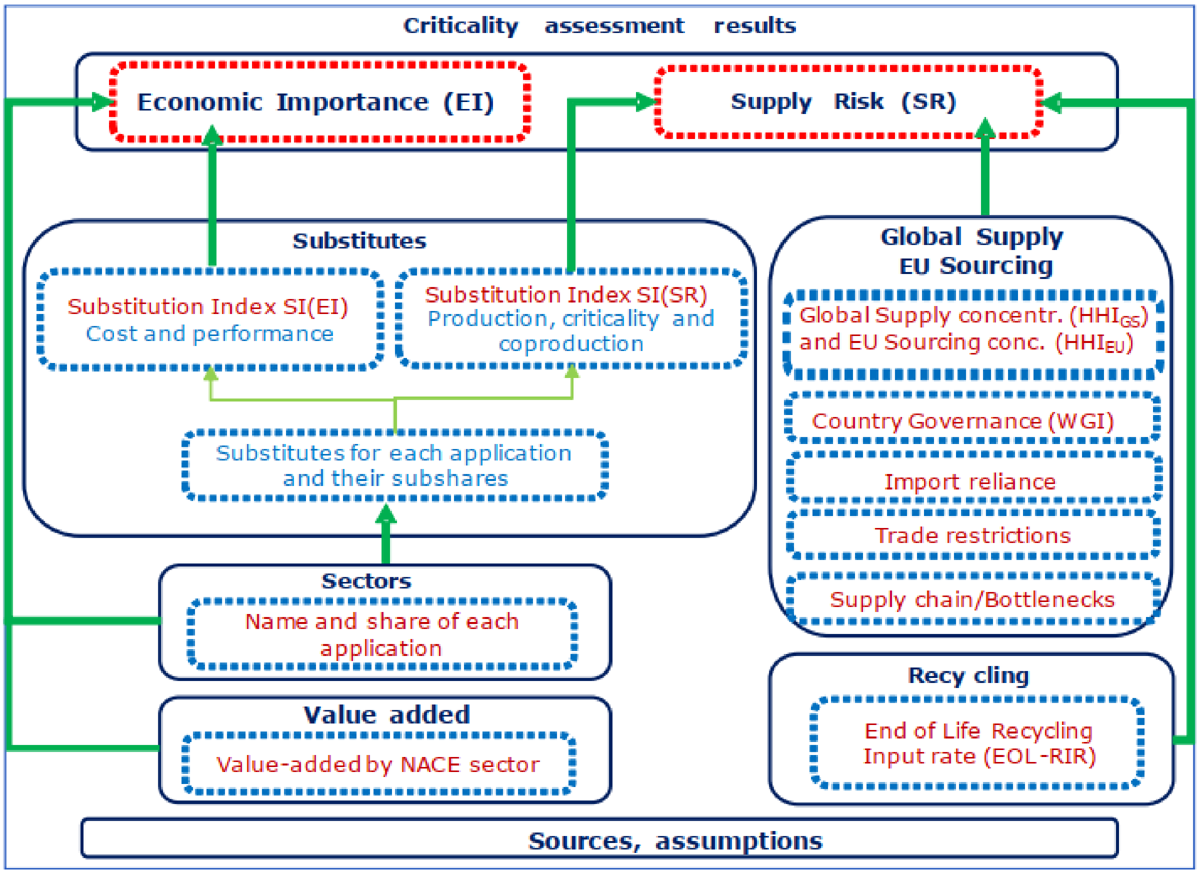



Figure 2.6: Overall structure of the EU CRM methodology[40]

The overall structure of the EU CRM methodology is shown in Figure 2.6. The methodology involves the calculation of supply risk and economic importance using the formulas presented in Equation 2.1 and Equation 2.2.

Supply risk refers to the assessment of the risk that the supply of a specific raw material is threatened by various factors such as geopolitical instability, limited reserves, difficult mining conditions or trade restrictions.

39. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.3.
40. Source: European Commission et al., fig.1; p.18

Economic importance assesses the importance of a raw material to European industry and the European economy, taking into account factors such as market volume, the number of applications in different industrial sectors and the value chain.[41]

Considers the **source diversity**

Considers **recycling**

Considers the availability of **substitutes**

$$SR = \left[ \left(HHI_{WGI,t}\right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t}\right)_{EU} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot \left(1 - EoL_{RIR}\right) \cdot SI_{SR} \tag{2.1}$$

$HHI_{WGI,t}$ ... Herfindahl-Hirschman Index of World Governance Index of countries
$GS$... Global Sourcing
$EU$... EU sourcing
$IR$... Import Reliance
$EoL_{RIR}$... End-of-Life Recycling Input Rate
$\mathrm{SI_{SR}}$ ... Substitution Index

$$\mathrm{EI} = \sum_{\mathrm{S}} \left(\mathrm{A_S} \cdot \mathrm{Q_S}\right) \cdot \mathrm{SI_{EI}} \tag{2.2}$$

$\mathrm{A_S}$ ...share of end-use of material in a NACE sector
$\mathrm{Q_S}$ ...NACE sector's gross value added (GVA) in M€
$\sum_{\mathrm{S}}$ ...sum of NACE sectors
$\mathrm{SI_{EI}}$ ...Substitution Index

Considers the **economic weight** into different sectors

Considers the existence of **possible substitutes** for the material

The EU CRM methodology relies exclusively on public data, which poses challenges in terms of data availability, especially for recycling (End-of-Life Recycling Input Rate) and specific metals such as scandium and gallium. Data quality and prioritisation are also issues, given the diversity of sources from the European Union, international organisations and the private sector. The methodology suggests a prioritisation of data sources (EU official data > EU national data > non-EU/international data > industry data). Data from the last five years are averaged and used for calculations. The EU is considering working with Eurostat to create unified databases to provide consistent data from national institutions for assessments.[42]

In addition, the combination of trade and production data for certain commodities, such as Rare Earth Elements (REEs), taking into account different stages of the supply chain, presents complexities that require careful consideration for accurate and comprehensive criticality assessments.[43]

41. European Commission et al., *Methodology for establishing the EU list of critical raw materials : guidelines* (Publications Office, 2017), p.3-18, https://doi.org/doi/10.2873/769526.
42. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.18.
43. Milan Grohol, *Methodology for establishing the EU list of Critical Raw Materials*, Presented at the Resources for Future Generations 2018, Vancouver, June 2018, https://irtc.info/vancouver2018/.

### VDI 4800

VDI 4800 is a guideline for the quantification and evaluation of individual substances, products, product groups or entire company divisions in order to make them comparable and assessable. Sheet 1 of VDI 4800[44] outlines the objectives, methodology of the assessment, implementation strategies and resource efficiency measures. Sheet 2 of VDI 4800[45] describes the calculation and limits of calculation of parameters for determining cumulative raw material demand and raw material criticality. The assessment is based on two dimensions: supply risk and vulnerability. Table 2.1 illustrates the hierarchical structure of categories, criteria, indicators and influencing factors for both dimensions of the VDI assessment methodology.

| **Supply Risk dimension of criticality** | | |
|---|---|---|
| **Categories** | **Criteria** | **Indicator** |
| Geological, technical and structural criteria | static range | ratio of reserves to global annual production |
| | co-product/by-product dependency | level of companionality |
| | recycling | spread of functional end-of-life recycling technologies |
| | logistic constraints | economic viability of storage and transport |
| | constraints due to natural disasters | geographical distribution of natural deposits/ growing regions |
| Geopolitical and regulatory criteria | country concentration of reserves | Herfindahl-Hirschman Index of reserves |
| | country concentration of production | Herfindahl-Hirschman Index of country concentration of production |
| | geopolitical risks of global production | political country risk |
| | regulatory situation for raw material projects | regulatory country risk |
| Economic criteria | company concentration of global production | Herfindahl-Hirschman Index of companies |
| | global demand impetus | level of demand growth |
| | substitutability | technical and economic feasibility of substitutions in main applications |
| | raw material price fluctuations | annualised price volatility |
| **Vulnerability dimension of criticality** | | |
| **Categories** | **Influencing factors for vulnerability** | |
| Level of exposure | share of risk-exposed raw material in total contribution margin | |
| | importance of a raw material to the product function/substitutability in the product | |
| | internal consumption of a raw material | |
| | raw material consumption relative to global annual production | |
| | purchase value of a raw material relative to the total raw material purchase value | |
| Strategic adjustment options | access to and feasibility of substitution solutions | |
| | ability to innovate | |
| | availability of a procurement strategy | |
| Operative and tactical adjustment options | ability to pass through raw material prices | |
| | bargaining potential/market power vis-a-vis suppliers | |
| | availability of raw material price hedging instruments | |
| | appropriate inventory levels/stockpiling | |

Table 2.1: Hierarchical structure of the categories of the supply risk and vulnerability dimensions of the VDI 4800 assessment methodology[46]

Indicators in the VDI 4800 are quantitatively classified on a 4-level scale (0; 0,3; 0,7; 1). The classification of indicator levels varies between qualitative and quantitative information in the VDI. The methodology specifies standardised measurement procedures for supply risks. For vulnerability indi-

44. Berlin Beuth Verlag, *VDI 4800 Blatt 1:2016-02 Resource efficiency - Methodological principles and strategies*, 2016, https://www.vdi.de/richtlinien/details/vdi-4800-blatt-1-ressourceneffizienz-methodische-grundlagen-prinzipien-und-strategien.
45. Beuth Verlag, *VDI 4800 Blatt 2:2018-03 Resource efficiency - Evaluation of raw material demand*.
46. Adapted from Beuth Verlag, table.1,15; p.18,34

cators, the guideline proposes a classification and possible measurement instructions, but the assessment remains subjective and relies heavily on company data. For practical application, the guideline suggests numerous public data sources like EU, USGS, World Mining Data and more.[47]

The VDI 4800 methodology is aimed at responsible parties for resource efficiency in various sectors, including production, procurement, R&D, industry associations, consultancies, research organisations, governments and public administrations. The methodology offers flexibility in the assessment of criticality, allowing for adaptation with different indicators based on a company's specific needs. However, for some indicators, current data quality and coverage may not be sufficient to produce meaningful results. For example, data on reserves for some materials are not sufficiently covered by publicly available sources.[48]

#### Augsburg Methodology

The Augsburg Methodology was developed by the Chair of Production & Supply Chain Management at the University of Augsburg. It uses an AHP (Analytic Hierarchy Process) approach and is structured into three sustainability dimensions: supply risk, environmental dimension and social dimension. Each dimension is further subdivided into categories and indicators. The overall hierarchy structure of the Augsburg Methodology is shown in Figure 2.7.

To assess the indicators, each indicator score is transformed to a scale of 0-100. Several indicators are combined into categories, and several categories are then grouped under the dimensions. Hierarchical scaling is achieved using a weighted mean, with weights based on expert estimates derived from pairwise comparisons of indicators or categories. For each new product to be assessed new weights of indicators and categories must be generated.[49]

Quantitative data for the assessment indicators are obtained from research reports (e.g. WHO), public databases or public institutional reports. The paper by *Kolotzek et al. 2018* applies the methodology to the materials aluminium, niobium and tantalum. The results of the paper are shown in Figure 2.8.[50]

The Augsburg Methodology is aimed at companies and provides a flexible approach to criticality assessment. The methodology can be adapted and customised according to a company's specific

47. Beuth Verlag, *VDI 4800 Blatt 2:2018-03 Resource efficiency - Evaluation of raw material demand*, p.51.
48. Schrijvers et al., "A review of methods and data to determine raw material criticality," supplementary material.
49. Christoph Kolotzek et al., "A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications," *Journal of Cleaner Production* 176 (2018): p.569-572, ISSN: 0959-6526, https://doi.org/https://doi.org/10.1016/j.jclepro.2017.12.162.
50. Kolotzek et al., p.574.
51. Source: Kolotzek et al., fig.2; p.570

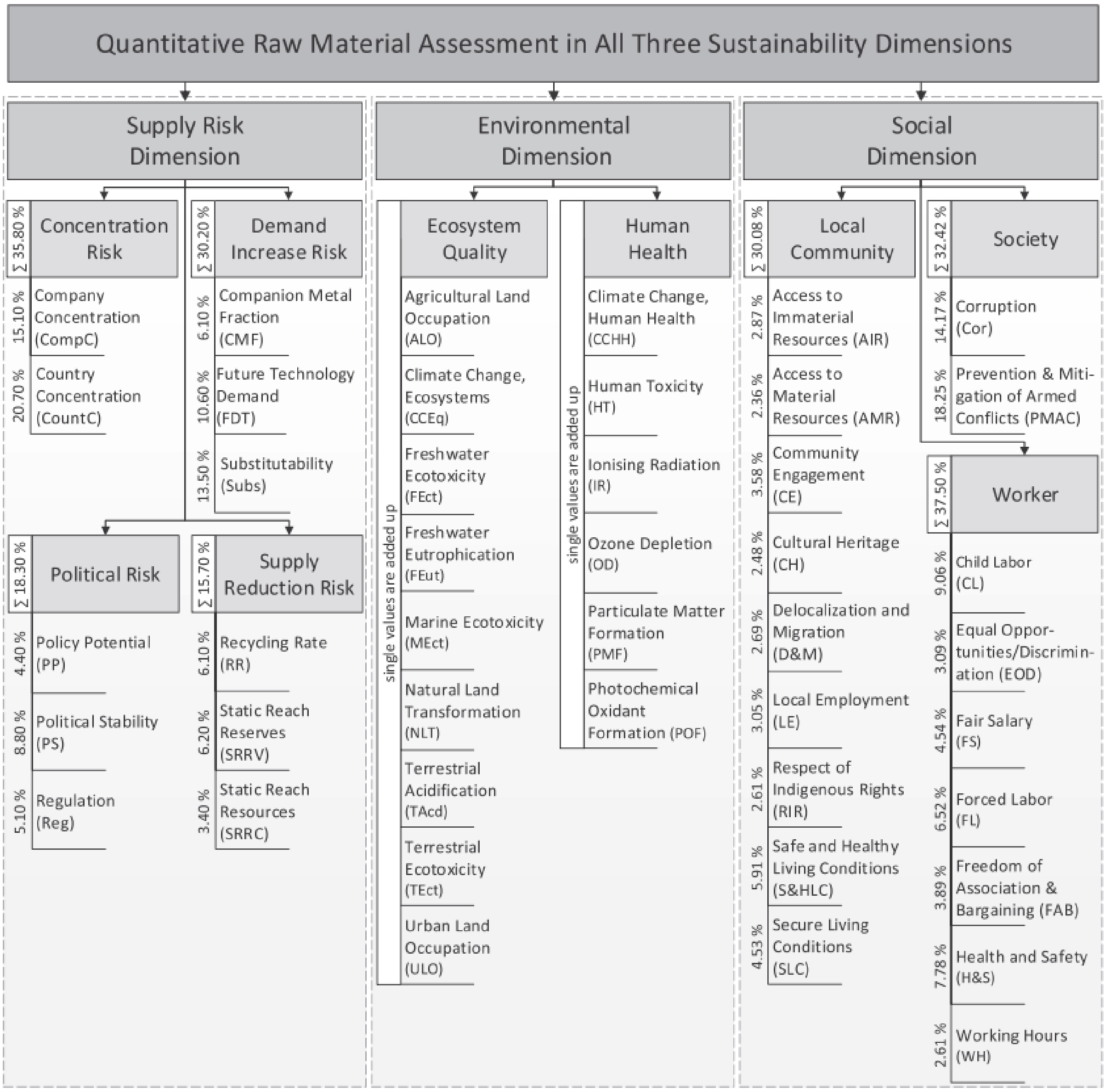



Figure 2.7: Structure of the quantitative assessment model with corresponding weighting of the Augsburg criticality assessment methodology[51]

needs. Expert consultation is essential to determine the weighting of indicators and categories for each assessment. When assessing social indicators, it is recommended to regionalize mine-specific indicators for environmental and social aspects. This means that, ideally, each mine from which a company extracts materials should be assessed individually, as local conditions can vary significantly.[52]

52. Axel Tuma, *Methodology: Stakeholder-oriented approach, Assessment of Technologies and integration of a Social Dimension*, Presented at the Resources for Future Generations 2018, Vancouver, June 2018, https://irtc.info/vancouver2018/.
53. Adapted from: Kolotzek et al., "A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications," fig.3; p.574

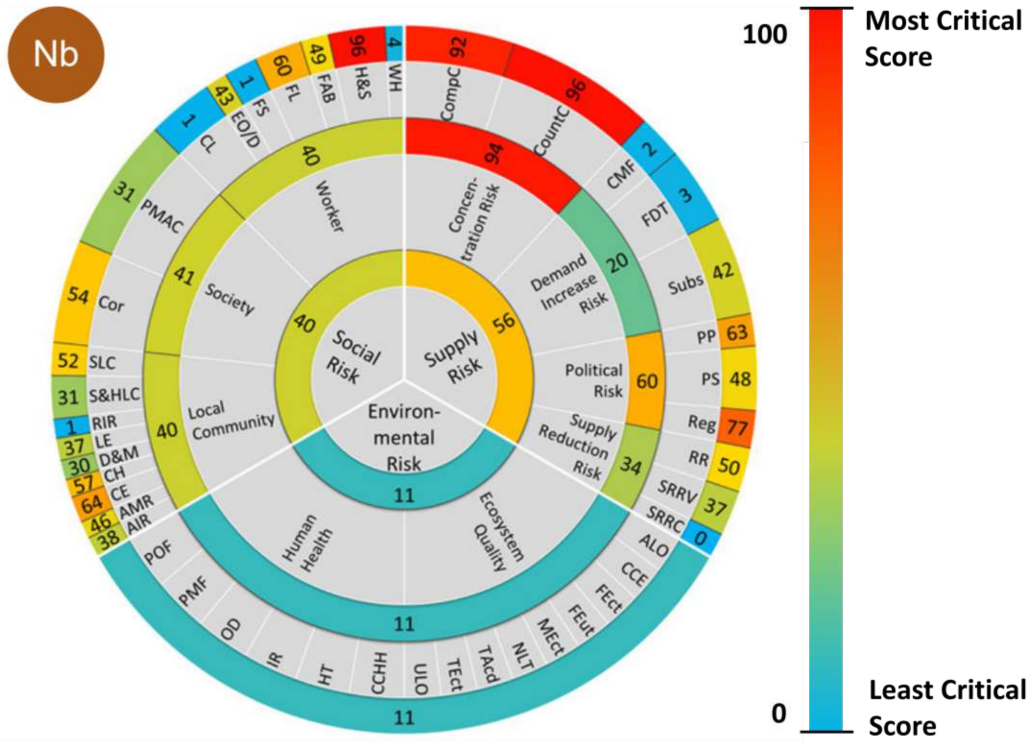



Figure 2.8: Assessment results of the Augsburg Methodology for niobium[53]

**Granta Design Product Risk**

Granta Design Product Risk has been developed in collaboration with the EMIT (Environmental Materials Information Technology) consortium. It is a data library (GRANTA MI) covering 65 abiotic elements, 10500 substances and over 4000 commercially available materials. The datasets include risk-based indicators for restricted substances, critical and conflict minerals, environmental and economic indicators, and product circularity metrics. The library is maintained as a service to Granta's clients as a module.

The module is used to identify risks for materials and products using bill of materials analysis tools via web applications or Computer Aided Design (CAD) plug-ins. By implementing the methodology in CAD software and providing real-time results during product development, the user's materials education is enhanced. The indicators assessed include annually maintained critical and conflict mineral risks such as supply monopoly risk, geopolitical risk, environmental country risk, conflict mineral risk (data taken from Dodd Frank and EU legislation), 5-year price volatility/variation and crustal abundance. In addition, environmental impact risks such as energy consumption, $CO_2$ emissions and water consumption of production are assessed using reference data from the Ecoinvent database.

54. Source: James RJ Goddin, "Identifying supply chain risks for critical and strategic materials," *Critical Materials-Underlying Causes and Sustainable Mitigation Strategies; World Scientific Publishing Co. Pte. Ltd.: Singapore*, 2019, fig.7.3; p.123, https://doi.org/https://doi.org/10.1142/9789813271050_0007

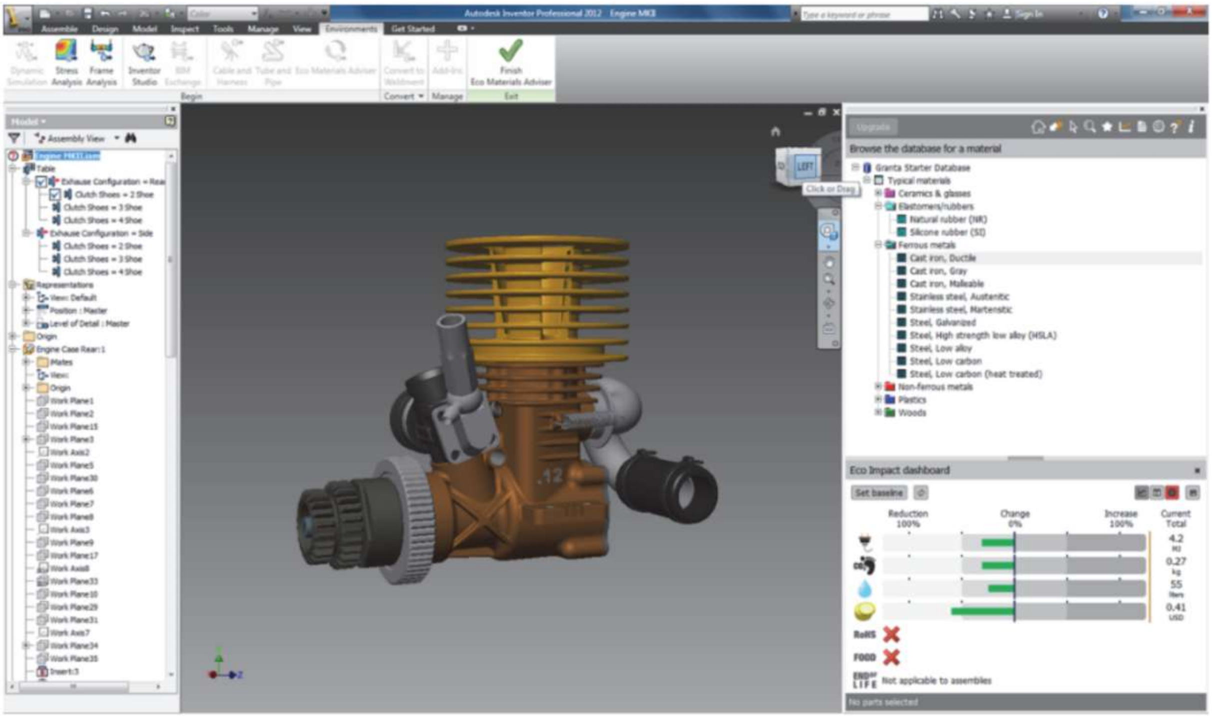



Figure 2.9: Example of a Computer Aided Design (CAD) tool from Autodesk incorporating the Granta Design plug in Eco-Materials Advisor[54]

The methodology has been extensively reviewed by industry stakeholders and user feedback has been very positive. The methodology, data, tools and reports are designed to provide users with the data needed to align critical material risk reduction/management requirements with regulatory, environmental and product performance requirements. The tools also allow users to consider circular economy business models as a possible route to risk reduction. The optimal balance between these factors is determined by the user. An example of the application of the Granta Design methodology is shown in Figure 2.9, which shows the Eco-Materials Advisor plug-in tool within the Autodesk Inventor CAD software.[55]

The presented examples for measuring and assessing circularity of raw materials aim to provide an overview of the existing methods. It is important to note that this selection does not provide a complete listing of all available techniques. The selection rather focuses on the most established and closely related methods aligning with the assessment of raw material criticality required for this thesis. The methodology developed in this work is based on features of the established methods described.

A final summary list of the established methods for measuring criticality are show in Table 2.2. The List describes advantages and limitations of the established methods. The adopted features of each

55. Goddin, "Identifying supply chain risks for critical and strategic materials," fig.7.3; p.123.

method for the generated criticality assessment are also listed.

| Methods | Advantages | Limitations | Adopted features |
|---|---|---|---|
| NRC | - first attempt to assess criticality<br>- the principle of a criticality matrix is still the basis for current methods | - not a definitive list, rather a preliminary evaluation of 11 materials or families of materials | |
| YALE | - further development of the NRC method<br>- hierarchical structure with three main dimensions<br>- assessed 62 metals and metalloids<br>- indicators are evaluated on a 0-100 scale | - noble gases, organic, soluble and radioactive elements were not included<br>- no plans for new methodology releases<br>- no critical/not critical boundaries<br>- no weighting of the indicators | - risk categories and parameters for calculation |
| CML of the USGS | - good data base for the 90 materials of the 2022 CML<br>- the data for the CML materials are updated monthly<br>- also takes historical values into account | - the data focus on the U.S. region<br>- the judgment is also based on subject-matter experts | - data for materials |
| EU CRM | - revision of the list every 3 years<br>- the data focus on the EU region<br>- priority of data sources data | - data availability, in particular on recycling (EOL-RIR)<br>- combining data from different sources | - list of critical raw material<br>- data for materials<br>- risk categories and parameters for calculation |
| VDI 4800 | - hierarchical structure of the supply risk categories with criteria and indicators<br>- guideline of the VDI, a reputable German association | - does not show application to materials<br>- only suggestions for databases | |
| Augsburg | - the indicators are normalized to make them comparable | - aggregation depends on available experts | - normalisation of criticality score |
| Granta Design | - can be integrated into cad<br>- data are linked to the material properties<br>- provide material, product and business specific risks | - commercially licenced tool and data | |

Table 2.2: Summary of established methods for measuring criticality

## 2.2 Principles of the circular economy

The Circular Economy (CE) has grown in importance in recent years and has become a popular subject in both academic and business circles. The growing number of scientific papers published on the subject reflects the increasing interest and relevance attributed to CE. Publications on CE have increased from 116 in 2015 to 917 in 2018 and further to 2355 in 2020.[56] But as the term 'circular economy' grows in popularity, it is crucial to develop a clear understanding of the concept, given the diversity of definitions and approaches, which are often very different.

*Kirchherr et al. 2017*[57] conducted an analysis of 114 definitions of the circular economy, revealing a wide range of interpretations, with CE meaning many different things to different people. In an attempt to summarise the results of their analysis, they offer the following definition: "We defined CE within our iteratively developed coding framework as an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers."[58]

Figure 2.10 illustrates the concept of the circular economy. The concept of CE is often equated with recycling alone, but this is only one of many and classified in the least desirable CE strategies. There are other 'R' strategies, such as reduce, reuse or repair, which offer greater value retention depending on the application.[60] The lack of uniform understanding underlines the need to maintain the clarity of the concept and to establish a consistent definition. Such an approach is central to moving beyond CE as a fashionable term to the development of concrete guidelines and applications.

### 2.2.1 Current initiatives and standards in circular economy

One existing series of standards which deals with environmental management and environmental standards is *DIN EN ISO 14000 ff.* . This series of norms is intended to help companies and organisations to reduce their environmental impact and to implement effective environmental management

56. Alberto Alcalde-Calonge, Francisco José Sáez-Martínez, and Pablo Ruiz-Palomino, "Evolution of research on circular economy and related trends and topics. A thirteen-year review," *Ecological Informatics* 70 (2022): Fig. 2; p. 4, ISSN: 1574-9541, https://doi.org/https://doi.org/10.1016/j.ecoinf.2022.101716.
57. Julian Kirchherr, Denise Reike, and Marko Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," *Resources, Conservation and Recycling* 127 (2017): 221–232, ISSN: 0921-3449, https://doi.org/https://doi.org/10.1016/j.resconrec.2017.09.005.
58. Kirchherr, Reike, and Hekkert, p.229.
59. Source:https://www.europarl.europa.eu/news/en/headlines/economy/20150701STO72956/circular-economy-the-importance-of-re-using-products-and-materials Accessed on 2023-07-21
60. Kirchherr, Reike, and Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," p.228.

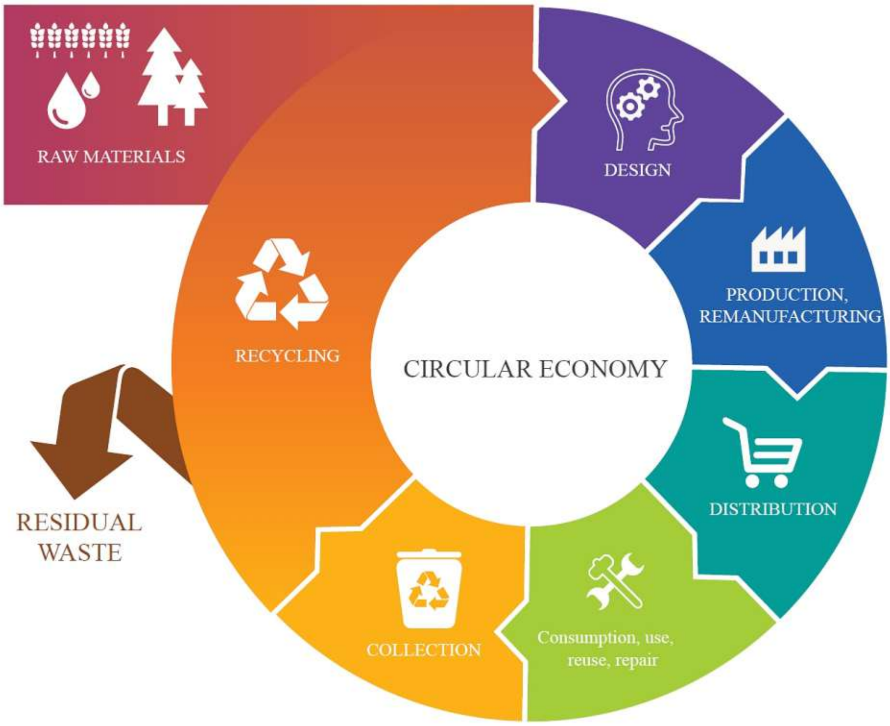



Figure 2.10: Illustration of the concept of circular economy[59]

systems. Relevant norms to this work are *DIN EN ISO 14025*, which defines the requirements for the preparation of an EPD (Environmental Product Declaration), and *DIN EN ISO 14040*, which is used in the conduct of Life Cycle Assessment (LCA), as it outlines the principles and framework for environmental management and life cycle assessment.[61]

The European Commission unveiled the new Circular Economy Action Plan (CEAP)[62] in March 2020. The CEAP stands as a cornerstone of the European Green Deal, which outlines Europe's new agenda for sustainable growth. This transition to a circular economy within the EU not only alleviates the strain on natural resources but also fosters sustainable economic growth and job creation. Furthermore, it serves as an essential prerequisite for attaining the EU's ambitious 2050 climate neutrality objective and for curbing the loss of biodiversity.

The CEAP aims to make sustainable products the standard. This will be achieved by empowering consumers and public purchasers. Special attention is given to sectors that consume significant resources and offer high potential for circularity, including electronics and information technology, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nu-

61. DIN Deutsches Institut für Normung e.V., *DIN EN ISO 14025:2011-10 – Umweltkennzeichnungen und -deklarationen – Typ III Umweltdeklarationen – Grundsätze und Verfahren*, 2011, https://www.beuth.de/de/norm/din-en-iso-14025/144319534; DIN Deutsches Institut für Normung e.V., *DIN EN ISO 14040:2021-02 – Umweltmanagement - Ökobilanzen: Prinzipien und allgemeine Anforderungen*, 2021, https://www.iso.org/standard/37456.html.

62. European Commission, *A new Circular Economy Action Plan For a cleaner and more competitive Europe*, technical report (2020), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN.

trients. The goal is to reduce waste production and make the circular economy beneficial for people, regions, and cities. Additionally, the EU aims to take a leading role in global efforts to promote the circular economy.
The CEAP lists 35 actions that the Commission intends to implement. However, a specific timeline for implementation has not been provided. In 2023 several initiatives were adopted including measures to reduce the impact of microplastic pollution on the environment.[63]

In particular, initiatives such as *ISO/TC 323 (Circular Economy)* already exist. This working group aims to develop standards for terminology, implementation principles, business models and frameworks for measuring circularity. The publication date for the norm could not be found.[64]

Another important initiative driving the development of the circular economy is the *Deutsche Normungsroadmap Circular Economy*. The roadmap was developed by the standardisation institutes DIN, DKE and VDI and presented in January 2023. It aims to identify areas in which standardisation is needed and to serve as a clear guide for companies, policymakers and society at large.[65]

### 2.2.2 Definition and concept of circularity

As described before, the circular economy is an economic model that aims to extend the lifespan of products, reduce waste and resource consumption, and promotes sustainable production and consumption practices. Circularity refers to a product's ability to retain or reintroduce resources in a closed loop. It focuses on designing products or materials in such a way that they can be re-entered into a previous step of the life cycle without loss of quality or value. Circularity is closely related to the circular economy, as it is a key objective within it. Circularity specifically emphasises the design of products and materials to increase their durability and reusability.[66]

The concept of circularity is illustrated schematically in Figure 2.11. This illustration shows how circularity strategies, referred to as 'R' strategies. By applying Rs to a product, it can be reintegrated into an earlier stage of its life cycle. When this is no longer possible, the product is recycled to reuse its raw materials. It is clear that recycling is one of the least preferred circularity strategies. The primary aim of circularity is to maximise value retention. Recycling needs the option to disassemble

63. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en Accessed on 2023-08-28
64. S Wurster, "Stichwort Circular Economy: Normen, Standards und Potential für Neuartige Taxonomische Positionierung," *DIN Mitteilungen*, 2022, p.5, https://din.one/pages/viewpage.action?pageId=98369740.
65. Christoph Winterhalter, Michael Teigeler, and Dieter Westerkamp, eds., *Deutsche Normungsroadmap Circular Economy* (DIN, DKE, VDI, 2023), p.15, https://www.din.de/en/innovation-and-research/circular-economy/standardization-roadmap-circular-economy.
66. Martin Geissdoerfer et al., "The Circular Economy – A new sustainability paradigm?," *Journal of Cleaner Production* 143 (2017): p. 766, ISSN: 0959-6526, https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.048.
67. Source: https://www.ese.com/en/ese-world/sustainability/kreislaufwirtschaft/ Accessed on 2023-07-12

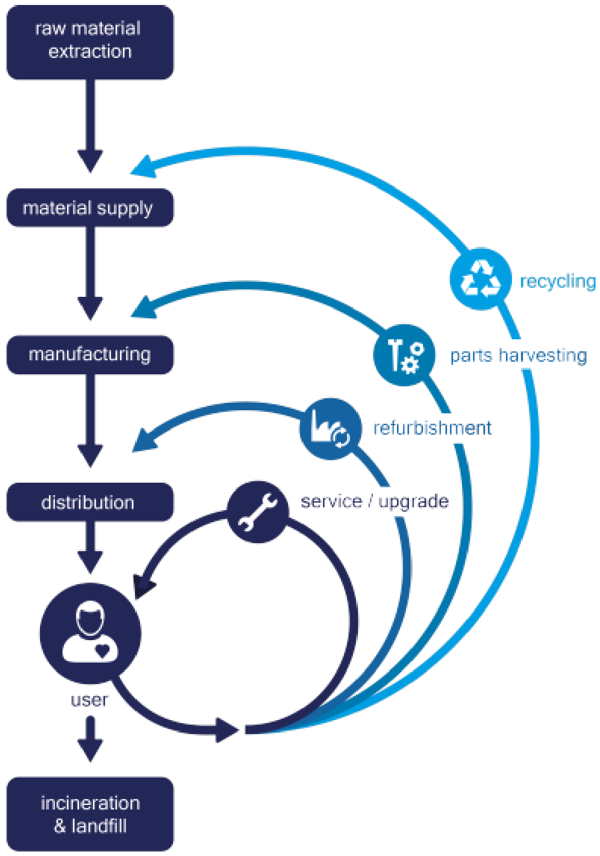



Figure 2.11: Illustration of the concept of circularity[67]

the product into its raw materials, resulting in the loss of the energy invested in the manufacturing process. In addition, recovering materials from discarded products often requires considerable energy and can lead to pollution and degradation of material quality.[68]

Despite the diversity of definitions and approaches, the overarching concept of circularity remains consistent for all. It is about creating a sustainable economic system that minimises resource consumption, reduces waste and makes a positive, long-term contribution to the environment. In the following sections, we will examine the concept of the circular economy in more detail and explore possible approaches to assessing it.

### 2.2.3 Methods for measuring circularity

A crucial aspect of implementing circularity strategies is measuring and evaluating their effectiveness. This evaluation aims to show how effectively a product is returned to the life cycle or how well a business model incorporates circularity strategies. This section examines different assessment

68. José Potting et al., "Circular Economy: Measuring Innovation in the Product Chain" (2017), p. 4, https://www.pbl.nl/en/publications/circular-economy-measuring-innovation-in-product-chains.

approaches to help companies evaluate and improve their circularity efforts. Some companies also offer consultancy services to help other companies to design more circular products or to have developed assessment methodologies to provide suggestions for improvement. The variety of aspects to be assessed, whether it is a product itself, an entire business concept or a company's strategies, highlights the complexity and challenges involved in successfully implementing circular economy strategies.

In the following sections methods used to assess circularity are described.

#### Life Cycle Assessment

A Life Cycle Assessment (LCA) is a systematic method for evaluating the environmental impacts of a product, service or process throughout its entire life cycle. From raw material extraction, manufacturing, distribution, use and end-of-life. The aim of an LCA is to obtain a comprehensive and scientifically assessment of environmental impacts of each life cycle stage in order to identify potential improvements and make environmentally beneficial decisions.[69]

LCA is used for a variety of purposes, including environmental assessment, product development and environmental communication. Companies use LCA results to develop greener products by considering environmental impacts at the design stage. A mandatory application of LCA is the preparation of Environmental Product Declarations (EPD). Both LCA and EPDs are based on Product Category Rules (PCR). LCA defines the methodology and principles for conducting an environmental assessment, while PCR provides rules and guidelines that define specific product categories and the parameters and methods for preparing an EPD.[70] An illustration of the process of creating an EPD is shown in Figure 2.12.

An Environmental Product Declaration (EPD) is a standardised environmental declaration based on the results of a LCA which provides comprehensive information on the environmental impacts of a product. It follows *DIN EN ISO 14025* (Type III environmental declarations). Type III declarations provide quantified environmental information throughout the life cycle of a product, enabling comparisons between products with the same functional unit.[72]

In order to ensure comparability, specific rules and methods for conducting a LCA within a given product category need to be defined in the PCR. A PCR shall be prepared for each product category.

69. DIN Deutsches Institut für Normung e.V., *DIN EN ISO 14040:2021-02 – Umweltmanagement - Ökobilanzen: Prinzipien und allgemeine Anforderungen*, p.15.
70. DIN Deutsches Institut für Normung e.V., *DIN EN ISO 14025:2011-10 – Umweltkennzeichnungen und -deklarationen – Typ III Umweltdeklarationen – Grundsätze und Verfahren*, p.5-6.
71. Source: https://www.sustainplan.at/e-p-d/epd-process/ Accessed on 2023-07-12
72. DIN Deutsches Institut für Normung e.V., *DIN EN ISO 14025:2011-10 – Umweltkennzeichnungen und -deklarationen – Typ III Umweltdeklarationen – Grundsätze und Verfahren*, p.5-6.

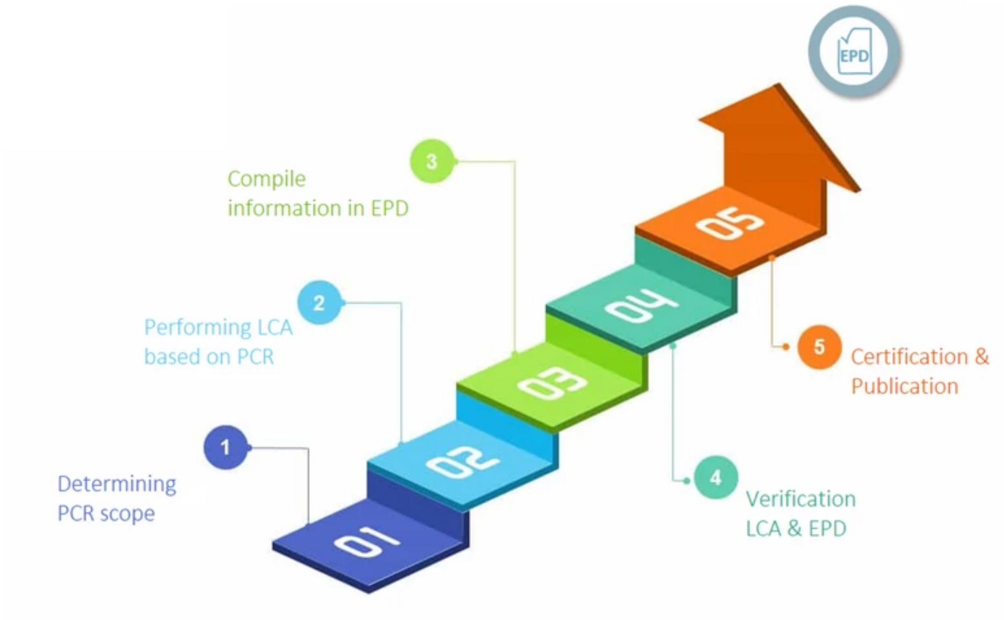



Figure 2.12: Illustration of the process to create an EPD[71]

The use of PCRs ensures that EPDs within the same product category are consistent and comparable. The PCR specifies, for example, the data to be collected, the environmental impacts to be considered and how the results should be communicated.[73]

Once an EPD has been produced, it must be certified by a third party certification organisation. The data are published in the form of a report and are available to all interested parties and stakeholders.[74] Ultimately, a Life Cycle Assessment provides a solid and objective basis for evaluating the environmental performance of a product.

### Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI) has been developed by the Ellen MacArthur Foundation and Granta Design to assess the circularity of products and companies based on facts and figures. The MCI aims to scientifically assess how effectively a company or product aligns with the concept of circularity. The MCI represents the circularity of the material flow on a scale from 0 to 1, as shown in Figure 2.13.[75]

"To get a result of 1, all the raw materials used would have to come from reused components or

73. DIN Deutsches Institut für Normung e.V., *DIN CEN ISO/TS 14027:2018-04 – Environmental labels and declarations – Development of product category rules*, 2018, p.13, https://www.beuth.de/de/technische-regel/din-cen-iso-ts-14027/277019140.
74. https://www.sustainplan.at/e-p-d/epd-process/ Accessed on 2023-07-12
75. Ct. https://sphera.com/glossary/what-is-a-circular-economy/ Accessed 2023-07-12
76. Source: https://sphera.com/glossary/what-is-a-circular-economy/ Accessed on 2023-07-12

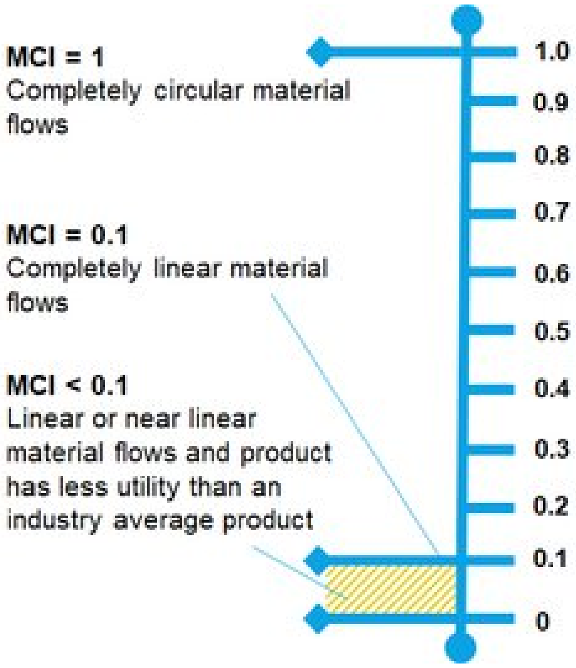



Figure 2.13: Scale of the Material Circularity Indicator (MCI)[76]

recycled materials, without any loss in recycling (100% recycling efficiency). Any waste generated during the production and end-of-life of the product would also have to be reused or recycled without any loss ('zero waste'). A product with completely linear material flows, where all raw materials come from virgin material and no waste is reused or recycled at all, is valued at 0.1. To achieve a value below 0.1, the benefit of the product would have to be lower than that of an average industrial product (i.e., the product would have to have a shorter life or lower intensity of use). A product with completely linear material flows but with a higher utility than an average industrial product would have an MCI > 0.1."[77]

The MCI is essentially a combination of three product characteristics. The mass $V$ of virgin raw material used in manufacture, the mass $W$ of non-recoverable waste attributed to the product, and a utility factor $X$ that takes into account the length and intensity of use of the product. The factors are shown along the material flow in Figure 2.14.[78]

The calculation of the mass of virgin materials $V$ requires the parameters $F_R$ (fraction of raw materials from recycled sources), $F_U$ (fraction from reused sources) and $F_S$ (fraction of biological materials used from sustainable production). These fractions are subtracted from the total mass ($M$) of the

77. "What Is a Circular Economy?"; Sphera's Editorial Team;https://sphera.com/glossary/what-is-a-circular-economy/ Accessed on 2023-07-12
78. Ellen MacArthur Foundation, *Circularity Indicators: An Approach to Measure Circularity. Methodology*, 2019, p. 22, https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o.
79. Source: https://sphera.com/glossary/what-is-a-circular-economy/ Accessed on 2023-07-12

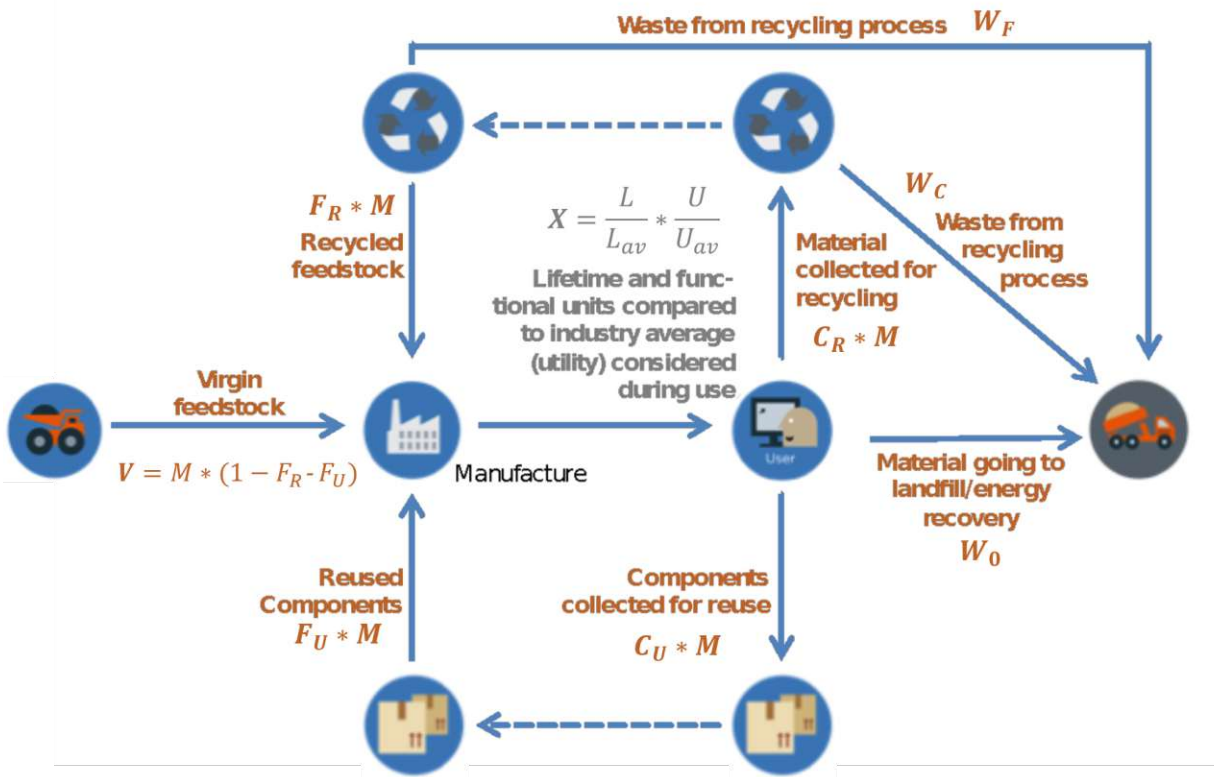



Figure 2.14: MCI calculation method using material flow[79]

product to give the mass of $V$.

$$V = M \cdot (1 - F_R - F_U - F_S) \tag{2.3}$$

The calculation of the mass of non-recoverable waste ($W_0$) is done in Equation 2.4. Non-recoverable waste is produced if a product going to landfill, waste to energy and any other type of process where the materials are no longer recoverable. The non-recoverable waste mass $W_0$ is calculated by subtracting parameters by the total mass $M$. The parameters are $C_R$ (fraction of the mass of the product that is collected for recycling at the end of its use stage), $C_C$ (mass of the product containing uncontaminated biological materials that are composted) and $C_E$ (mass of the product containing biological materials from sustainable production that are used for energy recovery).
In addition, the calculation of the total mass of non-recoverable waste $W$ requires the parameters $W_C$ (mass of non-recoverable waste generated in the process of recycling parts of a product) and $W_F$ (mass of non-recoverable waste generated in the process of producing recycled feedstock for a product). The calculation of $M$ is then done as follows

$$W_0 = M \cdot (1 - C_R - C_U - C_C - C_E) \tag{2.4}$$

$$W = W_0 + \frac{W_F + W_C}{2} \tag{2.5}$$

Two components are needed to calculate the utility $X$ (see Equation 2.6). The length component consists of the lifetime $L$ of the product and the lifetime of the industry average ($L_{av}$). The intensity component consists of the number (average) of functional units achieved during the use of a product $U$ and the number (average) of functional units achieved during the use of an industry average product of a similar type ($L_{av}$). A functional unit is a measure of product use, such as an hour worked or a kilometre driven. The two component relations are multiplied to give $X$.

$$X = \frac{L}{L_{av}} \cdot \frac{U}{U_{av}} \tag{2.6}$$

An additional parameter, the Linear Flow Index $LFI$, is required. It represents the proportion of material flowing in a linear chain. It is derived in Equation 2.7. It is important to note that the term $\frac{W_F - W_C}{2}$ becomes 0 in the case of 100% efficient recycling (the simplest scenario).

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \tag{2.7}$$

Finally, the MCI value requires another factor $F(X)$, which is a function of the utility $X$ and is intended to compensate for the fact that improvements in a product's utility (e.g. through extended use) have the same impact on its MCI as component reuse. The MCI is then calculated as follows, where the MCI value must not be less than 0, otherwise it is assumed to be 0.

$$MCI = 1 - LFI \cdot F(X) \tag{2.8}$$

The value of the MCI depends on the allocation of the material flow shares. The challenge of this method is to generate the necessary data. Only a small number of companies have sufficient knowledge of what proportion of their product goes to landfill or energy recovery or how much is recycled in the end-of-life stage.[80]

80. L Rocchi et al., "Measuring circularity: an application of modified Material Circularity Indicator to agricultural systems," *Agricultural and Food Economics* 9, no. 1 (2021): p.4, https://doi.org/https://doi.org/10.1186/s40100-021-00182-8.

This chapter has introduced the concept of circular economy. The understanding of the concept should illustrate the necessity of being able to assess the circularity of products. The presented methods for measuring and evaluating the circularity of products are intended to give an overview of the existing options. It is important to note that this selection is not intended to be a complete list of all the techniques. Rather the selection focuses on the most established and closely related methods that are consistent with the circularity assessment of products required for this thesis. The methodology developed in this work is based on elements of the established methods described.
A final summary list of the established methods for measuring circularity are show in Table 2.3. The List describes advantages and limitations of the established methods. The adopted features of each method for the generated circularity assessment are also listed.

| Methods | Advantages | Limitations | Adopted features |
|---|---|---|---|
| LCA | - standardized process based on norms<br>- detailed description of the environmental impact of the product over all life cycle stages | - elaborate evaluation process | - environmental impacts of the life cycle stages |
| MCI | - the MCI score is easy to understand and present<br>- the quantitative score offers good comparability of products | - the data of the material flows can be difficult to obtain | |

Table 2.3: Summary of established methods for measuring circularity

# 3 Methodological approach for the criticality and circularity assessment

This chapter provides a detailed explanation of the methodology used in the assessment methods. A general assessment model serves as the basis for the assessment of criticality and circularity.

The general assessment model aims to facilitate a systematic assessment development process and ensure comprehensive coverage of all sub-areas while maintaining applicability.

The criticality assessment methodology examines the raw materials used in a product. The term criticality of raw materials is defined and the most critical materials are identified and analysed.

The circularity assessment methodology focuses on how well a product and its components can be kept in a circular flow. This means how durable they are and how well they can be recirculated to earlier stages of their life cycle to create the greatest possible value retention of the product components. As a result of the assessment method, Value Retention Options (ROs) are proposed.

## 3.1 Development of a General Assessment Model (GAMo)

Both assessment methods generated in this thesis are based on the same template model for generating assessment methods. The template is called the General Assessment Model (GAMo). The GAMo is a compilation of findings in the literature review. During the investigation of different assessment methods, it was observed that the structure of these methods often shows similarities. This led to the development of the GAMo, a general framework for evaluation process. It serves as a guideline for the creation of evaluation methods. First, the overall functionality of the GAMo is explained. Each aspect of the model is then discussed in more detail.

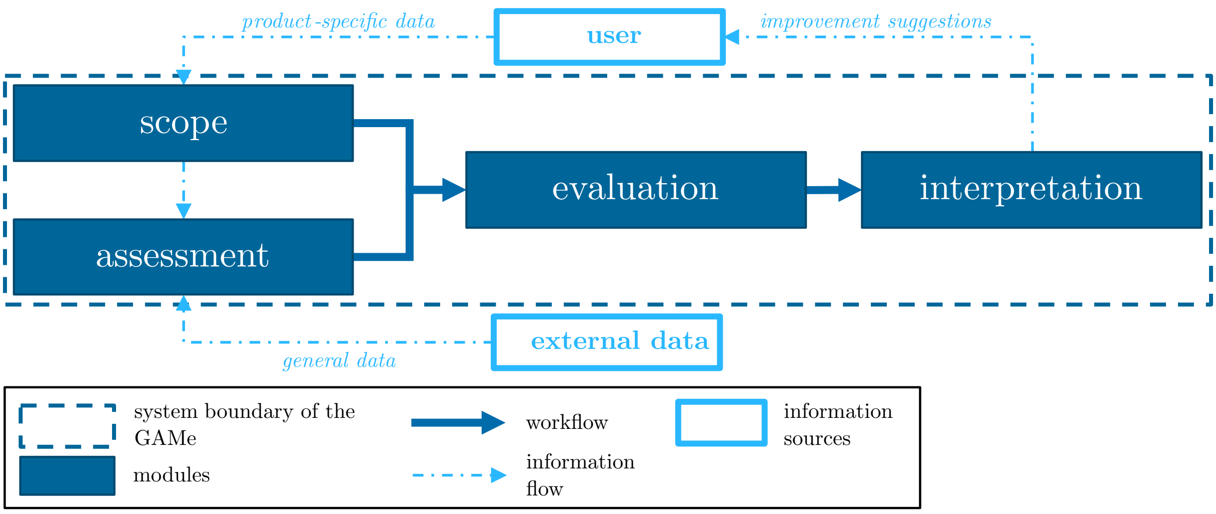



Figure 3.1: Illustration of the General Assessment Model (GAMo)

The structure of the GAMo is illustrated in Figure 3.1. The GAMo consists of the General Assessment Methodology (GAMe), the information flows and the information sources.

The GAMe is located within their system boundaries which are represented by a dark blue dashed line in Figure 3.1. There are four modules within the system boundary. The scope, assessment, evaluation and interpretation module. Each module is described in detail later in this chapter.
The light blue dotted arrows of the GAMo represent the information flows. They serve as import and export channels across the system boundaries. The information flow facilitate the transfer of data, documents and other information relevant to the assessment method. The user and external data serve as information sources for the information flows.

The user generally interacts with the GAMe at the beginning and end of the assessment process. Initially, the user acts as a source of information and is responsible for providing required data and information. Without the user's input, the assessment cannot proceed. The information can be provided in the form of a Bill of Materials (BOM), data sheets, questionnaires or other appropriate formats. The exact requirements should be defined during the adaptation process of the GAMo to the specific assessment method. In addition, the user can also act as an expert in case of product-related questions or ambiguities during the assessment process.
External data can also contribute to the GAMe. It is important to precisely define the requirements for external data, to prioritise data sources and to determine the availability of relevant standards such as standards, laws or guidelines.
Once the assessment is complete, the collected and interpreted results are returned to the user. It is important that the information flow back to the user presents the collected and interpreted results in an understandable and unambiguous way. This minimises misunderstandings and increases the likelihood that the experience gained will be incorporated into the product.

When developing a new assessment project, it is important to ensure that all four modules within the system boundary are adequately covered. It is advisable to create a list of requirements at the beginning of such assessment projects. Definitions and explanations of the creation of requirements lists can be found in the literature, such as *Naefe 2012*.[81]

A detailed explanation of the four modules of the GAMe as well as the information flow and information sources is provided in the following. The information should improve the understanding of the GAMo's methodology and serve as a guideline for creating customized assessment methods. The applications presented in the modules are filtered based on research and study of existing assessment methods in the literature.

81. Paul Naefe, *Einführung in das methodische konstruieren* (Springer, 2012), https://doi.org/https://doi.org/10.1007/978-3-658-00002-8.

### 3.1.1 General Assessment Methodology (GAMe)

The process of assessing takes place within the framework of the GAMe. It is divided into four modules. Each module has to be developed during the adaptation of the GAMe to the specific assessment project. It may be beneficial to combine or overlap modules. This is acceptable as long as all task areas of the individual modules are considered in the combined module structure.

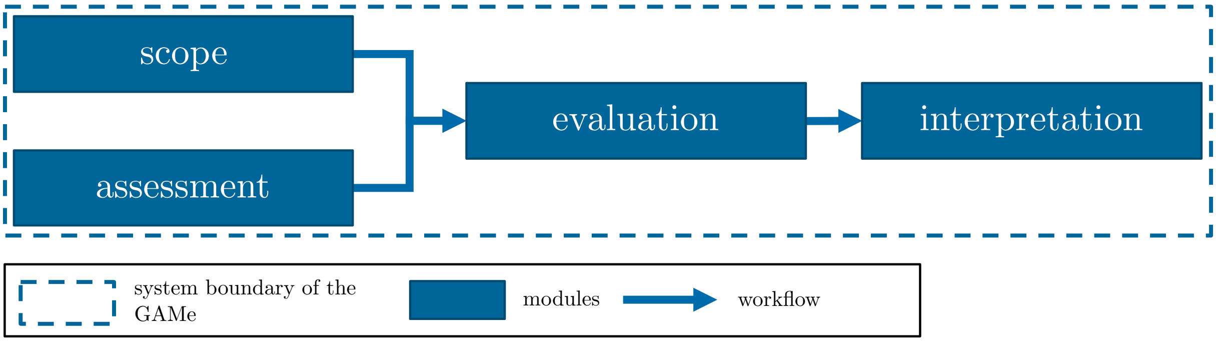



Figure 3.2: Illustration of the General Assessment Methodology (GAMe)

#### Scope module

The scope module is the first step in the GAMe. It defines what should be included or excluded from the assessment. For example, it determines whether the entire product should be assessed or only certain relevant areas, while excluding others that do not add information value. It is important to define the boundaries as narrowly as possible while ensuring the efficiency of the assessment. The information required also plays a role in defining the system boundaries. As an example, it may be necessary to break down the BOM into sub-assemblies, or a comprehensive list of parts may be sufficient. The scope module interacts closely with the assessment module to determine what should be assessed.

#### Assessment module

The assessment module defines the assessment approach. A selection of established assessment methods has been presented in the sections of Chapter 2 (see Chapter 2.1.2 and 2.2.3) . An important distinction is whether qualitative or quantitative parameters are used for the assessment. Quantitative evaluation methods involve numerical values, whereas qualitative evaluation methods involve descriptive analysis, subjective judgements and categorisation of data. Depending on the context, qualitative methods can provide a better understanding by simplifying the complexity of the results. When using quantitative methods, determining how to handle the numerical values by understanding their meaning becomes crucial.[82]

82. Torsten Becker, “Prozessbewertung,” in *Prozesse in Produktion und Supply Chain optimieren* (Berlin, Heidelberg:

Gathering information and data is an essential part of the assessment module. Assessment can only take place if the necessary information is available. Product specific data such as the bill of materials, life cycle information, life cycle assessment and manufacturing processes must be accessible to generate meaningful results. In addition to product specific data, general data relevant to the assessment process should be considered. The general data remains consistent across all assessed products and can be obtained from external sources.
To illustrate the difference between product-specific and general data, they are applied to an example. The energy consumption per wash cycle of a washing machine is product-specific data. The composition of electricity and the price of electricity from the socket are general data that can be used independently of model or wash programme and can be extracted from external databases.
Ensuring that data sources are reliable and ideally regularly updated is important. Establishing requirements for external data sources can ensure data quality standards and prioritise sources when in doubt. Common methods of data generation in the literature include integrating existing databases (using historical data and characteristics), conducting surveys or interviews with experts or focus groups, or generating data through experimentation.

Once the data is generated and applied to the product, weighting and aggregation steps may be required to obtain meaningful results. Weighting assigns different importance to data parameters, affecting the overall result. Aggregation summarises parameters based on similar characteristics.[83] Expert judgement is often used to weight assessment parameters. The experts compare parameters in pairs and rate their relevance. Statistical parameters are mainly used for parameter aggregation. A comprehensive overview of relevant statistical parameters can be found in Gabler 2008.[84]

#### Evaluation module

The evaluation module displays the results from the assessment module. If parts of the assessment need to be combined, they may need to be aggregated before visualisation. The output of the module should provide the result of the assessment within the defined system boundaries and present it in a clear manner. If there are critical values or areas identified by the assessment method, they should be easily recognisable, for example by colour marking or other highlighting techniques. Another option is to create rankings by sorting the values.
The choice of the most appropriate way to present the results depends on the type of assessment. The chosen presentation format must effectively summarise and organise the assessment results to

Springer Berlin Heidelberg, 2008), 169–208, https://doi.org/10.1007/978-3-540-77556-0_7.

83. https://wirtschaftslexikon.gabler.de/definition/aggregation-30653/version-254230 Accessed on 2023-06-19

84. Udo Bankhofer and Jürgen Vogel, “Statistische Maßzahlen,” in *Datenanalyse und Statistik: Eine Einführung für Ökonomen im Bachelor* (Wiesbaden: Gabler, 2008), 27–50, ISBN: 978-3-8349-9654-1, https://doi.org/10.1007/978-3-8349-9654-1_4.

facilitate interpretation in the next step. It is important not to lose the valuable information gathered during the assessment module. At the same time, the presentation should be simple enough to clearly show the relevant areas and values for easy interpretation.

#### Interpretation module

The interpretation module generates the output of the GAMe. The general assessment model and its modules are designed to provide expert interpretation rather than automated interpretation. The results of the assessment module are often influenced by many parameters. Developing a complex automated interpretation system is beyond the scope of this work. The delivery of well presented information in the evaluation module is therefore crucial to support expert interpretation based on the assessment module's results.
The scope of the output of the interpretation module should be defined before generation of a assessment method. This output could include specific suggested solutions or highlight areas identified as most relevant. When suggesting solutions to weaknesses, it is important to consider the feasibility-to-benefit ratio of the solutions. The user's knowledge of the product or production steps can also be valuable in this context. Feasibility assessments should include economic, logistical, social and environmental considerations.

The interpretation module is used to analyse the evaluation module. This analysis should result in added value in terms of information for the user. The interpretation module processes this information in a user-friendly way. The information obtained is then returned to the user via the information flow.

### 3.1.2 Information flow and information sources

The information flow is represented by light blue dashed arrows in Figure 3.3. It plays a crucial role in the GAMo. The user needs to provide specific information to initiate the assessment process within the GAMo. Which information is depending on the chosen requirements for the specific assessment. For smooth information exchange it is important to define the format in which the data should be provided. Standardised formats should be used to ensure consistency and ease of integration.
The data provided by the user is the fundamental basis for a comprehensive assessment. It is important to note that the assessment results can only be as accurate as the quality of input data.

External data sources can be used to avoid entering all data into the GAMe each time. External data sources can include databases. It should be noted that databases often do not provide product-specific information. They rather use data from reference products or average product data. It is

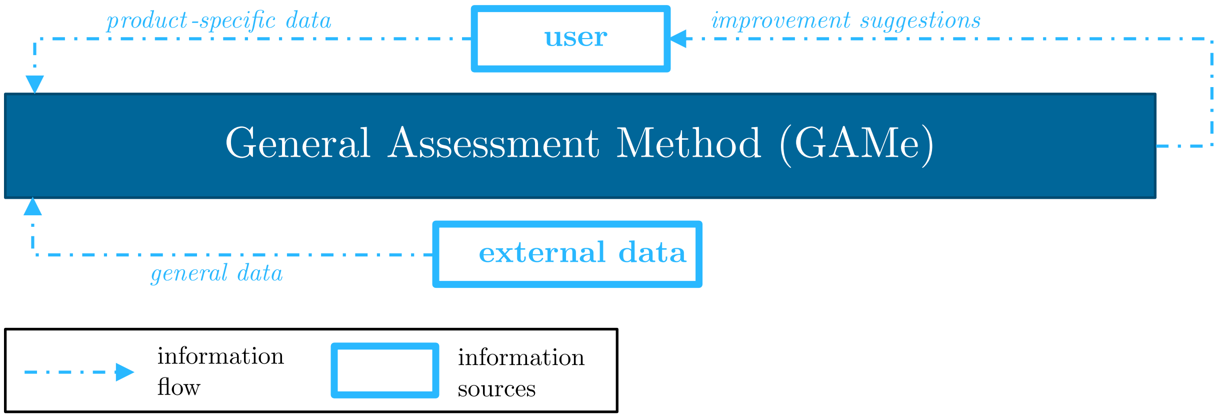



Figure 3.3: Illustration of the information flows and information sources of the GAMo

preferable to work with product-specific data whenever possible.

Establishing prerequisites and prioritising data sources can help to achieve the highest data quality for a specific product. Data provided by the user or product manufacturer should be prioritised over data from public databases or reference products. In addition, locally specific data relevant to the target regions should be preferred over global data. EU data should always be preferred to global values for products within the EU.

### 3.2 Raw material criticality assessment based on the GAMo

Assessing the criticality of raw materials is essential for companies to identify potential risks in their supply chains and take appropriate measures to secure their raw material sourcing. This section of the chapter develops a methodology for assessing the criticality of raw materials.

Formulating the requirements for the assessment methodology was the first step as recommended in the General Assessment Model (GAMo). This step is important to ensure the completeness and achievement of all required features in the methodology development process. The following list of requirements is used for the criticality assessment. The list has been compiled from a literature review of established criticality assessments. It is intended to combine the strengths of the assessments found. Identified weaknesses not addressed by any of the assessments should also be covered.

- The methodology can identify the critical raw materials in a product.
- The methodology allows the evaluation of critical materials in a product.
- Data for elemental raw material parameters are obtained from external databases.
- The data sources fulfil the requirements for external data. The list of requirements can be found in Chapter 3.2.2 below.
- The methodology is capable of assessing a wide range of products, with particular focus on electronic devices.
- The methodology is easily adaptable to changes resulting from current events such as wars, shortages and natural disasters.

The literature review did not identify established assessment methods that adequately met the requirements and included all modules of the assessment model. Some of the criticality assessments reviewed are described in Chapter 2.1.2. Nevertheless, the fundamental methodology of established assessment methods has been adopted and applied in the assessment methodology developed in this thesis.
An overview of the adaptation of the criticality assessment methodology to the GAMo is shown in Figure 3.4. The following chapters describe the raw material criticality assessment workflow and address relevant areas of the methodology. These are the data collection and prioritisation, the explanation of the raw material assessment parameters and the creation of a tool to apply the assessment methodology.

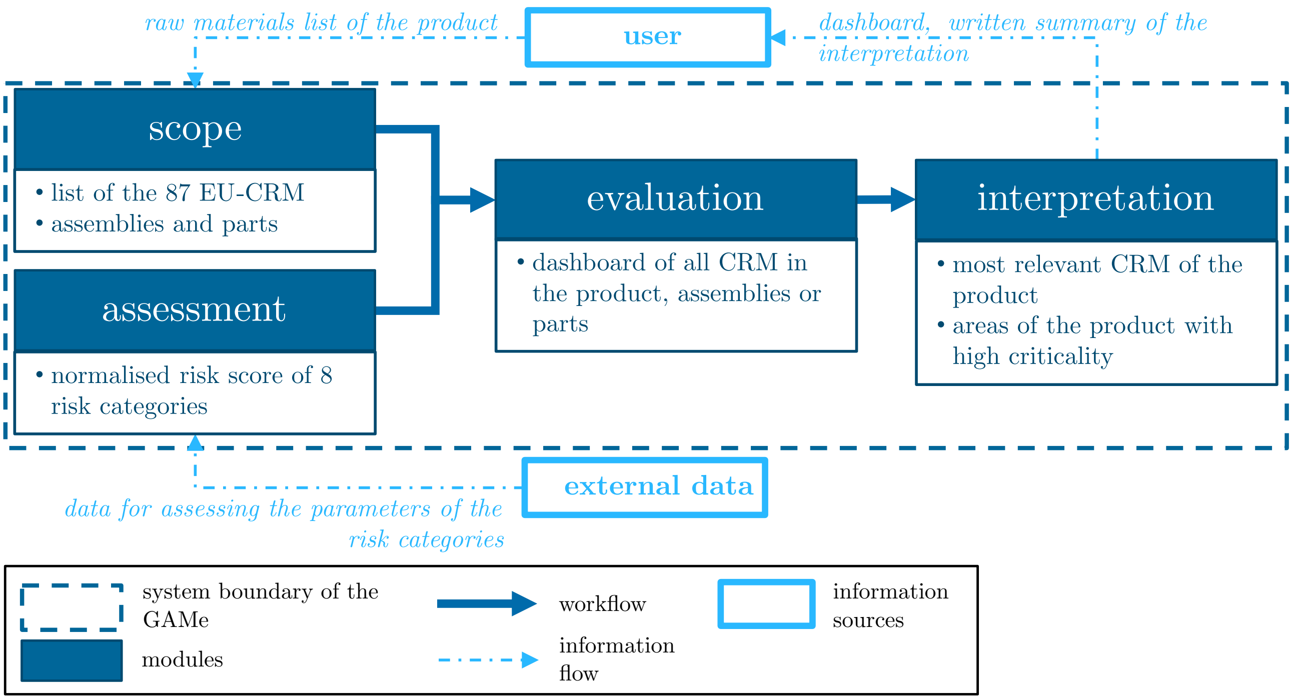



Figure 3.4: Workflow of the raw material criticality assessment methodology according to the GAMo

### 3.2.1 Workflow of the raw material criticality assessment methodology

The raw material criticality assessment methodology follows the 4 modules of the GAMe. The scope of the methodology is clarified first, followed by how the assessment is carried out. This is followed by visualisation in the evaluation stage. Finally, the results are interpreted.

Figure 3.5 illustrates the schematic structure of the scope module as defined in the GAMe. The structure shows the hierarchical composition of a product into assemblies, parts and raw materials. The aim of the assessment methodology is to find the areas of the product with critical materials. These areas can be the materials themselves. Often it is not useful to find only the individual materials of a product, but the critical parts.
According to *DIN199-1*, a part is defined as a component that cannot be disassembled without destruction, with non-detachable assemblies not being considered as parts.[85] Therefore, it makes sense to analyse the parts of a product as they represent the smallest interchangeable unit. If all the parts of an assembly are non-critical, then the assembly itself can be considered non-critical.

Before identifying the critical areas in the assessment module, it is necessary to decide which materials should be assessed. It is impossible to provide a database of all existing materials for selection. A requirement of the assessment methodology is to assess the materials of the product as comprehen-

85. DIN Deutsches Institut für Normung e.V., *DIN 199-1:2021-12:Technische Produktdokumentation (TPD) - Begriffe im Dokumentationswesen*, Draft, 2021, p.7, https://www.beuth.de/de/norm-entwurf/din-199-1/347281068.

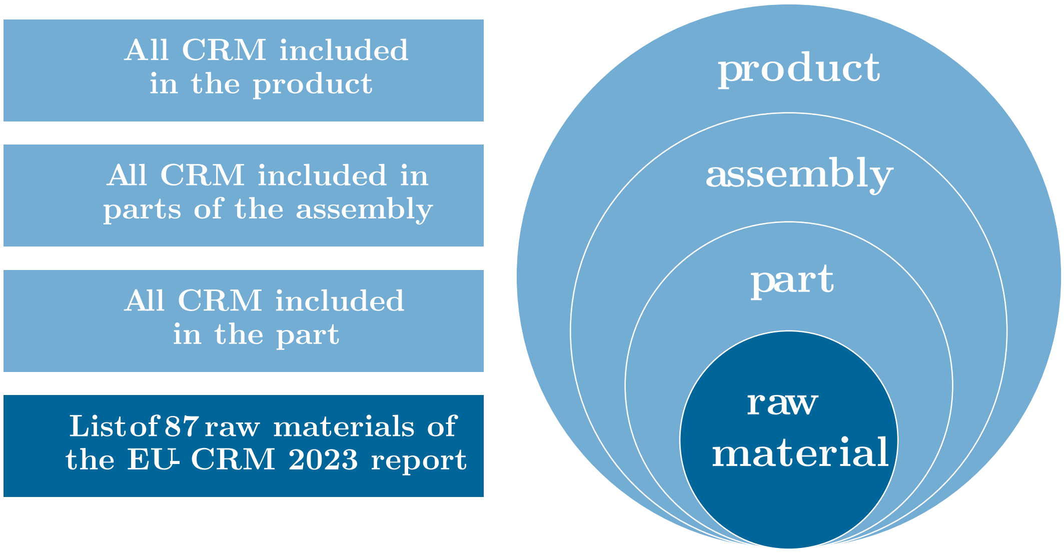



Figure 3.5: Schematic representation of the scope of the criticality assessment method

sively as possible or to identify the critical materials. A pre-selection of a list of materials identified as critical is therefore used.

The list of critical materials relevant to the assessment is taken from the European Union's Critical Raw Materials (CRM) assessment method. The EU assessment method is explained in detail in Chapter 2.1.2. The periodically published list of all CRMs in the European Union includes 34 raw materials according to the 2023 report. A total of 87 individual raw materials were assessed.[86] Most materials are listed as chemical elements, similar to those found in the periodic table of elements. This allows alloys and composites to be assessed. It takes into account the elements of which they are composed.

EU-CRM materials are also classified into different material groups to provide structure. The classification is taken from the *3rd EU Raw Materials Scoreboard* report.[87] The materials are divided into three main groups: metallic minerals and metals, non-metallic minerals and biotic materials. The first two main groups have further subgroups, with six and two subcategories respectively.[88] Table 3.1 shows the list of categorised materials that can be assessed using the criticality assessment methodology developed in this thesis.

Only materials classified as critical according to the latest EU CRM list are relevant for the developed criticality assessment. Only these materials will be considered in the GAMe assessment module. If the user provides the list of all materials contained in the product, only those materials classified as critical by the EU will be considered. This approach aims to minimise database maintenance.

86. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.3.
87. European Commission and DG GROW, *3rd Raw Materials Scoreboard : European innovation partnership on raw materials* (Publications Office, 2021), https://doi.org/doi/10.2873/567799.
88. European Commission and DG GROW, p.6.
89. Adapted from European Commission and DG GROW, table i; p.6

| Classification | | Material (chemical symbol) |
|---|---|---|
| Metallic minerals and metals | Iron & steel | iron ore (Fe) |
| | Ferro-alloy metals | chromium (Cr), manganese (Mn), molybdenum (Mo), tungsten (W), vanadium (V) |
| | Non-ferrous base metals | aluminium/bauxite (Al), copper (Cu), lead (Pb), nickel (Ni), tin (Sn), zinc (Zn) |
| | Precious metals | gold (Au), PGM [iridium (Ir), palladium (Pd), platinum (Pt), rhodium (Rh), ruthenium (Ru)], silver (Ag) |
| | High-tech and other non-ferrous metals and metalloids | antimony (Sb), arsenic (As), beryllium (Be), bismuth (Bi), cadmium (Cd), cobalt (Co), gallium (Ga), germanium (Ge), hafnium (Hf), indium (In), lithium (Li), magnesium (Mg), niobium (Nb), rhenium (Re), silicon metal (Si), strontium (Sr), tantalum (Ta), tellurium ( Te), titanium (Ti), titanium metal, zirconium (Zr) |
| | Rare earths | HREE [dysprosium (Dy), erbium (Er), europium (Eu), gadolinium (Gd), holmium (Ho), lutetium (Lu), terbium (Tb), thulium (Tm), ytterbium (Yb), yttrium (Y)], LREE [cerium (Ce), lanthanum (La), neodymium (Nd), praseodymium ( Pr), samarium (Sm)], scandium (Sc) |
| Non-metallic minerals | Construction materials | aggregates [sand, gravel, and crushed natural stone], gypsum ($Ca[SO_4]\cdot 2H_2O$) |
| | Industrial minerals | baryte ($BaSO_4$), bentonite, boron/borate (B), diatomite, feldspar ($AT_4O_8$), fluorspar ($CaF_2$), hydrogen (H), kaolin clay ($Al_4[(OH)_8 \mid Si_4O_{10}]$), limestone ($CaCO_3$), magnesite ($Mg[CO_3]$), natural graphite (C), perlite, phosphate rock, phosphorus (P), potash (KCl), silica ($SiO_2$), sulphur (S), (elemental) talc ($Mg_3Si_4O_{10}(OH)_2$) |
| | Noble gas | helium (He), krypton (Kr), neon (Ne), xenon (Xe) |
| Biotic materials | | natural cork, natural rubber, natural teak wood, roundwood (timber), sapele wood |
| Other | | coking coal, selenium (Se) |

Table 3.1: Presentation of the classification of all materials considered in the criticality assessment methodology with their chemical symbol[89]

The assessment module determines the criticality of each material on the EU-CRM list. The criticality of materials is assessed according to 8 risk categories (see Table 3.6). By-Product Risk (BPR), Concentration Risk (CR), Political Stability Risk (PSR), Social Stability Risk (SSR), Current Supply Risk (CSR), Future Demand Risk (FDR), Economic Risk of Importance (ERI) and Recirculation Risk (RR). The selection of these categories was not straightforward due to the lack of standards or guidelines for assessing the criticality of materials. Different evaluation parameters can be found in different assessment methods. Efforts have been made to consolidate these parameters. One such meta-study conducted by *Helbig et al. 2021* summarised 88 assessment methods (from 1977-2020) with 618 individual applications and 98 unique criteria belonging to 10 indicator categories.[90]

The 8 risk categories used in the assessment module of this work were defined based on the initial literature review and compared with meta-studies of criticality assessment. A detailed description of the risk categories and the calculation of their parameters can be found in Chapter 3.2.3.

Only the materials from the latest EU-CRM 2023 list are evaluated, as they are considered critical.

90. Christoph Helbig et al., "An Overview of Indicator Choice and Normalization in Raw Material Supply Risk Assessments," *Resources* 10, no. 8 (2021), ISSN: 2079-9276, https://www.mdpi.com/2079-9276/10/8/79.


Figure 3.6: Overview of the 8 risk categories for the assessment of raw material criticality

Out of a total of 87 materials in the EU list, only 34 are classified as critical. All 87 materials are included in the criticality assessment methodology as there is sufficient data availability for these materials. They are assessed by each of the 8 risk categories.
The EU-CRM list also includes groups of materials such as Heavy Rare Earth Elements (HREEs), Light Rare Earth Elements (LREEs) and Platinum Group Metals (PGM). HREE consists of ten materials, while LREE and PGM each consist of five materials.[91] Including these 3 groups, the table of all evaluated materials contains 90 entries. These entries are called the material database of the criticality assessment methodology (see Table 3.1).

Classification with HREE, LREE and PGM sometimes causes problems with external databases. Different databases provide either general data for the groups or for all or some of the materials included. It is also possible that data is only available for Rare Earth Elements (REE). REE includes both HREE and LREE materials.
The most accurate data available are used for the final results of the material risk categories. If elemental data are provided, they are given priority. Otherwise, the data of the higher group are used, which are HREE, LREE or PGM related data. Otherwise, for HREE or LREE materials, REE related data will be taken. The data entries remain empty if no data are available for certain risk categories for certain materials. For example, no by-product risk data were available for the whole group of biotic materials as classified in Table 3.1.

The organisation of the datasets for the 8 risk categories and the presentation of the scoring table was done using a Microsoft Excel file. All data sets of the risk score evaluation for the individual risk categories are shown in the appendix of this thesis (see Table A.1 to A.4). The exact determination of all risk categories is explained in the following chapter 3.2.3.

91. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.2.

The visualisation of the assessment results is also presented in a dashboard using the Excel file. The dashboard allows easy handling and quick filtering of relevant information. It represents the output of the assessment module. The functionality of all parts of the Excel file is described in the Chapter .

The interpretation of the results is the responsibility of an expert. Comments on the most critical areas and suggestions for improvement should be provided. It is important to identify the assemblies or parts where critical materials are present and to understand the reasons for the criticality of these materials. The materials may be scarce resources or dependent on imports. Forecasts may indicate increasing demand. Criticality may be caused by a significant loss of material in the disposal process. It is the responsibility of the expert to make these statements with the aim of clarifying the critical aspects, identifying the key components within these aspects and explaining the reasons for their classification as critical.

### 3.2.2 Collection and prioritisation of data

The quality of data from external sources plays a fundamental role in criticality assessment. The evaluation and interpretation of materials depends on the data provided. The reliability of the data quality directly influences the significance of the final results. Therefore, requirements and prioritisation rules for external data sources have been formulated. These are defined in four principles, which have been aligned with the guidelines for external data sources set out in the *EU-CRM 2023 report*.[92]

In addition, the literature review found that many criticality assessments have derived their data sources from other scientific papers. This approach often results in coverage of a snapshot of the prevailing data landscape, overlooking the maintenance and periodic updating of the data. For example, the work of *Graedel et al. 2015*[93] is often referenced by other assessment methodologies. The data from the paper have been widely cited for providing a comprehensive set of criticality parameters for 62 metals and metalloids in the periodic table. However, the timeliness of the data is not guaranteed as global events such as the COVID-19 pandemic in 2020 or the Russian-Ukrainian conflict in 2022 are not included. The four principles governing the data sources in this study were developed to mitigate these issues.

The four principles are outlined as follows:

- Data must originate from reputable and internationally recognised organisations. These sources should provide open access to ensure the long-term utility of the databases.

92. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.18.
93. Graedel et al., "Criticality of metals and metalloids."

- The data must be kept up to date, requiring regular updates. If it can be demonstrated that the data remain relevant, older data may be used.
- There is a clear hierarchy for prioritising data sources and the geographical regions they cover. First priority is given to official EU and member state data, where available. Next, data from EU or member state trade associations are used. In their absence, data from other specialised interest groups may be considered. In general, EU related data sets are preferred to global data sets.
- Only pre-existing datasets are used in the developed assessment. No original research is carried out, only published data is used.

Throughout the research process, organisations were identified that met all of these criteria. These organisations include the European Union, the U.S. Geological Survey (USGS), the United Nations Development Programme, World Mining Data, the Yale Center for Environmental Law&Policy and the Center for International Earth Science Information Network (CIESIN).
Each of these data sources are used to calculate the eight risk categories. The following chapter provides a comprehensive breakdown of the risk category calculations, together with detailed information on the data sources

### 3.2.3 Risk categories and parameter definition

The choice of categories or parameters to describe criticality is not straightforward. Depending on the assessment method, different parameters are used. This problem is also due to the lack of standardisation. There are no standards or guidelines for calculating the criticality of materials. In addition, even when using the same parameters, the assessment thresholds can vary significantly between different methods. As a result, there is no consistent definition of the level at which a parameter is considered critical or non-critical. This issue was well illustrated in the meta-study by *Helbig et al. 2021*. The paper presented graphs plotting the criticality indicators of several methods against the risk score. It can be seen that the ranges from which the indicator value is critical differ so significantly that no valid statements can be made. This should demonstrate that there is no single definition of criticality indicators.[94]

The criticality assessment methodology developed in this thesis includes 8 risk categories that are evaluated. The list of potential parameters for assessing the criticality of materials is considerably longer. The selection of the 8 categories was continuously narrowed down based on criteria such as

94. Helbig et al., "An Overview of Indicator Choice and Normalization in Raw Material Supply Risk Assessments," p.6.

significance, relevance, clarity and data availability. The 8 risk categories have been selected in the best knowledge and belief to provide the most complete and unambiguous assessment possible (see Table 3.2).

| Risk category | Parameters | Data sources |
|---|---|---|
| By-Product Risk (BPR) | Companion Metal Fraction (CMF) | Graedel et al. 2015, Kolotzek et al. 2018 |
| Concentration Risk (CR) | HHI (Herfindahl-Hirschman Index) | World Mining Data |
| Policy Stability Risk (PSR) | Worldwide Governance Index (WGI) | European Commission |
| Social Stability Risk (SSR) | Human Development Index (HDI) | United Nations Development Programme, European Commission |
| Current Supply Risk (CSR) | Supply Risk (SR) | European Commission |
| Future Demand Risk (FDR) | Future Demand in 2020, 2030, 2050 | European Commission |
| Economic Risk of Importance (ERI) | Economic Importance (EI) | European Commission |
| Recirculation Risk (RR) | End-of-Life Recycling Input Rate (EoL-RIR) | European Commission |

Table 3.2: The 8 risk categories with their parameters and data sources

Each risk category has at least one parameter associated with it. This parameter is calculated using a value or formula obtained from external databases. It is then normalised using a risk score that reflects the risk of the respective risk category for a particular material.
The risk score is used to make the risk categories comparable. It ranges from 0% to 100%. The risk score is divided into four risk ranges to categorise the assessed value:

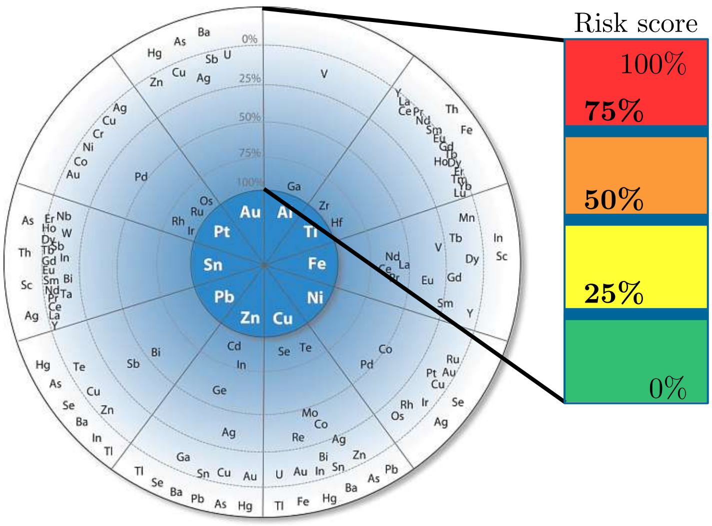
- [100%; 75%] High risk
- ]75%; 50%] Medium risk
- ]50%; 25%] Low risk
- ]25%; 0%] Very low risk

The following subsections introduce the 8 different risk categories. They explain the parameters used in the calculation, the data sources from which the values are derived and how the values are normalised to generate the risk score.

**By-Product Risk (BPR)**
The by-product risk of a material refers to the potential risk associated with it being a by-product of the extraction process of primary mining materials. This means that the production of this material is dependent on the production of the primary mining material.
As the by-product is not the main focus of the mining operation, there may be limited control over the market and pricing. Demand for the by-product may fluctuate, leading to price volatility and uncertainty. If the primary resource is depleted or production is stopped for any reason, this may also affect the production of the by-product. A disruption in the supply of the primary resource may result in the suspension or even cessation of the extraction of the by-product.

The economic profitability of the by-product can be highly dependent on the production levels and costs of the primary mining material. A decrease in the production of the primary material or an increase in costs can negatively affect the profitability of the by-product extraction. Long-term planning and investment in the extraction of the by-product can be challenging due to the uncertainty of its future availability and profitability. Companies may need to make strategic decisions to manage these risks and ensure the stability of by-product extraction.
Overall, the by-product risk can lead to increased uncertainty, profitability issues, and dependence on the conditions of the primary mining material market.

The companion metal wheel is a concept that can be used to describe and apply by-product risk to materials. It provides a way of visualising and describing the proportion of by-products in relation to the primary mining materials. The proportion of a material obtained as a by-product from the extraction of another primary mining material is defined as the Companion Metal Fraction (CMF).[95]
This value is normalised to the by-product risk score and used to calculate the by-product risk.
The companion metal wheel consists of a graphical representation with ten primary mining materials depicted in the centre of the wheel. The by-products are placed around the wheel. The position of the by-product material indicates the proportion of that material that is produced as a by-product in the extraction of the primary material. The CMF is calculated by summing all the proportions of a product that are obtained as by-products. The companion metal wheel assesses companionality for 62 different metals and metalloids. The latest version of the companion metal wheel can be found in *Nassar et al. 2015*.




| Transformation rule |
|---|
| $$CMF = \sum_{i}^{n} p_i(as\ by-product)$$ |
| $BPR = CMF$ |

| Parameter | Description |
|---|---|
| $p_i$ | Share as by product of the primary material |
| $CMF$ | Companion metal fraction |
| $BPR$ | By-product risk |

Figure 3.7: Illustration of the by-product risk score[96]

95. Kolotzek et al., "A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications," table S7; p.S18.
96. Adapted from N. T. Nassar, T. E. Graedel, and E. M. Harper, "By-product metals are technologically essential but have

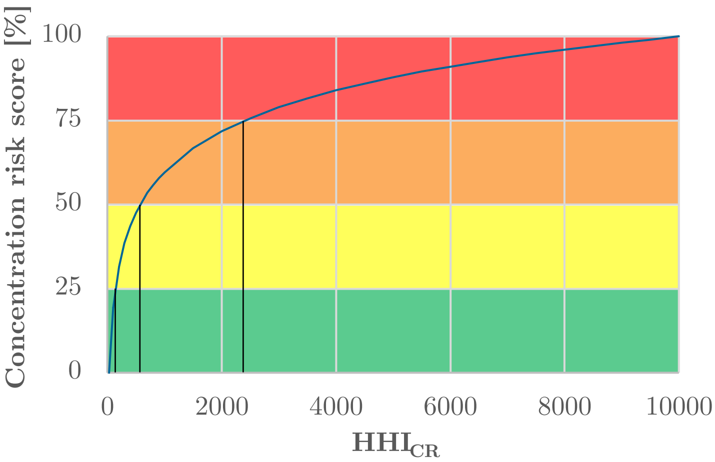
The data from the paper by Nassar, Graedel, and Harper were used to calculate the by-product risk scores. The CMF was used for normalisation to the risk score and evaluated with the risk score ranges. A representation of the companion metal wheel, the normalisation to the by-product risk score and the transformation rule is shown in Figure 3.7.

### Concentration Risk (CR)

Concentration risk refers to the distribution of countries involved in the extraction or production of a particular material. It takes into account the number of countries involved in the production of the material, as well as the presence of monopolies and related dependencies. Concentration risk can lead to various risks and issues, such as supply chain disruptions, price volatility or monopolistic positions.

To quantify the concentration distribution, the Herfindahl-Hirschman Index (HHI) is used in the assessment methodology. The HHI measures the concentration of a market by squaring and summing the shares of market participants. A high HHI value indicates greater concentration, while a low value indicates greater dispersion. The maximum achievable value of the HHI with a monopoly position, where a country has 100% of the material extraction, is 10 000.

In this study, the HHI of the world's producing countries is used to assess concentration risk. The HHI data are taken from the World Mining Data annual report. The most recent report, from 2023, is used as the data source.[97]




| Transformation rule | |
|---|---|
| $HHI_{CR} = \sum_{c}^{N} (100 * Share_C)^2$ | |
| $CR = 17{,}5 * \ln(HHI_{CR}) - 61{,}18$ | |

| Parameter | Description |
|---|---|
| $Share_C$ | Country's share of global mining of the material |
| $HHI_{CR}$ | Herfindahl-Hirschman-Index (countries share glob. prod.) |
| $CR$ | Concentration risk |

Figure 3.8: Illustration of the concentration risk score[98]

problematic supply," *Science Advances* 1, no. 3 (2015): fig.1; p.2, https://doi.org/10.1126/sciadv.1400180

97. Christian Reichl and M Schatz, "World mining data," *Minerals Production Inter-national Organizing Committee for the World Mining Congresses* 38, no. 1 (2023): 1–267, https://www.world-mining-data.info/?World_Mining_Data___PDF-Files.

98. Adapted from Graedel et al., "Criticality of metals and metalloids," p.4

To normalise the HHI values to the concentration risk score, a transformation rule established in the literature is used.[99] The transformation rule and the presentation of the HHI and the normalisation to the concentration risk score are shown in Figure 3.8.

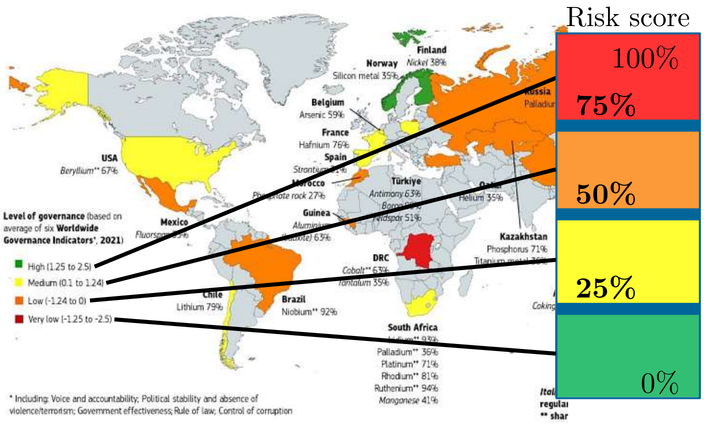
### Policy Stability Risk (PSR)

The Political Stability Risk (PSR) for a material refers to the potential risk of political instability in the countries where the material is mined. It takes into account the likelihood of political unrest, conflict or other forms of instability in these countries that could affect the production, trade and availability of the material.

The PSR is described using the Worldwide Governance Index (WGI). The WGI is an indicator developed by the World Bank that assesses the quality of governance in different countries. It measures factors such as political stability, the rule of law, anti-corruption efforts and effective governance. The WGI can be used to assess more than 200 countries. To assess the political stability risk of commodities, the WGI is adapted for each commodity. The five largest producing countries for each material are considered, and their WGI scores are weighted and averaged based on their share of material production. The data for the shares of the five largest countries are taken from the EU-CRM23 report. The WGI for the extraction stage was used as the data source.[100]

In order to normalise the WGI to the political stability risk score, the four dimensions of the WGI, as stated on the official World Bank WGI website, are mapped to the four ranges of the risk scores.

The WGI dimensions are illustrated in Figure 3.9. The figure also shows the normalisation to the PSR risk score and the transformation rules.




**Transformation rule**

$$WGI_M = \sum_{c}^{5} \frac{WGI_c * Share_C}{\sum_c^5 Share_C}$$

$$PSR = 1 - \frac{WGI_M + 2{,}5}{5}$$

| Parameter | Description |
|---|---|
| $WGI_c$ | WGI of the country |
| $WGI_M$ | WGI of the material |
| $PSR$ | Policy stability risk |

Figure 3.9: Illustration of the policy stability risk score[101]

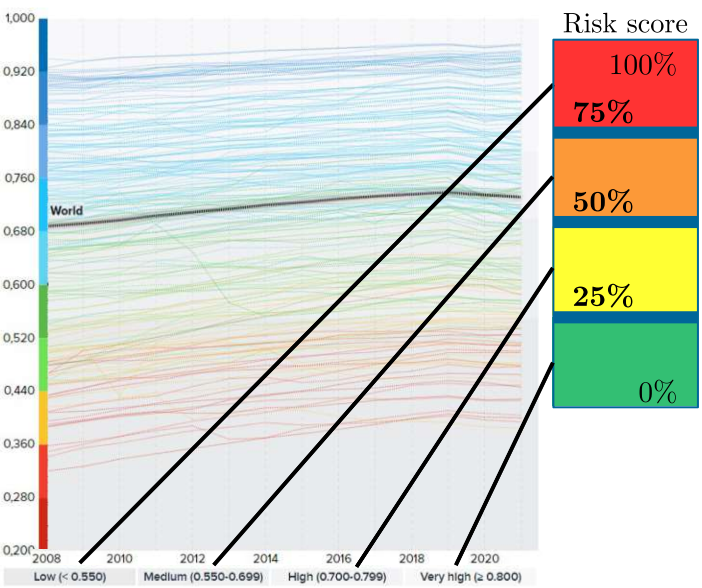
99. Kolotzek et al., "A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications," table S7; p.S18.
100. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, Annex7; p.78.

### Social Stability Risk (SSR)

The Social Stability Risk (SSR) for a material refers to the risk of social instability in the mining and producing countries. It assesses the social conditions in these countries, including population satisfaction and social standards. When people are dissatisfied and social standards are low, the risk of unrest, conflict, corruption and other social problems increases.

The Human Development Index (HDI) is used to assess SSR. The HDI is a measure of social progress and quality of life in different countries, developed by the United Nations Development Programme (UNDP). It ranges from 0 to 1, with higher values indicating greater social stability and development. The global average HDI has shown an overall improvement in recent decades, from 0.6 in 1990 to 0.73 in 2021, although there has been a declining trend in recent years.
As with the WGI, the thresholds for the assessment categories are taken from the UN website. The HDI is divided into four categories: low (< 0.550), medium (0.550-0.699), high (0.700-0.799) and very high ($\geq$ 0.800).[102]

To assess materials in terms of their social stability, the HDI values of the five largest mining and producing countries for each material are determined and weighted according to their share of material production. The procedure is identical to that used to calculate the WGI.
To normalise the HDI values to the SSR risk score, the four categories described by the UN are used. Since the intervals of the categories are of different sizes, some have to be scaled to match the four categories of the SSR.




**Transformation rule**

$$HDI_C = \begin{cases} \left(1 - \frac{HDI_c - 0}{0,55}\right) * 0,25 + 0,75 & HDI_c < 0,55 \\ \left(1 - \frac{HDI_c - 0,55}{0,15}\right) * 0,25 + 0,5 & 0,55 \leq HDI_c < 0,7 \\ \left(1 - \frac{HDI_c - 0,7}{0,2}\right) * 0,25 + 0,25 & 0,7 \leq HDI_c < 0,8 \\ \left(1 - \frac{HDI_c - 0,8}{0,2}\right) * 0,25 + 0 & 0,8 \leq HDI_c \end{cases}$$

$$SSR = \sum_{c}^{5} \frac{HDI_c * Share_C}{\sum_c^5 Share_C}$$

| Parameter | Description |
|---|---|
| $HDI_c$ | HDI of the country |
| $SSR$ | Social stability risk |

Figure 3.10: Illustration of the social stability risk score[103]

101. Adapted from European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.119
102. https://hdr.undp.org/data-center/human-development-index#/indicies/HDI Accessed on 2023-06-16

The presentation of the HDI, the normalisation to the SSR risk score and the transformation rule are shown in Figure 3.10.

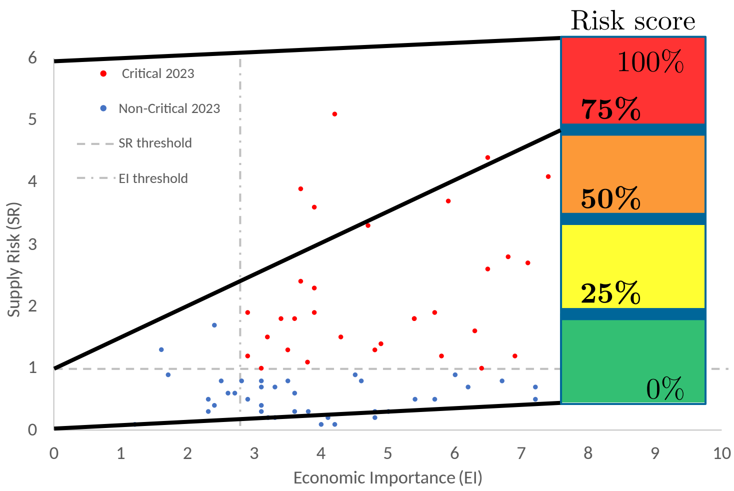
### Current Supply Risk (CSR)

The Current Supply Risk (CSR) for a material refers to the likelihood of the material not being delivered, becoming unavailable or experiencing a shortage. It addresses the question of the current risk of supply disruption for specific materials.

To assess CSR, the Supply Risk (SR) indicator from the EU-CRM assessment methodology[104] is used. This indicator forms one of the two axes of the assessment matrix of the EU method. As explained in the previous Chapter 2.1.2, the calculation of the supply risk indicator is based on several factors. In the EU assessment method, the supply risk values are reported on a scale from 0 to a maximum of 6.[105]

In order to normalise the supply risk indicator to the CSR risk score, the range from 0 to 6 is taken into account. According to the EU-CRM report, a material is classified as critical from a score of 1.[106] This means that the range from 1 to 6 in the risk score is classified as 'very high risk'. The values in the range 0 to 1 of the risk score indicator are evenly distributed among the remaining three ranges.

The criticality matrix of the EU-CRM methodology, the normalisation to the CSR risk score and the transformation rules are illustrated in Figure 3.11.




| Transformation rule | |
|---|---|
| $$CSR = \begin{cases} \left(\frac{SR-1)*0,75}{1-0}\right) & 0 \leq SR < 1 \\ \left(\left(\frac{SR-1)*0,25}{6-1} + 0,75\right) & 1 \leq SR < 6 \end{cases}$$ | |
| **Parameter** | **Description** |
| SR | Supply risk |
| *CSR* | Current supply risk |

Figure 3.11: Illustration of the current supply risk score[107]

103. Adapted from https://hdr.undp.org/data-center/human-development-index#/indicies/HDI Accessed on 2023-06-16
104. European Commission et al., *Methodology for establishing the EU list of critical raw materials : guidelines*, p.11.
105. https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials Accessed on 2023-06-27
106. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.2.
107. Adapted from European Commission et al., fig.A; p.5

**Future Demand Risk (FDR)**

The Future Demand Risk (FDR) for a material refers to the likelihood of increased demand for the material in the future. This assessment methodology considers the period up to 2050 and provides insight into the potential change in demand. The FDR is a key criterion in assessing the criticality of a material, as increased future demand can potentially lead to supply shortages and other challenges.

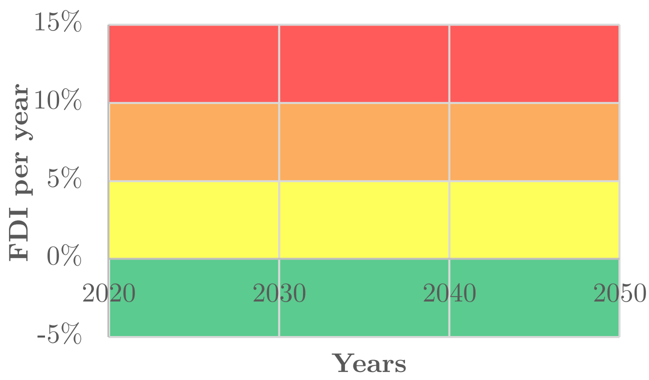
The FDR is calculated using data from the *EU Forecast Report*. This report is published periodically by the Joint Research Centre (JRC) in conjunction with the EU-CRM report, with a minimum interval of three years.
The data used to calculate the FDR are taken from the supplementary material of the *EU Forecast 2023 report*.[108] It takes into account the Future Demand data for the years 2020, 2030 and 2050 from different sectors. It should be noted that the forecast report represents a sample of key future technologies, including 15 key technologies in five strategic sectors (renewable energy, electric mobility, energy-intensive industry, digital technologies and aerospace and defence). The aim is to provide a representative indication of the future demand for materials.

The absolute future demand data for 2020, 2030 and 2050 were examined using regression analysis to determine linear increases between the respective points and normalised to average annual growth rates (in percent). The formula for exponential functions ($f(x) = a \cdot b^x$) was used for this purpose. The result of the annual demand growth for the material is referred to in this paper as the Future Technology Demand (FTD).[109]
To determine the FTD, the annual future demand data from 2020 to 2050 for the respective material were primarily used. In cases where data for 2050 was not available, data for 2030 was used.

In order to normalise the FDR, appropriate ranges for demand growth were defined based on an analysis of the available data for the materials. It was found that an annual increase of more than 10% is classified as high risk. An annual increase between 5% and 10% is considered medium risk, while an increase between 0% and 5% is considered low risk. When the increase becomes negative, indicating an expected decline in demand, the risk is considered very low.

The annual growth rate of future demand and the normalisation to the FDR risk score, together with the transformation rule, are shown in Figure 3.12.

108. European Commission et al., *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU : a foresight study* (Publications Office of the European Union, 2023), https://doi.org/doi/10.2760/386650.
109. Kolotzek et al., "A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications," table S7; p.S18.




**Transformation rule**

$$FDR = \begin{cases} \min\left(\left(\left(\frac{FDI-10\%}{5\%}\right)*0{,}25+0{,}75\right);1\right) & 10\% \leq FDI \\ \left(\frac{FDI-5\%}{5\%}\right)*0{,}25+0{,}5 & 5\% \leq FDI < 10\% \\ \left(\frac{FDI-0\%}{5\%}\right)*0{,}25+0{,}25 & 0\% \leq FDI < 5\% \\ \max\left(\left(\left(\frac{FDI+5\%}{5\%}\right)*0{,}25\right);0\right) & FDI < 0\% \end{cases}$$

| Parameter | Description |
|---|---|
| *FDI* | Future demand increase |
| *FDR* | Future demand risk |

Figure 3.12: Illustration of the future demand risk score

### Economic Risk of Importance (ERI)

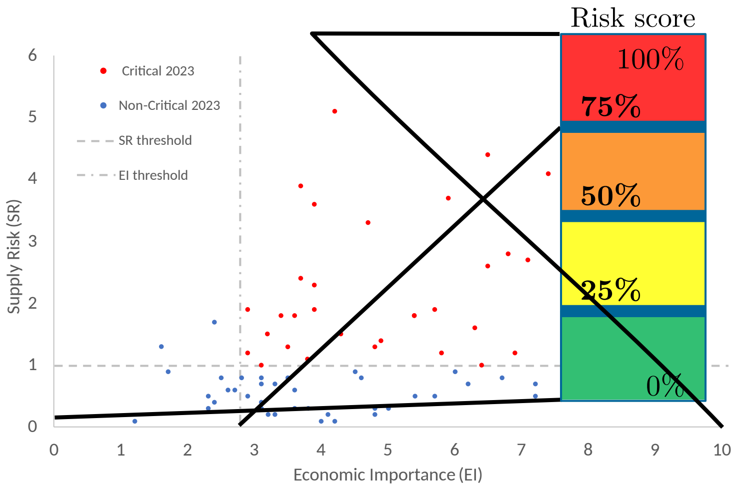
The Economic Risk of Importance (ERI) refers to the significance of a material to the domestic economy. It indicates how important the material is to the economic development of a country or region. A high ERI indicates that a material is very important to a country's economic performance and competitiveness. Shortages or fluctuations in the price of the material can have an impact on companies, supply chains and the wider economy. The risk is that the economy is heavily dependent on a particular material.

The ERI is assessed using the economic risk indicator of the EU-CRM assessment methodology.[110] The assessment of the ERI is based on the economic risk indicator of the EU-CRM assessment methodology. As described in Chapter 2.1.2, the economic risk indicator forms the second axis of the evaluation matrix in the EU-CRM method. The formula for evaluating the indicator is described in Chapter 2.1.2. The economic risk values are expressed on a scale from 0 to a maximum of 10 in the EU-CRM assessment method.[111]

The approach for normalising the economic risk indicator to the ERI risk score is the same as for the current supply risk score. Only the scoring limits are different. The range of 0-10 is considered in the *EU CRM methodology*. A material is classified as critical if its economic risk score is greater than 2.8.[112] This means that the range from 2.8 to 10 in the ERI is classified as 'very high risk'. The range from 0 to 2.8 of the risk score indicator is evenly distributed across the remaining three categories.

The criticality matrix of the EU-CRM method, the normalisation to the ERI score and the transformation rules are illustrated in Figure 3.13.

110. European Commission et al., *Methodology for establishing the EU list of critical raw materials : guidelines*, p.11.
111. https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials Accessed on 2023-06-27
112. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.2.
113. Adapted from European Commission et al., fig.A; p.5




| Transformation rule | |
|---|---|
| $ERI = \begin{cases} \left(\frac{EI-2{,}8)*0{,}75}{2{,}8-0}\right) & 0 \leq EI < 2{,}8 \\ \left(\frac{EI-1)*0{,}25}{10-2{,}8} + 0{,}75\right) & 2{,}8 \leq EI < 10 \end{cases}$ | |
| **Parameter** | **Description** |
| $EI$ | Economic importance |
| $ERI$ | Economic risk of importance |

Figure 3.13: Illustration of the economic risk of importance score[113]

### Recirculation Risk (RR)

Recirculation Risk (RR) is the extent to which a material is reintegrated into the product life cycle after its first use. It measures the efficiency and sustainability of a material's recovery, reuse or recycling. A low RR indicates a low recycling rate, inefficient recycling processes or challenges in collecting and processing used materials. This can lead to various risks and problems, such as increased resource consumption, environmental impacts from landfilling or the need to rely more on primary raw materials.

In this work, RR is assessed using the End-of-Life Recycling Input Rate (EoL-RIR). Unlike the End-of-Life Recycling Rate (EoL-RR), the EoL-RIR also takes into account the introduction of new materials into the product life cycle, thus indicating the amount of material that is recycled relative to the total amount of material. In contrast, the EoL-RR focuses only on the amount of material recycled relative to the total amount of material consumed and does not cover the whole recycling process. The EoL-RIR and EoL-RR are expressed as percentages, with a higher value indicating better end-of-life strategies.

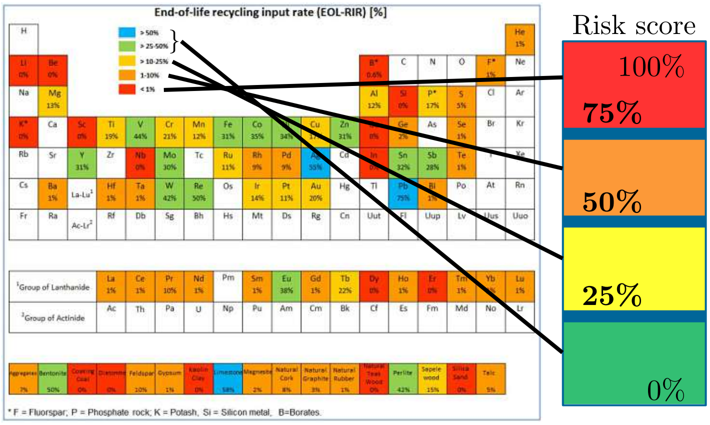
Data availability for EoL-RIR has improved in recent years. To calculate the EoL-RIR regional material flows for the countries of the European Union are needed. The needed data are increasingly available through the Material System Analysis (MSA) and Raw Materials Information System (RMIS) of the European Commission (EC).[114] For EoL-RR, no suitable database was found to meet the data source requirements for this evaluation method.

The data for the EoL-RIR is taken from the *EU CRM 2023 report*, where the EoL-RIR is provided for

114. Talens Peiro L et al., "Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data," (Luxembourg (Luxembourg)), no. KJ-NA-29435-EN-N (online) (2018): p.6, ISSN: 1831-9424 (online), https://doi.org/10.2760/092885.

all assessed materials.[115]

In order to normalise the EoL-RIR to the RR risk score, the five ranges of the EU EoL-RIR,[116] are mapped to the four ranges of the risk scores. The two least critical ranges are combined and represent the very low risk range of the assessment method. The normalisation to the RR risk score and the transformation rule are shown in Figure 3.14.




**Transformation rule**

$$RR = \begin{cases} \left(1-\frac{EoL_{RIR}-0}{0{,}01}\right)*0{,}25+0{,}75 & EoL_{RIR}<1\% \\ \left(1-\frac{EoL_{RIR}-1\%}{0{,}09}\right)*0{,}25+0{,}5 & 1\% \leq EoL_{RIR} \leq 10\% \\ \left(1-\frac{EoL_{RIR}-10\%}{0{,}15}\right)*0{,}25+0{,}25 & 10\% < EoL_{RIR} \leq 25\% \\ \left(1-\frac{EoL_{RIR}-25\%}{0{,}75}\right)*0{,}25+0 & 25\% < EoL_{RIR} \end{cases}$$

| Parameter | Description |
|---|---|
| $EoL_{RIR}$ | End of life recycling input rate |
| $RR$ | Recirculation risk |

Figure 3.14: Illustration of the recirculation risk score[117]

### 3.2.4 Development of a tool to assess the raw material criticality

The tool for applying the criticality assessment methodology has been developed using Microsoft Excel. The Excel file contains tables that integrate data from external sources. These data represent the general data set for the criticality assessment methodology. The risk score value for each individual risk category can be calculated by using the general data sets. To facilitate the traceability of each computational step, all necessary tables are presented in the appendix of this thesis (see Table A.1 to Table A.6). This chapter provides selected excerpts from the relevant tables to facilitate understanding of how the tool works. For a complete list, please refer to the appendix.

Table 3.3 shows an excerpt from the results table for all risk scores. This table serves as the material database for the criticality assessment method. It assigns risk scores for all eight risk categories to each material within the EU-CRM 2023 list. The total number of 90 entries results from the inclusion of 87 CRMs together with the three material groups HREE, LREE and PGM.

To calculate each risk category, support tables are needed. The transformation rules can be implemented with the support tables. The formulas of the transformation rules for each risk category are explained in the previous Chapter 3.2.3. Therefore, the specific calculations will not be repeated here, but the focus will be on the relationships between the tables in the tool.

115. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, Annex11; p.119.
116. L et al., "Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data," Fig.3; p.11.
117. Adapted from L et al., fig.3; p.11

| # | Material (EU-CRM 2023)[a] | Element symbol[f] | Classification[b] | Sub-classification[b] | By-Product Risk (BPR)[c] | Concentration Risk (CR)[d] | Policy Stability Risk (PSR)[e] | Social Stability Risk (SSR)[e] | Current Supply Risk (CSR)[d] | Future Demand Risk (FDR)[d] | Economic Risk of Importance (ERI)[d] | Recirculation Risk (RR)[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aggregates | - | Non-metallic minerals | Construction materials | | | | | 16% | | 81% | 53% |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 90 | Zirconium | Zr | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 73% | 33% | 31% | 64% | 100% | 82% | 47% |

[a]: Study on the EU's list of Critical Raw Materials 2023
[b]: 3rd Raw Materials Scoreboard 2021: p.7
[c]: Nassar et al. 2015: fig.1; p.2
[d]: Own table of risk score calculation (Table 7.3)
[e]: Own table of Top 5 Global Producer (Table 7.2)
[f]: https://www.consilium.europa.eu/en/infographics/critical-raw-materials/ (Accessed on 2023-07-04)

Table 3.3: Excerpt of the risk category results for all materials listed in the EU-CRM 2023 (complete listing in appendix Table A.4)

The PSR and SSR risk categories are calculated using country-specific parameters. Table A.1 in the appendix provides a comprehensive list of all countries and their corresponding parameters. the columns containing the term risk score includes the normalisation step of the risk scores. To convert the parameters to material-specific parameters, the five countries with the highest share of global production of the materials are used. The weighted average of the parameters is calculated on the basis of these shares. This procedure is shown in Table A.2 in the appendix.
The remaining risk categories are calculated by using material-specific parameters. The conversion of each parameter into a risk score is shown in Table A.3 in the appendix.
The results of all risk categories are summarised in Table 3.3. The complete table covering all 90 materials is presented in the appendix as Table A.4.

The general data are covered by the previously highlighted tables. However, product specific data are essential for the application of the criticality assessment. This data is entered in a separate list. A template for entering product specific data is shown in Table 3.4. For better understanding, two materials (aggregates and aluminium/bauxite) are filled in as examples. The materials are associated with an assembly (Ass1) and corresponding parts (P1 and P2).

The header of the table contains information about the name of the product being assessed, the assessment date and the version number. The first three columns, 'Material', 'Assembly' and 'Part' are filled with the product specific data. Each material is associated with its corresponding part and assembly. Instances where materials are associated with different parts are allowed. However, within

| Product: | | | | | | | | | | Edited by: | | Date: | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Version: | |
| | | | | | Very Low | | Low Risk | | Medium Risk | | High Risk | No Data available | |
| # | Material | Assembly | Part | Element symbol | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Comment |
| 1 | Aluminium/Bauxite | | | Al | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% | |
| 2 | Aggregates | | | - | | | | | 16% | | 81% | 53% | |

Table 3.4: Template for entering product-specific data

a single part, each material can only be mentioned once. An optional comment can be provided for each material, giving details such as weight, internal designations or other pertinent information. If the entered material is found in the material database, the risk values are automatically displayed in the risk category columns. In addition, a colour coding scheme corresponding to the risk score ranges is applied. This facilitates quick visualisation of material risks. Grey shaded cells within the risk categories indicates a missing data set for the corresponding materials.

| Assembly | Part | |
|---|---|---|
| Ass1 | P1 | P2 |

| Very Low Risk |
|---|
| Low Risk |
| Medium Risk |
| High Risk |
| No Data available |

| Materials | |
|---|---|
| Aggregates | Aluminium/Bauxite |

| Product: | | | | | Edited by: | | Date: | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Version: | | |
| Materials | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Average |
| Aggregates | | | | | 16% | | 81% | 53% | 50% |
| Aluminium/Bauxite | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% | 52% |

Table 3.5: Template of the criticality assessment dashboard

Table 3.5 represents the dashboard of the tool. The dashboard displays the data from Table 3.4. Using the dashboard, data can be quickly filtered based on different assemblies and parts. This functionality is facilitated by the slicers displayed at the top of the dashboard. It allows critical materials associated with assemblies, parts or the entire product to be easily displayed.

The dashboard represents the output of the criticality assessment evaluation module. By visualising the assessment results via the dashboard, experts can formulate their findings on the critical areas of the product. The tool developed serves as an instrument in this process.

## 3.3 Assessing the circularity of a product based on the GAMo

Achieving a sustainable and resource-efficient economy requires a stronger commitment to the circular economy, where products and materials are designed to comply with circularity strategies. To assess the circularity of products, an assessment methodology has been developed to assist companies in the development and optimization process of their products.

This chapter focuses on the development and description of the methodology for evaluating the circularity of products. In a first step, a list of requirements for the assessment methodology is defined. Based on the list, a search is made for established assessment methods and these are analysed against the requirements. Based on the results of the analysis, parts of established methods are adopted for the new assessment methodology.
The list of requirements was primarily based on the question of 'What are the necessary steps to assess the circularity of a product over its entire life cycle?'. You can then break down the answers to this question into requirements and criteria. This approach was inspired by *Van Oppen et al. 2018*.[118]
The following requirements were formulated:

- The methodology evaluates over the entire life cycle of the product.
- The data required for the assessment methodology should be based as much as possible on existing standards and guidelines. The issue of purchased components should also be taken into account, as producers of the final product often do not have access to information from component suppliers to protect trade secrets.
- The methodology identifies the areas of a product that have the strongest impact through improvements.
- The methodology provides strategies on how to improve the circularity of the product.

With the defined requirements, the assessment methodology was developed according to the guidelines of the General Assessment Model (GAMo). An overview of the adaptation of the circularity assessment methodology to the GAMo is shown in Figure 3.15.This chapter provides a detailed description of the developed circularity assessment methodology. Furthermore a tool was developed to apply the assessment methodology to a product. The application of the tool is also shown in this chapter.

118. Cécile Van Oppen, Godard Croon, and Dirk Bijl de Vroe, *Circular Procurement in 8 Steps* (Copper8, 2018), p.96, https://www.pianoo.nl/sites/default/files/media/documents/Circular-Procurement-in-8-steps-oktober2018.pdf.

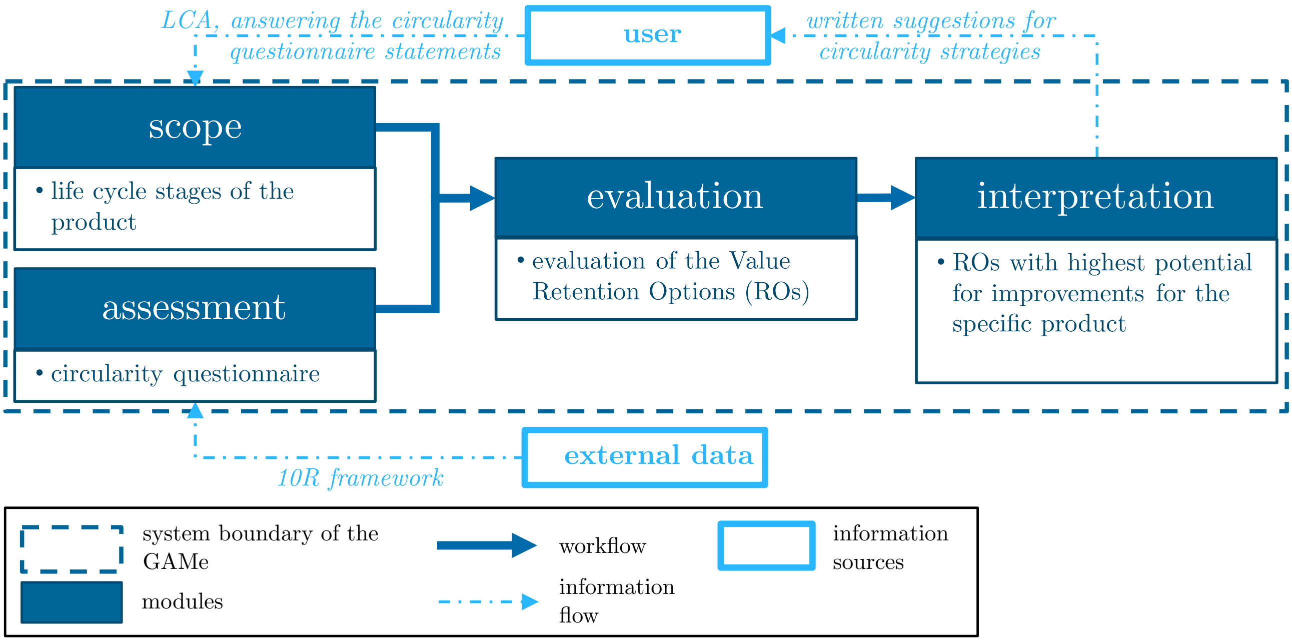



Figure 3.15: Workflow of the circularity assessment methodology according to the GAMo

### 3.3.1 Workflow of the circularity assessment methodology of a product

This chapter describes the workflow of the circularity assessment methodology. It is intended to describe the implementation of the individual parts of the GAMo. An overview has already been given in Figure 3.15.

The scope of the circularity assessment methodology is based on the life cycle stages of products. These stages allow for a better structuring of the product and can be individually assessed if necessary. This work distinguishes five life cycle stages: raw material extraction, manufacturing, distribution, use and end-of-life stage. These stages are adopted from *DIN EN ISO 14044*.[119] For the circularity assessment, all stages except the End-of-Life (EoL) stage are considered.

The EoL stage is not relevant for this assessment methodology because it does not exist in an optimal circular economy. For companies it is almost impossible to control what happens to the product at the end of its life cycle. It is the responsibility of the user to dispose of the product properly. The company can create incentives and opportunities, but the ultimate responsibility lies with the user. The uncertainty surrounding the disposal of the product makes the EoL stage irrelevant for the assessment method. The relevant life stages for the circularity assessment methodology are shown in Figure 3.16.

The circularity assessment methodology combines the assessment module and the evaluation module

119. DIN Deutsches Institut für Normung e.V., *DIN EN ISO 14040:2021-02 – Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen*, 2021, https://www.iso.org/standard/38498.html.

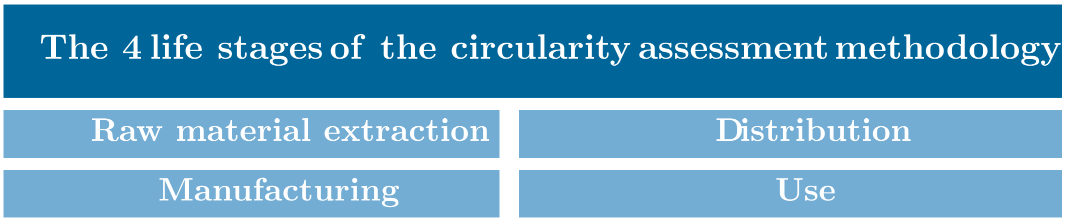



Figure 3.16: The 4 life cycle stages of the circularity assessment methodology

into a combined method. The assessment module is applied using a questionnaire. The questions are structured according to the life cycle stages, and each question is linked to the corresponding circular strategies. An evaluation of the most relevant strategies is generated, once the questionnaire is completed (evaluation module). A detailed description of the questionnaire's structure is provided in the following Chapter 3.3.2.

A recommended strategy for determining the environmental performance of the product is to use an Life Cycle Assessment (LCA). The results of such an LCA can be communicated with an Environmental Product Declaration (EPD). An EPD is a Type III environmental declaration that provides quantified environmental information about the entire life cycle of a product or service. It allows a comparisons between products or services with the same function. An EPD is based on independently verified data derived from life cycle assessments, material assessments or information modules, in accordance with the standards of the *DIN EN ISO 14040*. If necessary, it may include additional information. The creation of a Type III environmental declaration is defined in *DIN EN ISO 14025*.[120]

The EPD is of great importance as it provides specific information about the environmental impacts of the product. This information is obtained from the application of a Product Category Rule (PCR) established for various product categories.

The PCR is defined for a specific product category. It indicates the scope of the environmental assessment including the consideration of relevant life cycle stages. The life cycle stages often include raw material extraction, manufacturing, transportation, use and disposal. The PCR also specifies the data basis for the environmental assessment. The data refers to relevant norms and standards. Requirements for validation and verification are defined. The PCR serves as a guide for creating EPDs to provide comparable and reliable information about the environmental impacts of products.

The information from the EPD serves as a basis for answering the product related statements in the circularity questionnaire. The questionnaire asks statements that have an impact on the circularity of the product across all life cycle stages. The questionnaire is meant to be completed by a person which is familiar with the product. he questionnaire asks statements that have an impact on the

120. DIN Deutsches Institut für Normung e.V., *DIN EN ISO 14025:2011-10 – Umweltkennzeichnungen und -deklarationen – Typ III Umweltdeklarationen – Grundsätze und Verfahren*.

circularity of the product across all life cycle stages. To answer the questionnaire, the statements must be answered in terms of their relevance for the product. The question also asks to what extent the statement has been implemented in the product. The completed questionnaire represents the output of the assessment module.
The evaluation of the questionnaire is used to rank circularity strategies for the product. They are ranked according to the potential for circularity improvements. The circularity strategies are defined using the 10R framework. The 10R framework was described in *Reike et al. 2018*[121] and represents a selection of 10 R-imperatives. The R-imperatives are also called Value Retention Options (ROs). The ROs are ways to keep the value loss of the product as low as possible over the longest possible period of time. More information about the circularity questionnaire and the 10R framework is given in the following chapters.

Interpretations are defined based on the most relevant ROs for the product. These interpretations can include product guidelines or recommendations for applying specific circular strategies. The development of interpretations is performed by an expert.

### 3.3.2 Methodology of the circularity questionnaire

This chapter describes the methodology of the circularity questionnaire. It reveals the composition of the questionnaire statements, explains the process of selecting and formulating these statements and clarifies their interface with the ROs. It also explains the response options for the statements and how they are calculated. The full circularity questionnaire is provided in Table A.7 in the appendix, while excerpts are provided in this chapter for ease of reading.

The circularity questionnaire contains a total of 38 statements about the product. These statements are divided into four life cycle stages: 'Raw material extraction', 'Manufacturing', 'Distribution' and 'Use'. The statements aim to identify the circularity of the product. The statements have been drafted with an emphasis on clear language. To improve readability, key words within each statement are written in bold. Explanations or illustrative examples to help understand the statements were provided in brackets and in a reduced, italicised font. To ensure thorough coverage of circularity issues, the statements were cross-referenced with established circularity assessment tools found in the literature. Ecodesign Pilot[122], The Circularity Potential Indicator (CPI)[123], WeSustain Circularity

121. Denise Reike, Walter J.V. Vermeulen, and Sjors Witjes, "The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options," Sustainable Resource Management and the Circular Economy, *Resources, Conservation and Recycling* 135 (2018): 246–264, ISSN: 0921-3449, https://doi.org/https://doi.org/10.1016/j.resconrec.2017.08.027.
122. http://pilot.ecodesign.at/pilot/ONLINE/ENGLISH/MOTIV/INTRO.HTM Accessed on 2023-05-25
123. https://circulareconomyindicators.com/cpitool.php Accessed on 2023-05-25

Check[124], and D4R Pilot[125] were consulted and compared. An illustration of the statements from the questionnaire is given in Table 3.6.

**#1 Raw material Extraction**

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, ...)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 1.1 | Material supply | The company **choose secondary/recycled raw materials** instead of primary raw materials in the procurement process. | | | | R0 |
| 1.2 | Material selection | The product is revised with the aim of **replacing the primary rav** **materials** with secondary materials in the material selection proc possible. | yes<br>partially<br>prospective<br>no | | | R1 |

Table 3.6: Exemplary answer to a statement of the circularity questionnaire

In Table 3.6, the statement column is accompanied by additional columns. The last column, 'Relevant ROs' establishes the link between statements and improvement strategies. All linked ROs are influenced by the answer to the specific statement. In order to define the related ROs for each statement, consideration was given to which ROs would benefit if the statement's assertion were enacted. The relevant ROs were then selected.

| Questionnaire columns | Answers | | | |
|---|---|---|---|---|
| **Relevant for Product?**<br>*(Value)* | yes<br>*(1)* | partially<br>*(0,5)* | prospective<br>*(0,5)* | no<br>*(0)* |
| **Executed?**<br>*(Value)* | yes<br>*(1)* | partially<br>*(0,5)* | prospective<br>*(0,5)* | no<br>*(0)* |
| **Relevant ROs** | Short Loop: R0 (refuse), R1 (reduce), R2 (resell/reuse) | | | |
| | Medium L.: R3 (repair), R4 (refurbish), R5 (remanufacture), R6 (repurpose/rethink) | | | |
| | Long L.: R7 (recycle), R8 (recover), R9 (remine) | | | |

Table 3.7: Circularity questionnaire answer options

For each statement, the columns 'Relevant for product?' and ' Executed?' provide response options. Both questions can be answered with 'yes', 'partially', 'prospective' or 'no'. Each answer option has a corresponding value, which is summarised in Table 3.7. These values are the basis in determining the impact of the statement on the ROs score. The ROs evaluation involves the evaluation of the questionnaire result and will be explained later. The calculation involves multiplying the values of the two response options by the weight of the statement. The weight is derived from the environmental impact of the life cycle stage to which the statement corresponds. Equation 3.1 outlines the calculation for the ROs evaluation.

$$evaluation_{ROs} = \frac{{}^{n}_{q}\, relevance_q * execution_q * weighting_q}{{}^{n}_{q}\, relevance_q * weighting_q} \tag{3.1}$$

124. https://www.wesustain.com/en/en-software-overview/ Accessed on 2023-05-25
125. https://d4r-pilot.ecodesign.at/pilot Accessed on 2023-05-25

The calculated score for each statement with its associated ROs is aggregated to generate the ROs score. The scoring stage compares the achieved scores with the total scores. The formula is expressed in Equation 3.1, where the numerator consists of the cumulative values of all statements linked to the specific RO. The denominator consists of the maximum values achieved by the statements associated with the particular RO. The maximum value is reached if the statement is relevant to the product and has been executed - both answer options must be 'yes'. If relevance is answered 'no', the statement has no impact on the RO score.

| Recirculation loops | Potential for improvement | Value Retention Options (ROs) | Potential for improvement | Score (points / total) |
|---|---|---|---|---|
| Short | 75% | R0: refuse | 90% | 9 / 10 |
| | | R1: reduce | 80% | 8 / 10 |
| | | R2: resell/reuse | 70% | 7 / 10 |
| | | R3: repair | 60% | 6 / 10 |
| Medium | 40% | R4: refurbish | 50% | 5 / 10 |
| | | R5: remanufacture | 40% | 4 / 10 |
| | | R6: repurpose/rethink | 30% | 3 / 10 |
| Long | 10% | R7: recycle | 20% | 2 / 10 |
| | | R8: recover | 10% | 1 / 10 |
| | | R9: remine | 0% | 0 / 10 |

Table 3.8: Exemplary presentation of the ROs evaluation of the circularity questionnaire

An example of the ROs score is shown in Table 3.8. The 'Potential for Improvement' column is determined by dividing the achieved score by the total score in the 'Score' column. The equation 3.1 outlines this calculation. The potential of recirculation loops and their associated ROs (referred to as circularity strategies) is presented. These strategies are derived from the 10R framework and are explained in more detail in the following chapter.

### 3.3.3 The Value Retention Options (ROs) oft the 10R framework

This chapter describes circular strategies that can be used to improve the circularity of products. The research has revealed the absence of existing norms or standards for design guidelines in the circular economy. The literature often refers to the use of R-imperatives. They are strategies starting with the letter 'R'. Examples of the strategies are 'reuse', 'repair' or 'recycle'.

Different studies have employed various numbers of R-imperatives and different specific strategies, ranging from 3R to 10R's. In this work, the 10R framework proposed by *Reike et al. 2018* is used. It provides a comprehensive representation of circular strategies with its higher number of R-imperatives. Table 3.9 illustrates an overview of the 10R framework, which presents the R-imperatives as Value Retention Options (ROs). The term ROs refers to the idea that resources have intrinsic value. Preserving the value of resources means maintaining them as much as possible in their original state. In the case of finished products, their condition is maintained or reused with minimal entropy to enable them to have a further lifespan. The 10 ROs can be combined into 3 recirculation loops. These are the 'short loop', 'medium loop' and 'long loop'.

| Recirculation loops | Value Retention Options (ROs) |
|---|---|
| **Short loop** (smarter product use and manufacture) | R0: refuse |
| | R1: reduce |
| | R2: resell/reuse |
| | R3: repair |
| **Medium loop** (extend lifespan of products and its parts) | R4: refurbish |
| | R5: remanufacture |
| | R6: repurpose/rethink |
| **Long loop** (useful application of materials) | R7: recycle |
| | R8: recover |
| | R9: remine |

Table 3.9: Overview of the 10R framework ROs and recirculation loops[126]

The smaller the recirculation loop of the RO, the less energy is required to apply the circular strategy. The loop size in Figure 3.17 is indicated by the path taken by the ROs reaches back to previous life cycle stages. The closer the life cycle stage linked by the ROs are, the smaller the recirculation loop. The 10R typology consists of 8 reuse options (R2-R9) and 2 prevention options (R0-R1). Each RO can be associated with a closed-loop size. The smaller the loop, the shorter the path and the associated effort for reintegrating it into the life cycle. A smaller recirculation loop size is desirable as it also enhances the preservation of product value.[127] The following sections provide detailed descriptions of the loops and ROs based on the sources of *Vermeulen et al. 2019*[128] and *Potting et al. 2017*[129] .

126. Adapted from Walter JV Vermeulen, D Reike, and S Witjes, "Circular Economy 3.0; Solving confusion around new conceptions of circularity by synthesising and re-organising the 3R's concept into a 10R hierarchy," *Renewable Matter* 27 (2019): p.14, https://repository.ubn.ru.nl/handle/2066/230427
127. Reike, Vermeulen, and Witjes, "The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options," p.254.
128. Vermeulen, Reike, and Witjes, "Circular Economy 3.0; Solving confusion around new conceptions of circularity by synthesising and re-organising the 3R's concept into a 10R hierarchy," table 1, p.14.
129. Potting et al., "Circular Economy: Measuring Innovation in the Product Chain," fig.1, p.5.
130. Source: Reike, Vermeulen, and Witjes, "The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options," fig.3, p.258

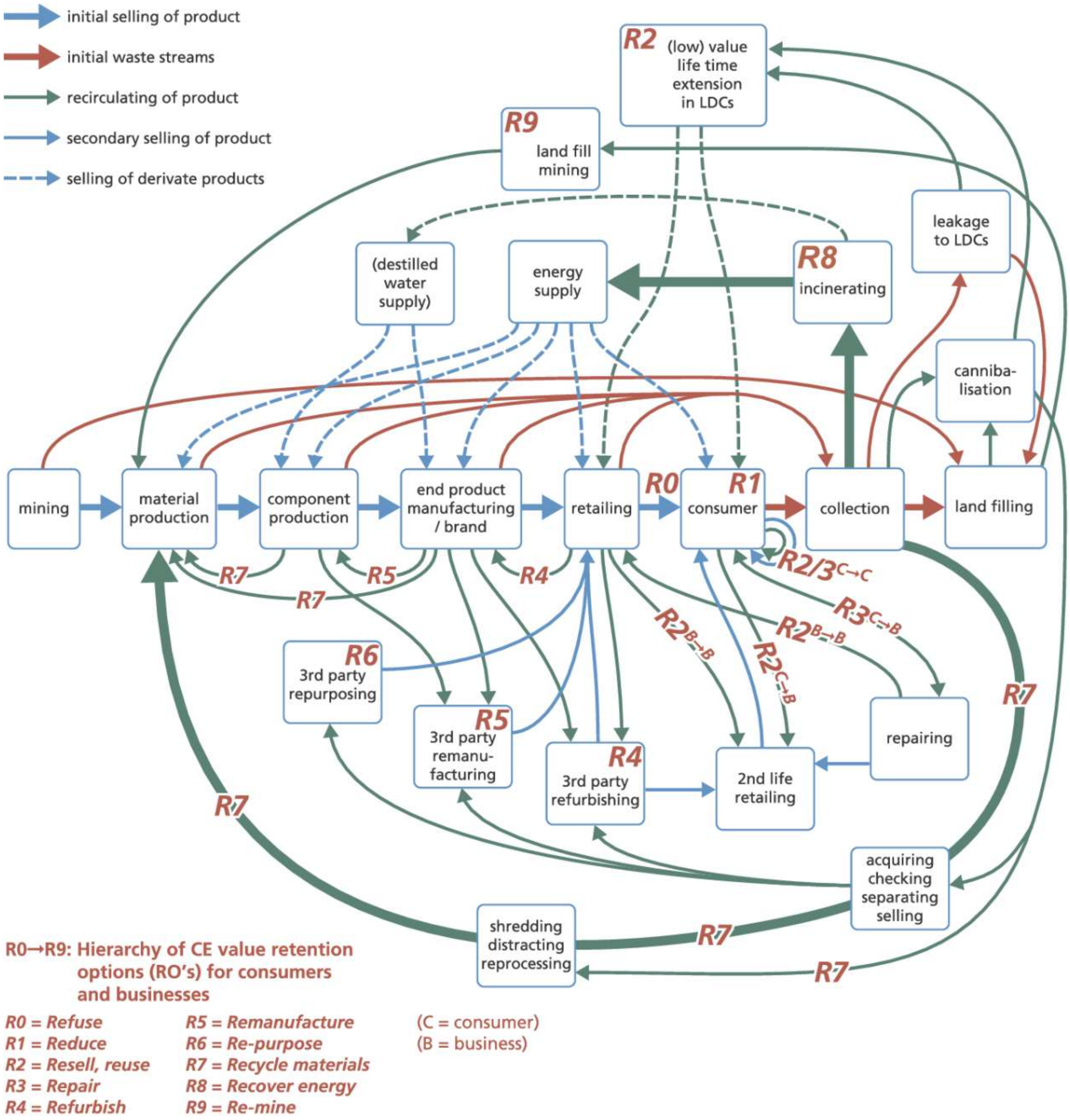



Figure 3.17: Representation of the 10R framework according to *Reike et al. 2018* [130]

**Short loop: client/user choices**

The first four ROs are categorized as short loops (R0-R3). This recirculation loop aims to prevent waste from being generated in the first place. One can either reduce consumption (R0, R1) or increase the lifespan and usage cycles (R2, R3) to achieve this goal. When considering the application of short loop strategies, it is essential to question the feasibility of increasing the lifespan As an example, if the technology is expected to change in a few years, rendering the current product obsolete. In such cases, the medium loop can provide an alternative by aiming for the continued use of the product through upgrades or modifications.

**R0 refuse:** Refuse from the consumer's perspective means rendering products redundant by either abandoning their function or offering the same function with a radically different product. This strategy entails avoiding the use of toxic or harmful materials and above all avoid waste in production processes. The overarching goal is to reduce the reliance on new materials.

**R1 reduce:** Reduce from the consumer's perspective means using products less frequently or with more care and for longer periods. While companies may help by assigning value to the product, the ultimate execution of this strategy lies outside their control. The strategy aims to increase efficiency in the manufacturing process by using fewer natural resources and materials.

**R2 resell/reuse:** Reselling or reusing from the consumer's perspective involves finding new owners for items that are not or barely used, as well as buying and selling second-hand products. Online consumer-to-consumer auctions can provide a platform for these transactions. Additionally, the concept of 'direct re-use' can be embraced as an economic activity facilitated by collectors and retailers. This process entails inspecting, cleaning and making minor repairs to products before making them available for sale, either commercially or non-commercially. Unsold returns or products with damaged packaging can also be directly re-used. Another aspect to reduce waste is the multiple re-use of transport packaging. Incorporating recycled materials in the fabrication process is another important practice. Lastly, consumers can contribute to sustainable consumption by reusing discarded products that are still in good condition and serve their original purpose. These initiatives promote a circular economy and reduce the overall demand for new products.

**R3 repair:** Repair aims to restore defective products to their functional state. For users, it is crucial to have repair options or readily accessible instructions for self-repair. Repair can be outsourced to third parties, creating new business opportunities. Designers can also incorporate features that facilitate easy repair. Maintenance also plays a significant role, requiring the establishment of appropriate infrastructure. By emphasizing repair and maintenance, defective products can be restored to their original function, extending their lifespan and reducing the need for new purchases.

#### Medium loop: product upgrade

The second group, consisting of three ROs, belongs to the medium loops (R4-R6). It includes refurbishment, remanufacturing, and repurposing, which are often confused with one another and with some other concepts. Commercial activity is the driving force behind these recirculation loops, often involving specialized third-party actors with high expertise. The medium loop aims to extend the lifespan of products or parts.

**R4 refurbish:** It is crucial not to confuse repair with refurbishment. As repair aims to restore the original function of a defective product while refurbishment involves comprehensive restoration by replacing or repairing individual components. This process results in an overall 'upgrade' of the product's quality. By restoring and bringing old products up to date, their functionality and performance can be improved, extending their lifespan and reducing the need for new replacements. This approach not only reduces waste but also conserves resources and minimizes the environmental impact associated with the production of new items.

**R5 remanufacture:** Remanufacturing is the process of disassembling a multi-component product entirely and subjecting it to an industrial process. Each component is checked, cleaned, and replaced or repaired as needed during remanufacturing. In some cases, recycled parts can be incorporated into the product, although their retained quality may be tempered. The aim is to bring the item up to the original state, like new. Alternatively, this could also involve repurposing parts from discarded products to create new items with the same function. By incorporating these salvaged components into new designs, valuable resources are conserved and reducing the demand for virgin materials and minimizing waste.

**R6 repurpose:** Repurposing means finding new uses for discarded goods or components. It involves adapting these items for alternative functions, allowing them to be reused instead of becoming waste. Repurposing extends the lifespan of these products and reducing the overall environmental impact. One approach to repurposing is to take discarded goods or their individual parts and incorporate them into new products with different functions. This creative process not only gives new life to these materials but also reduces the need for virgin resources. It promotes resource conservation and minimizes the environmental footprint associated with manufacturing entirely new items.

**Long loop: waste management**

The third group, consisting of three ROs, pertains to traditional waste management measures, including recycling, various forms of energy recovery, and more recently, waste-to-value practices. Many literature who apply clear hierarchies with their R's agree that these options are the least desirable. In long recirculation loop measures, all the energy invested in the production of the product is lost. This can be a viable strategy when the materials and parts hold no value. For example, plastic casings that are uniquely designed for a particular product can be melted down and subjected to new molding processes to create new products.

**R7 recycle:** Recycling involves transforming materials obtained from post-consumer products or post-production waste streams into usable resources of either the same high grade or lower quality. This process includes the separation of waste streams and the use of advanced technological equipment, such as shredding and melting, to extract (nearly) pure materials. Recycling gives these materials a new life and reduces the demand for virgin resources. It also plays a crucial role in waste management by diverting waste from landfills and reducing environmental pollution.

**R8 recover:** The concept of recovery involves the incineration of materials with the objective of capturing the energy embodied in waste and utilizing it for various purposes, such as energy production. It is important to note that recovery is considered a lower-value retention option compared to recycling. The primary goal of recovery is to retrieve at least the energy contained in the waste products, but ideally, this option should be avoided.

**R9 re-mine:** Re-mining refers to the process of retrieving materials that have been landfilled. It is also called 'cannibalization.' This practice involves extracting valuable resources from landfills through techniques like hi-tech landfill mining or urban mining. By re-mining, we can recover materials that were previously discarded and utilize them as recycled resources. It is important to note that re-mining becomes a viable option when a sufficient amount of raw materials has been disposed of in landfills. As resource scarcity and environmental concerns continue to rise, re-mining may play a more significant role in the future.

### 3.3.4 Development of a tool to assess the circularity of a product

The tool designed to implement the circularity assessment methodology has been developed using Microsoft Excel. This tool consists of two main sections: the circularity questionnaire and the evaluation of circular strategies. The circular strategies are the recirculation loops with their Value Retention Options (ROs). Through the evaluation process, the circularity strategies with the highest improvement potential for the assessed product can be identified.

The questionnaire is divided into five different sections: general questions, raw material extraction, manufacturing, distribution and use. The questionnaire also has a header to provide additional information. This header includes details of the name of the product being assessed, the date of the assessment, the version number and the person responsible for editing the questionnaire.

A representation of the header and the general questions section is given in Table 3.10. The general questions section collects essential information about the life cycle stages. This involves identifying

| **Product:** | **Date:** | | **Edited by:** |
|---|---|---|---|
| | **Version:** | | |

**#0 General Questions**

| St. | Category | Statement | Answer | Comments | |
|---|---|---|---|---|---|
| 0.1 | LCA | The **most critical life cycle stages** in relation to the highest environmental impact *(e.g. GWP, can be calculated by an LCA, EPD, ...)* of the product are known. | | | |
| 0.2 | LCA | If St.0.1 is answered "yes" continue with St.0.2: How are the environmental **impacts of the following 4 life cycle stages divided** in relation to each other? *(For the weighting of the 4 life cycle stages, 10 points in total are to be divided between them. The more points per stage are entered in the answer field, the more weight is given to the statements of this stage in the RO (Retention Option) evaluation. If every stage is equal important, answer "equal".)* | **no life cycle stages weighting** | | |
| 0.2.1 | LCA | - Raw material extraction | | | |
| 0.2.2 | LCA | - Manufacturing | | | |
| 0.2.3 | LCA | - Distribution | | | |
| 0.2.4 | LCA | - Use | | | |

Table 3.10: Template for the 'General Questions' section of the circularity questionnaire

the most relevant life cycle stages. Ideally, the information required to answer the general statements should be taken from an Environmental Product Declaration (EPD) or a Life Cycle Assessment (LCA). The influence of life cycle stages on environmental performance should be based on the Global Warming Potential (GWP) reported in the EPD or LCA.
To determine the weighting of the four life cycle stages, a total of 10 points can be distributed between these stages. The points are entered in the 'Answer' column for each life cycle stage. The 'Answer' field in Statement 0.2 serves as an information display, indicating whether the life cycle stages have been weighted. The weighting is only applied if exactly 10 points are allocated to the four life cycle stages. Depending on the distribution of points, the sections of the life cycle stages will have varying degrees of influence on the evaluation stage. If no information is available to weight the life cycle stages, all stages are weighted equally.

A representative section of the four life cycle stages is shown with the 'Raw Material Extraction' stage. An excerpt of this stage is shown in Table 3.11. A full listing of all life cycle stages and the full circularity questionnaire can be found in the appendix to this thesis in Table A.7.
For the 8 statements within the 'Raw Material Extraction' stage, both answer fields 'Relevant for Product?' and ' Executed?' have to be answered. Optional comments can be provided in the next column. The relevant ROs affected by the statement are listed in the last column. The score for each statement is calculated on the basis of the answers to the two answer fields. The calculation process is explained in the questionnaire methodology. The scoring of the questionnaire is automatically generated and presented in the evaluation section.

**#1 Raw material Extraction**

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, ...)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 1.1 | Material supply | The company **choose secondary/recycled raw materials** instead of primary raw materials in the procurement process. | | | | R0 |
| 1.2 | Material selection | The product is revised with the aim of **replacing the primary raw materials** with secondary materials in the material selection process if possible. | | | | R1 |
| 1.3 | Material selection | The company **choose renewable materials** *(wood, corn, rape, hemp...)* instead of materials of fossil origin in the material selection process. | | | | R0, R1 |
| 1.4 | Material selection | There are fulfilled requirements *(internal regulations, ISO, DIN, VDI, ...)* to ensure that **toxic/ecotoxic** *(dioxine, PCB, PVC, ...)* **materials are excluded** from the product hindering late recycling. | | | | R0 |
| 1.5 | Material selection | The product is revised with the aim of ensuring that all **materials are easy to separate with conventional recycling methods** | | | | R7, R9 |
| 1.6 | Material data | There is **product specific information** *(list (BOM) of all raw materials in the product/parts, on an element basis, ...)* **available** to support end-of-life strategies. | | | | R7, R8, R9 |
| 1.7 | Material data | The **most valuable materials** *(critical in supply, most expensive, not reusable, ...)* of the product are **known**. | | | | R1, R2, R3 |
| 1.8 | Material Production | The **raw material demand** of the product *(through targeted design, integration of functions, ...)* is revised to a **minimum**. | | | | R1 |

Table 3.11: Excerpt the 'Raw material Extraction' section of the circularity questionnaire

The evaluation of the circular strategies is presented in Table 3.12. As this evaluation is generated from an empty questionnaire, no scores are displayed. These scores are used to calculate and display the "Potential for Improvement'. In addition, a ranking of individual ROs is provided to facilitate sorting.

| Recirculation loops | Potential for improvement | Value Retention Options (ROs) | Potential for improvement | Ranking 1(bad)...10(good) | Score points / total |
|---|---|---|---|---|---|
| Short | 0% | R0: refuse | 0% | 1 | 0 / 0 |
| | | R1: reduce | 0% | 1 | 0 / 0 |
| | | R2: resell/reuse | 0% | 1 | 0 / 0 |
| | | R3: repair | 0% | 1 | 0 / 0 |
| Medium | 0% | R4: refurbish | 0% | 1 | 0 / 0 |
| | | R5: remanufacture | 0% | 1 | 0 / 0 |
| | | R6: repurpose/rethink | 0% | 1 | 0 / 0 |
| Long | 0% | R7: recycle | 0% | 1 | 0 / 0 |
| | | R8: recover | 0% | 1 | 0 / 0 |
| | | R9: remine | 0% | 1 | 0 / 0 |

Table 3.12: Template for the ROs evaluation

The evaluation of the circular strategies is the output of the tool. An expert continues with the interpretation based on the visualisation of the data.

In the next Chapter 4 the circularity and criticality assessment methodology is applied to a product. This application aims to demonstrate the functionality of the developed methodologies and tools. Any uncertainties in the understanding of the methods in this chapter will hopefully also be clarified.

# 4 Results regarding the assessment of a smartphone (Fairphone 4)

This chapter presents an assessment of the Fairphone 4 in terms of raw material criticality and product circularity. For the sake of simplicity, the Fairphone 4 will be referred to as 'Fairphone' in the remainder of this thesis.

The Fairphone stands out as a pioneer in sustainability and social responsibility. One reason for this is the modular design of the smartphone (see Figure 4.1). There are several good reasons for selecting this product for applying and testing the criticality and circularity assessment method. The transparent structure of the Fairphone company provides a wealth of publicly available reports and data, which is essential for a comprehensive assessment. Comparable products do not provide such accessible reports. The Fairphone 4 is the latest iteration of the Fairphone product line, to be released in 2021 and embodies the company's latest standards and developments.

Fairphone B.V. is the company behind the Fairphone. The company is characterised by its goals and

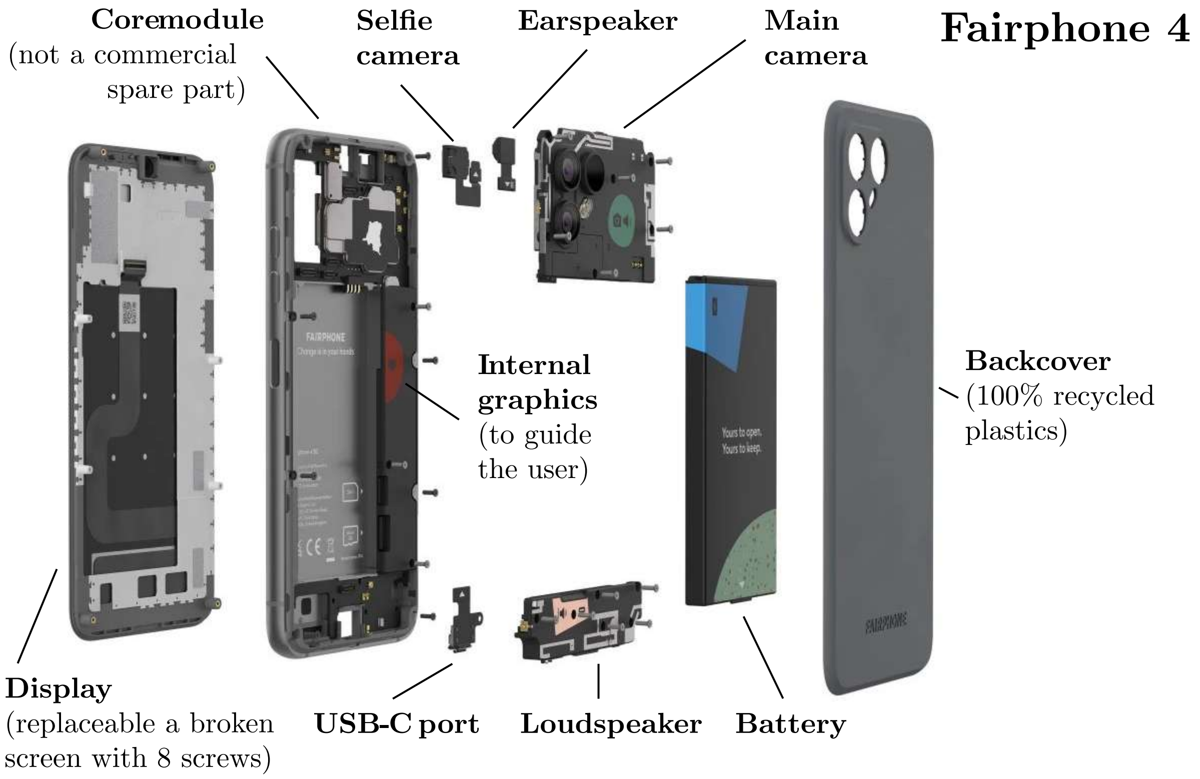



Figure 4.1: The modules of the Fairphone 4 [131]

principles. Founded in the Netherlands in 2013, the company's mission is to make the electronics industry more sustainable and fair. To achieve this, Fairphone B.V. promotes ethical mining, fair working conditions and the use of fairtrade certified and recycled raw materials.[132]

131. Adapted from https://shop.fairphone.com/de Accessed on 2023-07-24
132. https://www.fairphone.com/en/story/?ref=header Accessed 2023-07-24

An annual published *Fairphone Impact Report* is providing insight into the company's progress and actions. Combined with reports from external parties, this extensive data enables a comprehensive assessment of critical raw materials and product circularity. The existing data about the Fairphone are supplemented by a Life Cycle Assessment (LCA) conducted by Frauenhofer IZM (Institute for Reliability and Microintegration). The LCA provides information about the Fairphone manufacturing process and the origin of the raw materials. Another unique aspect of the Fairphone is its openness in conducting internal product assessments. These internal evaluations, which are publicly available, serve as valuable references for comparison with the results generated in this thesis. Further insights into this aspect are explained in Chapter 5.

## 4.1 Assessment of the criticality of raw materials for the Fairphone 4

This section describes the evaluation process and results for determining the criticality of the Fairphone's raw materials. The first step in the assessment is to define the scope of the assessment. The smartphone under consideration is the Fairphone 4. Relevant assemblies and parts are then identified and the data relevant to the assessment process is collected. This data is then integrated into the assessment tool to generate the criticality results. It is important to emphasise that the results are only as meaningful as the underlying data. The results are then presented in a way that allows further interpretation.

### 4.1.1 Data infrastructure for assessing the criticality of raw materials

The first step in the raw material criticality assessment methodology is to define the assessment scope for the product, in this case the Fairphone 4. Relevant assemblies and parts that make up the Fairphone must be identified. All parts are then linked with their respective raw materials.

An attempt has been made to structure the modules of the Fairphone as shown in Figure 4.1. It was not possible to find a Bill of Materials (BOM) of the Fairphone 4. The BOM would have been a direct link between the raw materials and the Fairphone's replaceable modules. Available Information of Fairphone is a list of 14 focus materials that are present in the smartphone.[133] A detailed information with the exact allocation of the focus materials to the modules could not be found.
The structuring and material allocation of the Fairphone which is used for the assessment in this thesis is based on data from conventional smartphones, supplemented and compared with the limited data from the *Fairphone Impact Report 2022*.[135]

133. Monique et al., *Fairphone Impact Report 2022*, p.32.
134. Source: https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/ Accessed on 2023-07-21
135. Monique et al., *Fairphone Impact Report 2022*, p.33.

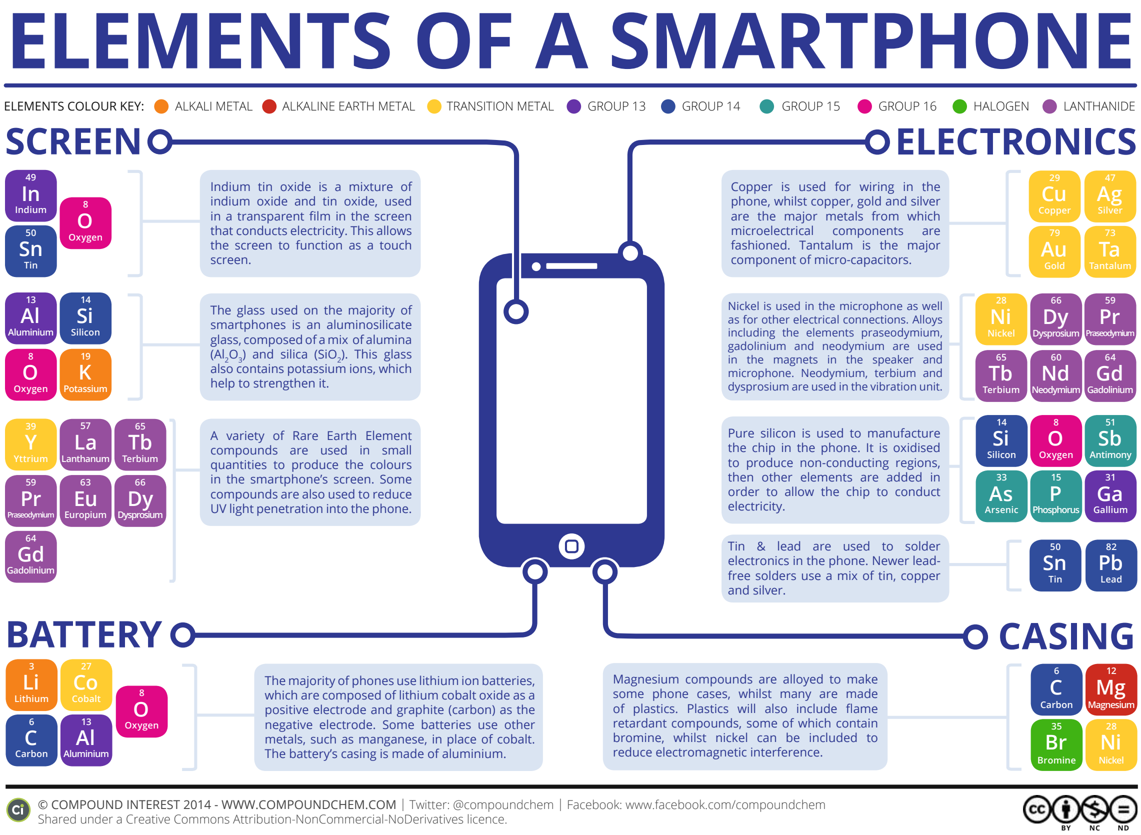



Figure 4.2: Elements of a smartphone[134]

The basic structuring of assemblies and parts has been adapted from Figure 4.2, which provides a list of materials found in conventional smartphones. The data for this list of materials found in conventional smartphones is from the website *Compound Interest*. A *Technical Report of the Joint Research Centre (JRC)* of the European Commission[136] complement and compare the product structure of the Fairphone.

As a result, the final structure of the Fairphone 4 consists of 30 different raw materials, divided into 4 assemblies and a total of 11 parts. The exact allocation can be found in Table 4.1.
The assembly, part and raw material data mentioned above are product specific. In addition, general data is provided for all critical raw materials based on the 8 risk categories (more details in Chapter 3.2.3). The external data is already included in the assessment tool and does not need to be collected again. The next step in the assessment process is to integrate the product specific data into the assessment tool.

136. Joint Research Centre et al., *Guidance for the assessment of material efficiency : application to smartphones* (Publications Office, 2020), https://doi.org/doi/10.2760/037522.
137. Joint Research Centre et al., *Guidance for the assessment of material efficiency : application to smartphones*, p.61; Monique et al., *Fairphone Impact Report 2022*, p.33; https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/ Accessed on 2023-07-21

**Fairphone 4**

| Assembly | Part | Materials |
|---|---|---|
| Battery (3) | Lithium-ion battery (3) | aluminium/bauxite (Al), carbon*, cobalt (Co), lithium (Li), oxygen* |
| Casing (2) | Case (2) | bromine*, carbon*, magnesium (Mg), nickel (Ni) |
| Electronics (18) | Chip (5) | antimony (Sb), arsenic (As), gallium (Ga), oxygen*, phosphorus (P), silicon metal (Si) |
| | Microelectrical components (4) | copper (Cu), gold (Au), silver (Ag), tantalum (Ta) |
| | Microphone (4) | HREE gadolinium (Gd), LREE neodymium (Nd), LREE praseodymium (Pr), nickel (Ni) |
| | Solder (2) | lead (Pb), tin (Sn) |
| | Speakers (3) | HREE gadolinium (Gd), LREE neodymium (Nd), LREE praseodymium (Pr) |
| | Vibration unit (4) | HREE dysprosium (Dy), HREE terbium (Tb), LREE neodymium (Nd), tungsten (W) |
| Screen (11) | Display (7) | HREE dysprosium (Dy), HREE europium (Eu), HREE gadolinium (Gd), HREE terbium (Tb), HREE yttrium (Y), LREE lanthanum (La), LREE praseodymium (Pr) |
| | Glass (2) | aluminium/bauxite (Al), oxygen*, potassium*, silicon metal (Si) |
| | Touchscreen (2) | indium (In), oxygen, tin (Sn) |

* No Data available
() Values of the number of different materials with existing data set written in brackets

Table 4.1: Assemblies, parts and materials of the Fairphone 4 [137]

### 4.1.2 Integration of product data into the criticality assessment tool

The raw material criticality assessment tool was done using a Microsoft Excel file. The methodology and structure of the tool has been explained in detail in Chapter 3.2.4.

The tool consists of several linked tables. Data only needs to be entered into one table and other tables and the dashboard can access the data that have been entered.

| Product: | *Fairphone 4* | Edited by: | Date: | *21.07.2023* |
|---|---|---|---|---|
| | | *Thomas Mandl* | Version: | *1.0* |

| Very | Low Risk | Medium | High | No Data |
|---|---|---|---|---|

| # | Material | Assembly | Part | Element symbol | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aluminium/Bauxite | Battery | Lithium-ion battery | Al | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% | lithium-ion batteries |
| 2 | Carbon | Battery | Lithium-ion battery | | | | | | | | | | lithium-ion batteries |
| 3 | Cobalt | Battery | Lithium-ion battery | Co | 85% | 87% | 76% | 67% | 87% | 70% | 91% | 30% | lithium-ion batteries |
| … | … | … | … | … | … | … | … | … | … | … | … | … | … |
| 46 | Tin | Screen | Touchscreen | Sn | 3% | 69% | 57% | 26% | 72% | 35% | 85% | 23% | used in a transparent film in the screen that conducts electricity |

Data for the Fairphone 4 Materials are taken from *Joint Research Center et. al 2020; Sánchez et. al 2022; https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/ (Accessed on 2023-07-21)*

Table 4.2: An excerpt of the implementation and evaluation of material data for the Fairphone 4

In order to implement the previously developed structure of assemblies, parts and raw materials of the Fairphone, the corresponding table has to be filled in. Table 4.2 shows an excerpt of the completed input form for the product structure. The complete input form can be found in the appendix in Table A.5.

Initially, the first row of the input form contains information about the name of the evaluated product, the editor, the evaluation date and the version number. The version number is used to identify subsequent changes to the assessment.
The first three columns, 'Material', 'Assembly' and 'Part', are filled with product data. For each material, the corresponding part and assembly are entered. The 'Comments' column contains additional information about the use of materials in the product. The entered information are taken from Table 4.2.

When entering data into the tool, care was taken to select the appropriate materials from the tool's database. Element symbols have been compared between the product material and the database materials as a helpful indicator to check whether they are the same material. By analysing element symbols, unique identifications were made. For example, the choice between silica ($SiO_2$) and silicon metal ($Si$). Both materials are present in the tool's database. However, based on the product description of the smartphone, it was determined that pure metal is used, so silicon metal ($Si$) was selected.
Out of the 30 different materials provided of the product information of the Fairphone, 26 data sets matched with the tool's datasets. It is important to note that the selection of these 30 materials already covers the critical materials. The Fairphone consists of more than 50 different materials.[138] The remaining materials in the Fairphone, which are not included in this assessment, are not classified as critical according to the *EU CRM list*. For example, any form of plastic is not considered.

### 4.1.3 Presentation of the results of the Fairphone 4 criticality assessment

To present the results of the criticality assessment, the assessment tool uses a dashboard. A dashboard is a graphical overview or visualisation of information, data or metrics consolidated into a single interface. It provides a quick and easy-to-understand representation of relevant information, allowing users to understand complex data at a glance.

Table 4.3 shows an excerpt of the criticality assessment results dashboard. The complete dashboard can be found in the appendix in Table A.6. The selection fields on top of the dashboard allow assemblies and parts to be filtered by the materials they contain, facilitating efficient data exploration.

The results of the criticality assessment only consider the 26 materials present in the smartphone and for which risk category data is available. Looking at all the raw materials, columns such as By-Product Risk (BPR), Concentration Risk (CR), Current Supply Risk (CSR) and Economic Risk of

138. Monique et al., *Fairphone Impact Report 2022*, p.33.

| Assembly |
|---|
| Battery |
| Casing |
| Electronics |
| Screen |

| Part | | | |
|---|---|---|---|
| Case | Chip | Display | Glass |
| Lithium-ion battery | Microelectrical co... | Microphone | Solder |
| Speakers | Touchscreen | Vibration unit | |

| Materials | | | |
|---|---|---|---|
| Aluminium/Bauxite | Antimony | Arsenic | … |
| Carbon | Cobalt | Copper | Gallium |
| Gold | HREE Dysprosium | HREE Europium | HREE Gadolinium |
| HREE Terbium | HREE Yttrium | Indium | Lead |
| Lithium | LREE Lanthanum | LREE Neodymium | LREE Praseodym... |
| Magnesium | Nickel | Oxygen | Phosphorus |
| Potassium | Silicon metal | Silver | Tantalum |
| Tin | Tungsten | | |

| |
|---|
| Very Low Risk |
| Low Risk |
| Medium Risk |
| High Risk |
| No Data available |

| Product: | Fairphone 4 | Edited by: Thomas Mandl | Date: 21.07.2023 / Version: 1.0 |
|---|---|---|---|

| Materials | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Average |
|---|---|---|---|---|---|---|---|---|---|
| Aluminium/Bauxite | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% | 52% |
| Antimony | 80% | 78% | 61% | 26% | 83% | 66% | 87% | 24% | 63% |
| Arsenic | 92% | 82% | 52% | 16% | 84% | 85% | 80% | 100% | 74% |
| … | | | | | | | | | … |
| Tantalum | 28% | 69% | 68% | 60% | 81% | 34% | 86% | 75% | 62% |
| Tin | 3% | 69% | 57% | 26% | 72% | 35% | 85% | 23% | 46% |
| Tungsten | | 92% | 55% | 13% | 81% | 32% | 96% | 19% | 55% |

Table 4.3: An excerpt of the Fairphone 4 raw material criticality assessment dashboard

Importance (ERI) are highlighted in red. The red highlighting indicates that they are considered high risk (risk score >75%) for that risk category. The last column of the dashboard calculates the average of all risk categories per material.

The dashboard can be used to perform analyses of critical materials. One can start by looking at the numbers of different materials per assembly and part. The values of the amount of CRMs per assembly or part can be found in Table 4.1 in brackets. Notably, the highest number of materials is observed in the electronics and screen assemblies. The electronic parts show no significant difference in material diversity. However, within the screen assembly, the 'display' part stands out with 7 different critical materials.

As an illustration, the 'display' part is examined further. The evaluation results of the part are shown in Table 4.4 using the dashboard. It can be seen that all materials have a high CR, CSR and ERI. In

| Assembly |
|---|
| Screen |
| Battery |
| Casing |
| Electronics |

| Part | | | |
|---|---|---|---|
| Case | Chip | Display | Glass |
| Lithium-ion battery | Microelectrical co... | Microphone | Solder |
| Speakers | Touchscreen | Vibration unit | |

| Materials | | | |
|---|---|---|---|
| HREE Dysprosium | HREE Europium | HREE Gadolinium | HREE Terbium |
| HREE Yttrium | LREE Lanthanum | LREE Praseodym... | Aluminium/Bauxite |
| Antimony | Arsenic | Bromine | Carbon |
| Cobalt | Copper | Gallium | Gold |
| Indium | Lead | Lithium | LREE Neodymium |
| Magnesium | Nickel | Oxygen | Phosphorus |
| Potassium | Silicon metal | Silver | Tantalum |
| Tin | Tungsten | | |

| Legend |
|---|
| Very Low Risk |
| Low Risk |
| Medium Risk |
| High Risk |
| No Data available |

| Product: | Fairphone 4 | Edited by: Thomas Mandl | Date: 21.07.2023 | Version: 1.0 |
|---|---|---|---|---|

| Materials | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Average |
|---|---|---|---|---|---|---|---|---|---|
| HREE Dysprosium | 100% | 85% | 56% | 18% | 98% | 64% | 94% | 75% | 74% |
| HREE Europium | 100% | 85% | 48% | 19% | 98% | 19% | 81% | 75% | 66% |
| HREE Gadolinium | 100% | 85% | 48% | 19% | 89% | 32% | 81% | 75% | 66% |
| HREE Terbium | 100% | 85% | 56% | 18% | 96% | 47% | 90% | 75% | 71% |
| HREE Yttrium | 29% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | 66% |
| LREE Lanthanum | 93% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | 74% |
| LREE Praseodymium | 100% | 85% | 48% | 19% | 89% | 48% | 92% | 75% | 69% |

Table 4.4: The results of the Fairphone 4's dashboard filtered by the part 'Display'

addition, six out of the seven materials have a high BPR. The Recirculation Risk (RR) is considered to be a moderate risk for all materials, bordering on high risk. The Future Demand Risk (FDR) is estimated to be high for yttrium and lanthanum.

The final step of the criticality assessment methodology is the responsibility of an expert. All identified results are presented to the expert, who carefully examines the presentations and draws conclusions that are relevant and valuable to the user.

## 4.2 Circularity assessment of the Fairphone 4

In this section, a circularity assessment of the Fairphone is carried out to identify the potential for implementing smartphone circularity strategies. The circularity assessment methodology is described in Chapter 3.2. To apply this methodology to the Fairphone, a tool has been developed by using a Microsoft Excel file. The tool contains a questionnaire to be completed by a person familiar with the product. Answering the questionnaire requires knowledge of the life cycle stages with the highest environmental impact and information on all life cycle stages of the product. Based on the answers, the questionnaire is automatically scored and improvement opportunities are identified using Value Retention Options (ROs) from the 10R framework (see Chapter 3.3.3). These ROs describe ten strategies for improving the circularity of the product and serve as a basis for future product improvements.

### 4.2.1 Data structure for the Fairphone 4 circularity assessment

The Fairphone has a large number of publicly available reports and studies that are crucial to answering the circularity questionnaire adequately. Only publicly available data was used for the analysis. Two main sources that provided the most relevant information were the literatures by *Sánchez et al. 2022* and the *Fairphone Impact Report 2022*.

The study by *Sánchez et al. 2022* conducted a Life Cycle Assessment (LCA) of the Fairphone, taking into account all stages of the smartphone's life. The report also includes key data on the environmental impact of each of the Fairphone's modules. For the LCA, the report has simplified the life cycle stages into 'raw material extraction and manufacturing', combining 'raw material extraction' and 'manufacturing'.
The annual Fairphone Impact Report provides valuable information about Fairphone B.V. as a company, describing customer services, achievements over the past year and future company goals. In addition, the 2022 report contains product-specific information about the Fairphone as product.
Other sources, such as specific sections of the Fairphone B.V. website, were used to obtain information about special offers such as the Fairphone Easy programme, special reports on mining conditions and hazardous materials[139] in the Fairphone and the company's warranty policy[140]. External assessments of the disassembly of the Fairphone[141] and external circularity reports[142] were also considered.
With this comprehensive database, the next step was to answer the circularity questionnaire.

139. https://support.fairphone.com/hc/en-us/articles/360018631398-Safety-and-Hazardous-Materials (Accessed on 2023-06-26)
140. https://www.fairphone.com/en/warranty/ (Accessed on 2023-06-26)
141. https://www.ifixit.com/Device/Fairphone_4 (Accessed on 2023-06-26)
142. https://circular-iq.com/circular-economy-fairphone-successful-innovation/ (Accessed on 2023-06-26)

### 4.2.2 Answering the circularity questionnaire with the Fairphone's 4 data

The questionnaire to assess the circularity potential of the Fairphone was modelled in an Excel file. An excerpt of the questionnaire is shown in Table 4.5, the complete questionnaire can be found in the appendix in Table A.7.

| | | | | | |
|---|---|---|---|---|---|
| **Product:** | **Fairphone 4** | | **Date:** | 21.07.2023 | **Edited by:** |
| | | | **Version:** | 1.0 | Thomas Mandl |
| **#0 General Questions** | | | | | |
| **St.** | **Category** | **Statement** | **Answer** | **Comments** | |
| 0.1 | LCA | The **most critical life cycle stages** in relation to the highest environmental impact *(e.g. GWP, can be calculated by an LCA, EPD, ...)* of the product are known. | yes | | |
| 0.2 | LCA | If St.0.1 is answered "yes" continue with St.0.2: How are the environmental **impacts of the following 4 life cycle stages divided** in relation to each other? *(the weighting of the 4 life cycle stages, 10 points in total are to be divided between them. The more points per stage are entered in the answer field, the more weight is given to the statements of this stage in the RO (Retention Option) evaluation. If every stage is equal important, answer "equal".)* | **life cycle stages weighted** | | |
| 0.2.1 | LCA | - Raw material extraction | 3,9 | The data for the weighting of the life cycle | |
| 0.2.2 | LCA | - Manufacturing | 3,9 | stages are adopted by the LCA of the | |
| 0.2.3 | LCA | - Distribution | 0,5 | Fairphone 4. The LCA was done by | |
| 0.2.4 | LCA | - Use | 1,7 | Frauenhofer IZM (Source 1) | |
| **#1 Raw material extraction** | | | | | |
| **St.** | **Category** | **Statement** | **Relevant for Product?** | **Executed?** | **Optional comments/bottlenecks** *(economic, technical, social, ...)* |
| 1.1 | Material supply | The company **choose secondary/recycled raw materials** instead of primary raw materials in the procurement process. | yes | yes | Source 2; p.37 |
| ... | ... | ... | ... | ... | ... |
| 1.8 | Material Production | The **raw material demand** of the product *(through targeted design, integration of functions, ...)* is revised to a **minimum**. | partially | no | Weight Fairphone 3: 190,4 g<br>Weight Fairphone 4: 225 g<br>Higher raw material demand can be compensated by a longer lifetime |
| **#2 Manufacturing** | | | | | |
| **St.** | **Category** | **Statement** | **Relevant for Product?** | **Executed?** | **Optional comments/bottlenecks** *(economic, technical, social, ...)* |
| 2.1 | Strategy | The customer has the option to **purchase only the use of the product** *(circular business model like "Product-as-a-Service").* The **ownership** of the product **remains within the company**. | yes | yes | Source 2; p.4 |
| ... | ... | ... | ... | ... | ... |
| 2.13 | Return | There is a **return-system** (provide in-house or by third-party companies) to return used products directly **to the company** for a recirculation process. | yes | yes | Via the fairphone website (Source 7) |
| **#3 Distribution** | | | | | |
| **St.** | **Category** | **Statement** | **Relevant for Product?** | **Executed?** | **Optional comments/bottlenecks** *(economic, technical, social, ...)* |
| 3.1 | Packaging | The company **uses reusable/standard packaging** *(European Pallet Association (EPAL), Returnable Plastic Crates (RPCs), International Fruit and Vegetable Container (IFCO), ...)* if possible. | partially | partially | "The packaging is optimized to use it as a package to send in an old device" (Source 8) |
| ... | ... | ... | ... | ... | ... |
| 3.5 | Distribution | The **$CO_2$ emission** during the **distribution process** is reduced to a **minimum** *(prefer environmentally sound types of transport, short distribution routes, ...)* . | yes | no | No sources were found for actions to reduce emissions in the distribution process |
| **#4 Use** | | | | | |
| **St.** | **Category** | **Statement** | **Relevant for Product?** | **Executed?** | **Optional comments/bottlenecks** *(economic, technical, social, ...)* |
| 4.1 | Strategy | The product was analysed with the aim of **detecting the most valuable parts** *(critical materials, high production effort, high costs, ...)* . **Actions** have been taken to design the parts circular *(modular, removable, extendable, upgradable, ...)* . | yes | no | Only F*ocus materials* are analysed (Source 2; p.33) |
| ... | ... | ... | ... | ... | ... |
| 4.10 | Utilisation | The **material consumption** of the product in the **utilisation stage** is reduced to a **minimum** *(minimize consumption materials, use renewable consumption materials, closed cycles for process materials, avoid waste, reuse waste, ...)*. | yes | yes | Possibility to send back the old modules |

Table 4.5: Excerpt of the circularity questionnaire assessing the Fairphone 4

The first line of the questionnaire was filled with information about the name of the evaluated product, the editor, the evaluation date and the version number. The version number is used to identify subsequent changes to the assessment.

Using the data from the LCA by *Sánchez et al. 2022*, the general questions in the questionnaire were answered. The weighting was done using the GWP (Global Warming Potentials) emissions per life cycle stage. The percentages can be taken from the report, and the relative impacts per life cycle were chosen from the 3-year scenario.[143]

The LCA divides the life cycle stages into four categories: 'Raw material extraction and manufacturing', 'Transport', 'Use' and 'End-of-life' (EoL). These differ from the life cycle stages in the questionnaire.
The stage 'Raw material extraction and manufacturing' has the largest share with 75% and covers two life cycle stages ('Raw material extraction' and 'Manufacturing') of the circularity assessment methodology. Therefore, half of the LCA GWP share is allocated for each life cycle stage, resulting in 37,5% for each.
The remaining GWP impact shares are 'Transport' (5%), 'Use' (16%) and 'EoL' (-4%). The EoL stage is not included in the circularity assessment methodology. The 4% is therefore divided between the remaining 4 stages. All shares are divided by 0,96 to normalise the values.

After weighting the life cycle stages, the questionnaire was completed. The data sources mentioned above were used, and in the column 'Optional comments/constraints' each question includes the source and, if necessary, a short explanation.
Despite the wealth of information available, some questions could not be answered definitively. These questions relate to internal company processes that cannot be assessed by outsiders. Such questions were left unanswered with a comment as an explanation.

The circularity questionnaire consists of 36 statements. 5 statements could not be assigned to a single life cycle stage and were classified as belonging to two life cycle stages. These statements were marked as identical.
30 statements were considered **relevant** for the Fairphone, while 2 statements were considered **partially** relevant. 2 statements were considered as **not relevant**. None of the statements were considered **prospective** relevant due to insufficient information about the product or internal company processes. 2 statements were left unanswered for the same reason.

143. David Sánchez, Marina Proske, and Sarah-Jane Baur, "Life Cycle Assessment of the Fairphone 4," 2022, Fig. 11; p.37, https://www.fairphone.com/wp-content/uploads/2022/07/Fairphone-4-Life-Cycle-Assessment-22.pdf

Of the 30 **relevant** statements, 20 were classified as **executed**, 6 as **partially** executed and 4 as **not** executed. None of the statements were considered **prospective**.
Of the 2 **partially** relevant statements, 1 were classified as **not** implemented and 1 as **partially** executed.

Each statement classified as **partially**, **prospective** or **relevant** is taken into account in the evaluation of the Value Retention Options (ROs). By linking the statements to the relevant ROs, the RO score can be generated after completion of the questionnaire.

### 4.2.3 Ranking of the circular strategies by highest potential

The ROs are generated using the completed questionnaire and the methodology for their calculation can be found in Chapter 3.3.2. The scoring of the ROs is presented in Table 4.6.

| Recirculation loops | Potential for improvement | Value Retention Options (ROs) | Potential for improvement | Score (points / total) |
|---|---|---|---|---|
| Short | 22% | R0: refuse | 5% | 9,5 / 10 |
| | | R1: reduce | 37% | 7,6 / 12 |
| | | R2: resell/reuse | 24% | 42 / 55,1 |
| | | R3: repair | 21% | 38,6 / 48,7 |
| Medium | 22% | R4: refurbish | 24% | 31,3 / 41,4 |
| | | R5: remanufacture | 20% | 28,5 / 35,8 |
| | | R6: repurpose/rethink | 21% | 27,3 / 34,6 |
| Long | 12% | R7: recycle | 8% | 22,5 / 24,4 |
| | | R8: recover | 16% | 10,3 / 12,2 |
| | | R9: remine | 17% | 9,8 / 11,7 |

Table 4.6: Evaluation of the most relevant ROs of the Fairphone 4

The fourth column of Table 4.6 shows the potential of each RO. The potential for improvement is generally low across all RO options. The RO **reduce** has the highest improvement potential with 37%, while **recycle** (7%) and **refuse** (5%) has the lowest improvement potential. The remaining seven ROs fall in between, with an improvement potential of around 20%.

The aggregated improvement potential within the recirculation loops of the ROs is shown in the second column. The **short** and **medium** loops show a higher potential of 22 % compared to the **long** loop with 12%.

The fifth column of Table 4.6 shows the scores of the individual RO's. The first value is the score achieved. The first value represents the achieved score, calculated using the predefined values of the response options. A higher score indicates a more positive response to the statements.

The second value is the total score, which results from the number of statements associated with each RO. Each statement is multiplied by its respective weighting factor and the total score is obtained by summing all statements.

With the scoring of the RO potentials, the results of the Fairphone criticality assessment are complete. The next step is to interpret the results and formulate improvement strategies.

# 5 Interpreting assessment results and formulating improvement strategies

This chapter discusses the results of the assessment of the Fairphone's criticality and circularity. The results obtained were analysed in detail and are presented here with particular emphasis on the relevant findings. The aim of this discussion is to derive improvement suggestions for the Fairphone's sustainability strategies based on the results of the assessment.

## 5.1 Discussion of the results of the criticality assessment

The results of the criticality assessment were presented using the dashboard introduced in Chapter 4.1.3. The advantage of the dashboard is that the assessment data can be easily filtered by assembly, part or material, allowing the results to be reviewed efficiently. The results are presented in the form of risk scores (colour coded according to risk level) for each of the 8 risk categories. The following sections not only look at the conspicuous aspects of the results, but also analyse other notable aspects of the criticality assessment.

### 5.1.1 The critical areas of the Fairphone 4

Several analyses were carried out, one of which was to determine the number of materials for which datasets were available. These records are crucial because they indicate the presence of a material in the database. The database contains all 87 materials examined in the *EU CRM 2023 report*. Therefore, the number of materials with datasets per assembly or part indicates how many potentially critical materials are used in these areas of the smartphone. The results of this analysis are shown in Table 4.1. Electronic assemblies (**electronics** and **screen**) had significantly more material entries than the other two assemblies (**battery** and **housing**). The parts of all assemblies had a consistent number of material entries, with the exception of the **display** part, which stood out with 7 material entries. The table also shows that the electronic parts (**electronics** and **screen**) have the highest density of critical materials. According to this evaluation, the **display** part of the Fairphone should be given the highest attention in terms of its criticality.

### 5.1.2 The critical raw materials of the Fairphone 4

The average risk score was calculated for each material, and the list of materials with the highest average risk scores is shown in Table 5.1 (see Table 4.3 for the entire list). Among the top 13 materials with the highest average risk scores, 8 are REE (Rare Earth Elements). However, the top three materials do not contain REEs, they are **gallium**, **cobalt** and **arsenic**.

| # | Material | Average risk score of the risk categories |
|---|---|---|
| 1 | Gallium | 77,7% |
| 2 | Cobalt | 74,2% |
| 3 | Arsenic | 73,9% |
| 4 | HREE Dysprosium | 73,8% |
| 5 | LREE Lanthanum | 73,8% |
| 6 | Phosphorus | 73,4% |
| 7 | LREE Neodymium | 71,8% |
| 8 | HREE Terbium | 70,8% |
| 9 | LREE Praseodymium | 69,4% |
| 10 | Lithium | 68,5% |
| 11 | HREE Gadolinium | 66,2% |
| 12 | HREE Yttrium | 65,8% |
| 13 | HREE Europium | 65,7% |

Table 5.1: Fairphone 4 materials with the highest average risk score of the risk categories

The materials **gallium**, **cobalt** and **arsenic** have similar risk scores in many risk categories (see Table 5.2). They show strong dependencies on other materials (By-Product Risk (BPR)) as well as on other countries (Concentration Risk (CR)). In addition, both the Current Supply Risk (CSR) and the Economic Risk of Importance (ERI) are high. These materials are essential for the economy, but are still critical in terms of sourcing due to existing dependencies.

| **Product:** | ***Fairphone 4*** | | | | **Edited by:** Thomas Mandl | | **Date:** 21.07.2023 **Version:** 1.0 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Materials** | **By-Product Risk (BPR)** | **Concentration Risk (CR)** | **Policy Stability Risk (PSR)** | **Social Stability Risk (SSR)** | **Current Supply Risk (CSR)** | **Future Demand Risk (FDR)** | **Economic Risk of Importance (ERI)** | **Recirculation Risk (RR)** | **Average** |
| Arsenic | 92% | 82% | 52% | 16% | 84% | 85% | 80% | 100% | 74% |
| Cobalt | 85% | 87% | 76% | 67% | 87% | 70% | 91% | 30% | 74% |
| Gallium | 100% | 99% | 55% | 11% | 92% | 82% | 83% | 100% | 78% |

Table 5.2: Dashboard of the Fairphone 4 materials with the highest average risk score

**Cobalt** stands out with a high Policy Stability Risk (PSR). Therefore, special attention should be paid to the sourcing of this material. The mining companies and mines involved in the extraction of **cobalt** should be independently certified or personally inspected.

For **gallium** and **arsenic** the Future Demand Risk (FDR) is very high. In addition, the Recirculation Risk (RR) is high, indicating low material recirculation. The combination of these risk factors suggests the need to develop circularity strategies for parts containing these materials. End-of-life strategies that result in material loss (landfill, recovery) should be avoided at all circumstances.

### 5.1.3 Risk score normalisation process

The risk scores in the criticality assessment dashboard are colour-coded according to their risk level, ranging from red for high risk to green for very low risk. Looking at the dashboard for all Fairphone materials (see Table 4.3 in the previous chapter), it is noticeable that 2 of the 8 risk categories tend to be marked as less critical. This observation is further supported by the calculation of the average risk score per risk category for all Fairphone materials, as shown in Table 5.3. The **Social Stability Risk (SSR)** stands out with the lowest average risk score of 23,3%, and the **Political Stability Risk (PSR)** has an average score of 49,4%, which is about 10% lower than the other risk categories.

| | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) |
|---|---|---|---|---|---|---|---|---|
| Average risk score of the Fairphone 4 materials | 59,7% | 79,1% | 49,4% | 23,3% | 75,1% | 59,6% | 84,9% | 61,7% |

Table 5.3: Average risk score of the risk categories of the Fairphone 4 materials

These discrepancies are due to the normalisation process. For the **SSR** and **PSR**, the normalisation boundaries for the risk scores were taken from the official websites (as described in Chapter 3.2.3). As a result of this boundary setting, all materials appear to be less critical overall compared to other risk categories. The issue of different normalisation boundaries was also recognised by *Helbig et al. 2016*, which illustrates the challenge of comparing parameter thresholds across different assessment methods. As a result, the assessment methods lose their comparability between each other.

While the different normalisation thresholds do not affect the comparability of materials within the same risk category, they do affect the comparability of risk categories to each other, introducing an offset. By adjusting the boundaries during the normalisation process, the offset in risk scores can be eliminated and the comparability between risk categories improved.

### 5.1.4 Consistency of data quality and availability of the Fairphone 4

The Fairphone is a modular smartphone consisting of 9 modules that can be easily replaced (see Figure 4.1 in previous chapter). This modular structure is desirable for implementation in the Excel tool. However, it was not possible to find any publicly available data that would accurately assign parts and materials to these modules. Therefore, data from general smartphones were used. During the analysis of different data sets[144] [145], there were inconsistencies between the material data. Ma-

144. Joint Research Centre et al., *Guidance for the assessment of material efficiency : application to smartphones*, p.61; Monique et al., *Fairphone Impact Report 2022*, p.33.
145. https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/ Accessed on 2023-07-21

terials were assigned to different areas of the smartphone or were not included in the product at all. The use of original Fairphone data would have provided more accurate information. It is therefore crucial to have access to the most reliable data from the product manufacturer.

The findings of the raw material criticality assessment of the Fairphone 4 are summarised in Table 5.8. The table is intended to provide an overview of the assessment method results. The detailed explanations of the various findings can be found in the sections above.

| Findings of the criticality assessment |
|---|
| A total of **26 different materials** of the Fairphone 4 were assessed |
| The electronic assemblies (**electronics** and **screen**) are the **most critical areas** of the Fairphone |
| The **display** part of the Fairphone should be given the **highest** attention in terms of its criticality |
| The **REE** (Rare Earth Elements) are often found in the most critical materials with the highest average risk scores |
| The **gallium**, **cobalt** and **arsenic** should be given the **highest attention** in terms of its criticality |
| For **cobalt** special attention should be paid to the **sourcing** of the material |
| For **gallium** and **arsenic** special attention should be paid in develop circularity strategies to **avoid material loss** (by landfill, recovery) in the end-of-life stage |

Table 5.4: Findings of the criticality assessment for the Fairphone 4

## 5.2 Discussion of the circularity assessment results

The Fairphone is a smartphone that has been designed with a strong focus on sustainability aspects. It is therefore not surprising that the results of the circularity assessment are very positive. The results were generated using the Criticality Questionnaire. In this section possible anomalies that occurred during the completion of the questionnaire are discussed. The presentation of the results is based on an evaluation of the most relevant Value Retention Options (ROs). The ROs consist of 10 R-imperatives for maintaining resource value. Although the Fairphone has been optimised for sustainability the ROs can help identify areas for improvement. The viability and feasibility of these strategies are also analysed in the following.

### 5.2.1 Analysis of the circularity questionnaire

The completed circularity questionnaire serves as the basis for the circularity assessment of the Fairphone. The entire questionnaire can be found in the appendix, in Table A.7. This section focuses on the statements from the questionnaire that led to an increase in the ROs (Value Retention Options) improvement potential. Therefore, Table 5.5 lists all statements which have answers resulted in an increase in potential. The last three columns of the table are particularly important as they represent the corresponding ROs. Each RO which would be affected by the action described in the statement of the questionnaire is linked with the related statement. When this statement is answered negatively the potential for improvement of linked ROs increases.

The circularity assessment questionnaire was completed using only Fairphone B.V.'s publicly available data. This approach carries the risk of not being able to make statements about internal company processes. All information must be derived from reports provided by the manufacturer. These reports may be biased and formulated for marketing purposes. It is therefore essential to use articles from independent third parties. In the case of Fairphone, sufficient independent information was available.[146][147][148] Nevertheless, two of the 36 statements could not be answered due to missing information.

30 statements were considered as relevant for the Fairphone. Of these, only 4 (St. 2.11/4.6; 3.5; 4.1) were declared as not executed. This combination of answers to the statements resulted in the largest increase in RO potential. All 4 statements were classified as not executed for the same reason: the lack of sources to confirm the implementation of these statements. This situation raises questions about the difficulty of obtaining internal company information, given the limitations of using only

146. Sánchez, Proske, and Baur, "Life Cycle Assessment of the Fairphone 4."
147. https://circular-iq.com/circular-economy-fairphone-successful-innovation Accessed on 2023-06-26
148. https://www.ifixit.com/Device/Fairphone_4 Accessed on 2023-06-26

| Product: | Fairphone 4 | Date: | 21.07.2023 | Edited by: |
|---|---|---|---|---|
| | | Version: | 1.0 | Thomas Mandl |

Excerpt of statements from the questionnaire with identified potentials

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/ bottlenecks (economic, technical, social, ...) | Relevant ROs | RO Points | RO Total |
|---|---|---|---|---|---|---|---|---|
| 1.8 | Material Prod-uction | The **raw material demand** of the product *(through targeted design, integration of functions, ...)* is revised to a **minimum**. | partially | no | Weight Fairphone 3: 190,4 g<br>Weight Fairphone 4: 225 g<br>Higher raw material demand can be compensated by a longer lifetime | R1 | 0,00 | 1,95 |
| 2.7<br>4.2 | Durability | The **visual appearance** of the product is designed to be **durable** *(durable materials, replaceable housing design, timeless design, ...)* .* | yes | partially | The visual appearance cannot be changed (different back covers,...) | R2, R4 | 1,95 | 3,9 |
| 2.8<br>4.3 | Durability | The parts of **non-dismountable modules** *(soldered components, battery packs, displays, ...)* are designed to have a **similar lifespan**.* | yes | partially | The modules can be replaced as a whole, but there is no information about the lifespan of the part within the module | R2, R3 | 1,95 | 3,9 |
| 2.11<br>4.6 | Durability | The product is designed to **provide functionality checks for consumable parts** (*software functionality check, wear indicators, main dimensions for proof of functionality, ...*) .* | yes | no | No sources found for functionality checks | R2, R3, R4, R5, R6 | 0,00 | 3,9 |
| 3.1 | Packa-ging | The company **uses reusable/standard packaging** *(European Pallet Association (EPAL), Returnable Plastic Crates (RPCs), International Fruit and Vegetable Container (IFCO), ...)* if possible. | partially | partially | "The packaging is optimized to use it as a package to send in an old device" (Source 8) | R2 | 0,06 | 0,25 |
| 3.5 | Distribu-tion | The **$CO_2$ emission** during the **distribution process** is reduced to a **minimum** *(prefer environmentally sound types of transport, short distribution routes, ...)* . | yes | no | No sources were found for actions to reduce emissions in the distribution process | R0, R1 | 0,00 | 0,5 |
| 4.1 | Strategy | The product was analysed with the aim of **detecting the most valuable parts** *(critical materials, high production effort, high costs, ...)* . **Actions** have been taken to design the parts circular *(modular, removable, extendable, upgradable, ...)* . | yes | no | Only Focus materials are analysed (Source 2; p.33) | R2, R3, R4, R5, R6 | 0,00 | 1,7 |
| 4.10 | Utilisation | The **material consumption** of the product in the **utilisation stage** is reduced to a **minimum** *(minimize consumption materials, use renewable consumption materials, closed cycles for process materials, avoid waste, reuse waste, ...)*. | partially | no | No sources found for reducing energy consumption during use, use stage according to LCA not very relevant for GWP impact | R0, R1 | 0,00 | 0,85 |

* The statement occurs in the "Use" and "Manufacturing" life cycle stage
Source 2: Fairphone Impact Report 2022
Source 8: https://www.fairphone.com/de/legal/fairphone-4-tagline-explained/ (Accessed on 2023-06-26)

Table 5.5: Statements from the circularity questionnaire that identified potential for the Fairphone 4

publicly available data sources.

In the general questions section of the questionnaire, life cycle stages were weighted. An adjustment had to be made due to a difference in the allocation of life cycle stages between the LCA and the circularity questionnaire. The raw material extraction and manufacturing life cycle stages were combined in the Fairphone LCA conducted by *Sánchez et al. 2022*. This was justified by the inability to differentiate the data for these two life cycle stages in the product.[149]

To address this issue of different life cycle stage allocation, a split was made between the ’raw material extraction’ and ’manufacturing’ life cycle stages in the questionnaire. The solution was to split the GWP (Global Warming Potential) of the ’raw material extraction and manufacturing’ life cycle stage in the LCA equally between these two life cycle stages. As a result, both life cycle stages (’raw material extraction’ and ’manufacturing’) have the same weighting in the questionnaire.

### 5.2.2 Identifying the most relevant circular strategies

In the evaluation process, the recirculation loops with their Value Retention Options (ROs) are ranked using the completed questionnaire. The ranking is based on the potential for improvement, which

149. Sánchez, Proske, and Baur, “Life Cycle Assessment of the Fairphone 4,” p.21.

| Value Retention Options (ROs) | Potential for improvement | Ranking 1(bad)...10(good) | Score (points / total) |
|---|---|---|---|
| R1: reduce | 37% | 1 | 7,6 / 12 |
| R4: refurbish | 24% | 2 | 31,3 / 41,4 |
| R2: resell/reuse | 24% | 3 | 42 / 55,1 |
| R6: repurpose/rethink | 21% | 4 | 27,3 / 34,6 |
| R3: repair | 21% | 5 | 38,6 / 48,7 |
| R5: remanufacture | 20% | 6 | 28,5 / 35,8 |
| R9: remine | 17% | 7 | 9,8 / 11,7 |
| R8: recover | 16% | 8 | 10,3 / 12,2 |
| R7: recycle | 8% | 9 | 22,5 / 24,4 |
| R0: refuse | 5% | 10 | 9,5 / 10 |

Table 5.6: Ranking of the ROs according to their potential for the Fairphone 4

indicates the extent of the possibilities for improvement. The higher the potential, the more important the specific circular strategy is and the more attention it should receive.

Overall, the improvement potential of all ROs for Fairphone is relatively low, with no significant outliers. This is in line with Fairphone B.V.'s corporate philosophy, as positive evaluation results were expected from the example of the Fairphone 4 product. The modular design of the device, together with the availability of spare parts from the manufacturer and the resulting extended product life, contribute significantly to the positive assessment of circularity.

Despite the generally positive assessment, a closer analysis of the ranking is necessary. Recycling emerges as the least relevant strategy, with only 8% potential for improvement. Fairphone B.V. often emphasises its strong focus on recycling. However, recycling is primarily a strategy for long recirculation loops, which cause a significant loss of material value. It is therefore best suited to low-value materials, such as the plastics used in device casings. For Fairphone B.V., recycling is particularly relevant for plastic modules, as all plastics used in the Fairphone are 100% recycled. However, the recycling strategy does not show much potential for improvement.

At the top of the ROs evaluation, the reduce strategy stands out with a potential for improvement of 37%. In order to make meaningful improvement suggestions, it is crucial to understand the meaning of the reduce strategy in relation to the Fairphone. Reduce is a short loop strategy that aims to act preventively by reducing the overall material consumption in the Fairphone. Reduction has the largest impact when focused on materials with a high environmental impact, such as gallium, cobalt

| Recirculation loops | Potential for improvement | Ranking 1(bad)..3(good) | Score (points / total) |
|---|---|---|---|
| Short | 22,3% | 1 | 97,7 / 125,8 |
| Medium | 22,1% | 2 | 87,1 / 111,8 |
| Long | 11,8% | 3 | 42,6 / 48,3 |

Table 5.7: Ranking of the Fairphone 4 recirculation loops potential for improvement

and arsenic. These materials have been identified as significant critical in the criticality assessment. The reduction strategy can be applied throughout the manufacturing process. By increasing efficiency, the need for natural resources and materials is minimised. According to the LCA of the Fairphone 4, 78% of the $CO_2$ equivalent emissions occur during the 'raw material extraction and manufacturing' life cycle stage.[150] This information represents an opportunity for improvement. However, without detailed information on the exact manufacturing processes of the Fairphone, the identified potential remains limited and requires further investigation with the required data.

The analysis of the recirculation loops is also discussed. Table 5.7 provides a ranking of the three recirculation loops.

All recirculation loops show a very low potential for improvement. Of these, the short loop has the highest potential at 22%. The short loop includes waste reduction and resell/reuse strategies. The short loop strategies involve the least material value loss, mainly due to the preventive approaches of the refuse and reuse strategies. The strategies are based on the idea that materials are either avoided or used in minimal quantities.

The Fairphone can effectively use this approach of short loops strategies. Many improvement potentials of medium and long loop ROs are limited due to the sustainable design of the Fairphone. Therefore, strategies to reduce or substitute critical materials (like the identified materials of the raw material criticality assessment) in the smartphone can be considered. These circularity strategies may face technological implementation bottlenecks which provide new areas for improvement identified through the application of the circularity assessment methodology.

The findings of the circularity assessment of the Fairphone 4 are summarised in Table 5.8. The table

150. Sánchez, Proske, and Baur, "Life Cycle Assessment of the Fairphone 4," p.37.

is intended to provide an overview of the assessment method results. The detailed explanations of the various findings can be found in the sections above.

| **Findings of the circularity assessment** |
|---|
| Many circularity strategies have already been carried out for the Fairphone 4. It can be shown with the **high execution rate** (30 out of 36) of the **relevant statements** of the circularity questionnaire |
| For a **answer to all statements** of the questionnaire, **internal company information** of the Fairphone 4 is necessary |
| The potentials of the ROs are very balanced. **Reduce** (37%) shows the **highest** potential for improvement, **recycle** (8%) and **refuse** (5%) the **lowest**. |
| **Short** recirculation **loop strategies** may **face technological implementation bottlenecks** which can provide new areas for improvement |

Table 5.8: Findings of the circularity assessment for the Fairphone 4

## 5.3 Recommendations for improving the Fairphone 4

The following section presents strategies for improving the Fairphone 4 based on the results and findings of the criticality and circularity assessment. Due to the company's ideology, efforts have already been made to design the Fairphone 4 with environmental considerations in mind. These efforts will also be taken into account.

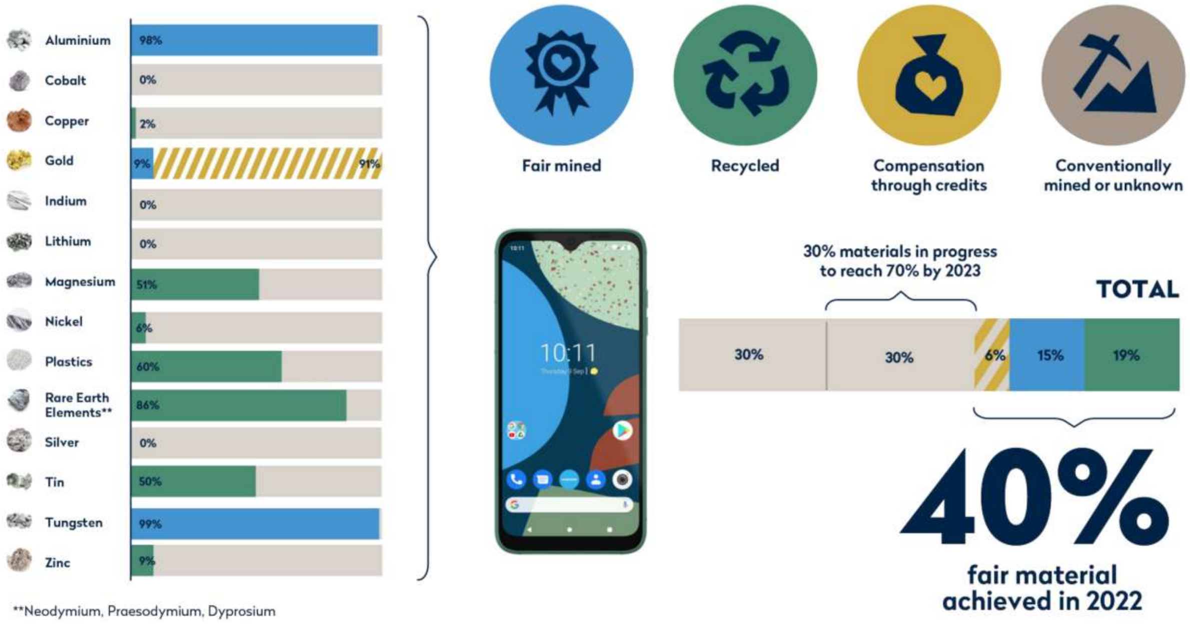



Figure 5.1: Focus materials with the fair materials sourcing status of the Fairphone 4[151]

The company Fairphone B.V. has already defined 14 focus materials for the Fairphone 4. Breaking down the 3 REEs within the selection the focus materials results in 16 entries (see Figure 5.1). In the raw material criticality assessment of the Fairphone smartphone 14 of these 16 materials are included. The assessment includes all materials except plastics and zinc (although present as data, they could not be attributed to any component of the Fairphone). Table 5.9 ranks the Fairphone's materials based on their average risk score. The table combines the criticality assessment results with the focus materials defined by the Fairphone B.V.. It indicates whether a material is a focus material and the extent to which it is fairly sourced in the Fairphone 4. In the definition of the Fairphone B.V. fair sourcing of materials can be achieved by responsible mining, use of recycled materials or compensation through credits during material extraction. These three approaches are used by the company to calculate the 'Fair material sourcing status'.[152]

The comparison between the 14 focus materials reveals variations in their risk scores. Cobalt has the highest average risk score of the focus materials with 74%. The fair sourcing status for cobalt is still

151. Source: Monique et al., *Fairphone Impact Report 2022*, p.34
152. Monique et al., p.34.

| # | Materials | Focus Material[a] | Fair material sourcing status of Fairphone[a] | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Gallium | no | | 100% | 99% | 55% | 11% | 92% | 82% | 83% | 100% | 78% |
| 2 | Cobalt | yes | 0% | 85% | 87% | 76% | 67% | 87% | 70% | 91% | 30% | 74% |
| 3 | Arsenic | no | | 92% | 82% | 52% | 16% | 84% | 85% | 80% | 100% | 74% |
| 4 | HREE Dysprosium | yes | 86% | 100% | 85% | 56% | 18% | 98% | 64% | 94% | 75% | 74% |
| 5 | LREE Lanthanum | no | | 93% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | 74% |
| 6 | Phosphorus | no | | | | 51% | 15% | 89% | 100% | 85% | 100% | 73% |
| 7 | LREE Neodymium | yes | 86% | 100% | 85% | 48% | 19% | 94% | 61% | 92% | 75% | 72% |
| 8 | HREE Terbium | no | | 100% | 85% | 56% | 18% | 96% | 47% | 90% | 75% | 71% |
| 9 | LREE Praseodymium | yes | 86% | 100% | 85% | 48% | 19% | 89% | 48% | 92% | 75% | 69% |
| 10 | Lithium | yes | 0% | 52% | 81% | 20% | 29% | 84% | 99% | 83% | 100% | 68% |
| 11 | HREE Gadolinium | no | | 100% | 85% | 48% | 19% | 89% | 32% | 81% | 75% | 66% |
| 12 | HREE Yttrium | no | | 29% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | 66% |
| 13 | HREE Europium | no | | 100% | 85% | 48% | 19% | 98% | 19% | 81% | 75% | 66% |
| 14 | Indium | yes | 0% | 100% | 84% | 37% | 19% | 48% | 72% | 71% | 75% | 63% |
| 15 | Antimony | no | | 80% | 78% | 61% | 26% | 83% | 66% | 87% | 24% | 63% |
| 16 | Tantalum | no | | 28% | 69% | 68% | 60% | 81% | 34% | 86% | 75% | 62% |
| 17 | Silicon metal | no | | | | 50% | 13% | 82% | 38% | 86% | 100% | 61% |
| 18 | Silver | yes | 0% | 71% | 61% | 51% | 16% | 64% | 38% | 85% | 67% | 57% |
| 19 | Tungsten | yes | 99% | | 92% | 55% | 13% | 81% | 32% | 96% | 19% | 55% |
| 20 | Aluminium/Bauxite | yes | 98% | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% | 52% |
| 21 | Nickel | yes | 60% | 2% | 73% | 42% | 28% | 40% | 87% | 88% | 40% | 50% |
| 22 | Magnesium | yes | 51% | 5% | | 53% | 11% | 92% | 32% | 93% | 45% | 47% |
| 23 | Tin | yes | 50% | 3% | 69% | 57% | 26% | 72% | 35% | 85% | 23% | 46% |
| 24 | Gold | yes | 1% | 14% | 47% | 33% | 26% | 32% | 43% | 62% | 64% | 40% |
| 25 | Copper | yes | 2% | 9% | 61% | 38% | 32% | 8% | 65% | 83% | 15% | 39% |
| 26 | Lead | no | | 10% | 73% | 44% | 14% | 8% | 37% | 84% | 6% | 35% |

[a]: Fairphone Impact Report 2022: p.34

Table 5.9: Average risk score ranking of the Fairphone 4 raw material criticality assessment

0%. The analysis of the risk categories with a 'high risk' for cobalt suggests that efforts should be focused on assessing local mining conditions (SSR) and the selection of the sourcing countries (BPR and CR).

Comparatively, the risk categories for HREE dysprosium are similar. But for dysprosium 86% of the material is obtained through recycling (see Figure 5.1). Therefore, primary efforts should be focused on other critical materials with a lower fair material sourcing status.

The *Fairphone Impact Report 2022* notes the consideration of additional focus materials. These materials are not yet included but are in progress to cooperate with mines where impact programs are running.[153]

Regarding the selection of focus materials, it is advisable to include more than just the 3 REEs (Rare Earth Elements) based on the risk assessment results. Currently, Fairphone B.V. only considers dys-

153. Monique et al., *Fairphone Impact Report 2022*.

prosium, neodymium and praseodymium among the REEs. All assessed REEs (including HREE and LREE) of the Fairphone 4 have an average risk score exceeding 63%. The potential relevance of more than the 3 REEs already included in the focus materials should be considered.
Further materials should also be assessed for relevance based on the criticality assessment results, particularly those not currently designated as focus materials by Fairphone B.V.. These include gallium and arsenic, in addition to the REEs. Both materials exhibit similar risk characteristics in terms of risk scores with gallium being more critical than arsenic. Given the dependency on other materials (BPR) and countries (CR) for the supply of these materials, an increased focus on recycling should be emphasised. Presently, neither of these materials undergo recycling due to the RR.

The results of the circularity assessment for the Fairphone 4 are generally very positive. It is noticeable that the company has made a concerted effort to implement its circular strategies effectively. The results of the circularity questionnaire, together with the calculated improvement potentials for various ROs, range from 5% to 37% (see Figure 5.6). The potential for improvement in the recirculation loops is also low, ranging from 12% to 22% (see Figure 5.7). This means that the recommendations for improvement in the Fairphone 4 may not have a significant impact.
A first step in formulating recommendations was to examine the individual statements in the questionnaire that contribute to the potential for improvement (see Figure 5.5). The modular design and easy disassembly of the Fairphone contribute significantly to its high circularity performance. Repairing or upgrading individual modules prolongs the life of the product and its usability for the user. However, one aspect of the Fairphone 4 that cannot be easily changed is its appearance. The possibilities to expand or change the aesthetics of the smartphone are limited. In this respect, a modular outer shell and a choice of colours could provide a solution.
Among all ROs the R1 (reduce) has the greatest potential for improvement for the Fairphone. Based on this, efforts should focus on reducing the required material input at all stages of the smartphone's life cycle. This includes reducing critical materials and waste generated during the manufacturing process. According to the results of the circularity assessment, the "reduce" RO has the greatest leverage for the Fairphone 4.
In conclusion, the circularity performance of the Fairphone 4 is excellent and the focus should be on improving the criticality performance.

Table 5.10 summarise the improvement ideas based on the results of the criticality and circularity assessments. Both assessments aim to identify relevant components or areas within the product. These areas can be assemblies, parts or raw materials. They need to be kept circular through ecodesign strategies such as short recirculation loop strategies. This can be achieved by sourcing materials

| Assessment | Improvement Ideas |
|---|---|
| Raw material criticality | **Increasing** the **fair material sourcing status** of **cobalt** as it is a very critical material and the status is 0%, pay attention to the regional mining conditions |
| | Include **more** than just the current **REEs** (dysprosium, neodymium, praseodymium) in the list of **focus materials** like lanthanum, terbium, gadolinium, yttrium or europium |
| | Include **gallium** and **arsenic** in the list of **focus materials**, pay attention on the reduction of dependence on other materials or countries in the procurement through an increase of the recycling rate |
| Circularity of a product | Improve the possibilities to **upgrade or change** the **visual appearance** of the Fairphone 4 |
| | The **reduction** of materials and waste **along** all **life cycle stages** |

Table 5.10: Summary of the recommendations for improving the Fairphone 4

circularly, employing recycled materials or minimising the reliance on newly mined products.

# 6 Conclusions on the assessment methods used and potential for the future

The criticality of the Fairphone 4 raw materials and the circularity of the smartphone as a whole were analysed in the previous chapters. The application of the assessment methods were supported by the developed tools. The results of the assessments were presented (see Chapter 4), followed by a comprehensive analysis and interpretation (see Chapter 5.1 and 5.1). By analysing the assessment results, efforts were made to identify valuable materials and components within the smartphone. Relevant processes were studied from a holistic perspective across all life cycle stages. Improvement approaches were formulated for the most valuable areas of the product (see Chapter 5.3).

In this chapter the topics addressed in this thesis with the key findings are summarised. In addition, prospects for future developments in environmental assessment methods are presented.

## 6.1 Summary and potential for improvement of the developed criticality and circularity assessment methods

Before developing the criticality and circularity assessment methods, a literature review was conducted to identify existing standard methods used for similar assessments. None of the established methods met all the requirements. Therefore, new assessment methods had to be developed. It is notable that both criticality and circularity assessments are based on established methods.

For the criticality assessment, the basic structure of the European Union's Critical Raw Material (CRM) methodology was used. This approach was combined with a scaled risk factor system to allow comparison between selected risk categories. Similar approaches are commonly found in the literature (e.g. *Graedel et al. 2015* or *Kolotzek et al. 2018*).
For the circularity assessment, a questionnaire was used to identify existing potential for improving circularity. This process was based on pre-existing Life Cycle Assessment (LCA) data of the product, which can be obtained through Environmental Product Declaration (EPD) according to standardised guidelines (*DIN EN ISO 14025*, *DIN EN ISO 14040*). The statements in the questionnaire were inspired by various online tools (see Chapter 3.3.2) to comprehensively cover all relevant aspects of the product's life cycle.

Due to limited resources and the requirement to develop two different assessment methods (criticality and circularity) within this thesis, the methods had to be kept rather simple. Consequently, the tools for both assessment methods were implemented using Microsoft Excel files.

The assessment of the Fairphone 4 should be seen as a first step towards developing environmental assessment methods such as raw material criticality and circularity. For each assessment, methods were developed based on existing norms and standards. In addition, the methods were designed to be easily extended and improved.

This allows more complex thematic areas like macro economy and global market aspects to be included within the criticality assessment. The increasing complexity leads to more meaningful results of the criticality of materials, but the demands on the data quality for the evaluations also increase. This is not yet possible with the data quality currently available.

The circularity assessment questionnaire has potential for future expansion. It should also be tailored to specific product categories. If there are standards or guidelines for these products, these should also be included in the questionnaire.

The final step of interpreting the results for criticality and circularity currently requires an expert. The use of a checklist with resulting actions can address this need.

In the future, the establishment of standards for environmental assessment methods in industry will be crucial. At the time of writing this thesis in 2023, there are numerous assessment methods, each developed for different product niches but providing non comparable results. Meta-studies have been conducted for both criticality (*Helbig et al. 2021*) and circularity (*Kirchherr et al. 2017*), revealing a diverse landscape of assessments. Many new methods have emerged, often following similar approaches to established methods, but producing non-comparable results. Addressing this issue will require the intervention of standardisation bodies and legislators to ensure uniformity.

Equally important is the creation of future standards for assessment methods within educational institutions and universities. Scientific work like this thesis contributes to the advancement of sustainable product development.

## 6.2 Influence of data availability on assessment methods

One of the main challenges in developing the assessment methods has been the collection of data. Such data includes both product-specific information and data on raw material properties. No new data was generated for the assessments, only publicly available databases and information were used. In addition, there was no direct contact with the manufacturer of the assessed product, the Fairphone 4. These circumstances, combined with the general problem of availability of high quality and comparable data, resulted in several challenges.

In the context of assessment methods, only what is known can be assessed. The accuracy of the raw

data directly affects the quality of the assessment results.
The issue of data scarcity was more prominent in the criticality assessment. Requirements have been set for data sources used in this assessment to ensure a minimum standard of data quality. While well known institutions such as the European Union or the United States Geological Survey provide high quality raw material data, even they face challenges in ensuring data consistency to produce comparable assessment results. For this reason, the EU CRM report for 2023 sets the expansion of Eurostat's resource database as an objective to improve the results of the CRM assessment method in the future.[154]

To improve data quality, it is crucial to tailor data collection to specific needs and specifications. For example each mine producing a particular raw material must be assessed individually by its social standards to guarantee good data quality. Rather than use generalised national average data of social standards of mining.
Data quality will play a major role in the future of assessment methods and will determine their relevance for legislative action and industry acceptance.
In the Fairphone 4 circularity assessment, the lack of information on internal company processes was a challenge. 6 out of 36 statements in the circularity questionnaire could not be fully answered due to this information shortage.

Data availability plays a fundamental role in achieving meaningful and verifiable assessment results. Relevant industry stakeholders and regulators need to work together to address this challenge and create a win-win situation where better data leads to improved assessment methods and vice versa. With the help of a coordinated effort, more accurate and effective product sustainability assessment methods can be developed.

## 6.3 Potential of assessment methods to support circular economy development

Actual there are a number of parallel initiatives focusing on the development of assessment methods to evaluate circular economy concepts. Notable examples include the *ISO/TC 323 - Circular Economy*[155] or the *Deutschen Normungsroadmap Circular Economy*.[156] Standardisation committees are working to create the basis for standardised evaluation methods. Legislators have also taken initial steps in this direction, in particular the European Union with programmes such as *SCRREEN* (Solutions for Critical Raw Materials - A European Expert Network) and the *EU Circular Economy Action Plan*.

154. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*, p.42.
155. https://www.iso.org/committee/7203984.html Accessed on 2023-07-27
156. Winterhalter, Teigeler, and Westerkamp, *Deutsche Normungsroadmap Circular Economy*.

As part of the *EU Circular Economy Action Plan*, the EU published the *Directive 2009/125/EC*[157] on June 16th, 2023, which establishes ecodesign requirements for smartphones, mobile phones other than smartphones, cordless phones and slate tablets. This directive requires smartphone manufacturers to implement ecodesign regulations in their products by 2025. The directive includes provisions such as a two-year warranty period during which defective devices must be repaired or replaced free of charge. Critical spare parts must be made available to professional repairers for at least 7 years after the end of sales of the product model on the EU market. System upgrades must be available for at least 5 years after the product is shipped. Professional repairers must have non-discriminatory access to any necessary software or firmware for replacement. These are just some of the ecodesign requirements that will be mandatory for all smartphone manufacturers in Europe by 2025.
Table 6.1 provides a comparison of how many of the requirements outlined in the directive are covered by the assessment methods developed in this thesis. The assessment methods were developed independently and without any influence from the requirements of the directive. The comparison was done after the assessment methods had been finalised. It was found that there was agreement between the assessment methods and 8 of the 16 summarised requirements of the directive. The purpose of this comparison is to demonstrate that the assessment methods can be used in part to assess electronic equipment for compliance with *Directive 2009/125/EC*. Of course, adjustments to the assessment methods will have to be made in practice.

It is hoped that such initiatives will be extended to other product categories in the future. As a result, the importance of assessment methods to support the development of these guidelines will increase, requiring further efforts to improve existing assessment methods.
Increased adaptability and a situational approach are crucial for the improvement of circular economy strategies.

Furthermore, it is necessary to support the adaptation of assessment methods for developing countries. Most methods are currently tailored to first world countries, leaving the question of how to assess critical commodities in developing countries. This discussion should be intensified in order to broaden the scope and applicability of assessment methods to other parts of the world.

Creating a sustainable circular economy requires a concerted effort by all stakeholders. A structural change in the mindset of all sectors of society is essential to achieve this goal. Everyone has a role to play, whether through more conscious consumption, sustainable production or supporting circular

157. European Commission, *C(2023) 3538 final COMMISSION REGULATION (EU) of 16.6.2023 laying down ecodesign requirements for smartphones, mobile phones other than smartphones, cordless phones and slate tablets pursuant to Directive 2009/125/EC of the European Parliament and of the Council and amending Commission Regulation (EU) 2023/826*, technical report (2023), https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=PI_COM:C(2023)3538.

| Directive 2009/125/EC requirements | Implementation in the assessment methods |
|---|---|
| Availability of spare parts until at least 5 years after end of market placement (e.g. battery, display, speakers, camera, etc.) | Circularity Questionnaire (CQ) Statement (St.) 4.9: There are **spare parts/software updates provided** for a reasonable period of time (*in relation to the product lifetime)*. |
| Parts should be publicly accessible on a free website and be delivered within 5 working days | |
| Repair instructions should be publicly accessible for at least 7 years after the end of market placement | CQ St. 4.7: There is information/instruction provided for the **user** to carry out **services** *(repairs, maintenance, life-extending measures, ...)* **by his own.** |
| Fasteners should be removeable and the repair should be feasible by a generalist with no tools or with commercially available tools | CQ St. 2.4: The **housing** of the product can be **opened easily and damage-free** in order to access the internal components.<br>CQ St. 2.6: The **electronic modules** *(PCB, CPU, sensors, ...)* of the product are designed with **detachable connections** *(plug-in connections)* instead of being soldered. |
| Resistance to at least 100 drops from 1 meter without functionality loss in defined parameters (e.g. pixels, wifi-connection, buttons, vibration alarm, etc.) | |
| Scratch resistance against level 4 on Mohs hardness | |
| Dust (> 1mm) and splash water resistance | |
| At least 500 cycles of battery with 80% remaining capacity & function to disable charging over 80% to avoid battery damages | |
| Free software updates at least for 5 years (security) and 3 years (functionality) after end of market placement | CQ St. 4.9: There are **spare parts/software updates provided** for a reasonable period of time (*in relation to the product lifetime)*. |
| No performance loss due to software updates | |
| Plastic components heavier than 50g should be marked by specifying the type of polymer if technically possible, some exceptions exist (e.g. PCB assemblies, PMMA boards, speakers, etc.) | |
| Disassembly information for at least 15 years after the end of market placement | CQ St. 4.7: There is information/instruction provided for the **user** to carry out **services** *(repairs, maintenance, life-extending measures, ...)* **by his own.** |
| Information about the amount of specific critical raw materials (cobalt, tantal, gold, neodymium) | CQ St. 1.6: There is **product specific information** *(list (BOM) of all raw materials in the product/parts, on an element basis, ...)* **available** to support end-of-life strategies.<br>CQ St. 1.7: The **most valuable materials** *(critical in supply, most expensive, not reusable, ...)* of the product are **known**. |
| Information about the percentage of recycled content in the product | Dashboard of the criticality assessment<br>CQ St. 1.6: There is **product specific information** *(list (BOM) of all raw materials in the product/parts, on an element basis, ...)* **available** to support end-of-life strategies. |
| Information about the recyclability rate (Rcyc) | Dashboard of the criticality assessment |
| Information about the battery (e.g. date of first use, number of charges, etc.) | |

Table 6.1: Correspondence of the *Directive 2009/125/EC* requirements with the assessment methods

economy initiatives.

For policy makers, assessment methods play an important role in decision making. As many decision-makers are afraid of making mistakes, these methods serve as a protection. Continuous development and improvement of assessment methods is necessary to carry the burden of decision making and to provide a solid basis for legislative action. By continuously improving these methods, decisions can be made on a solid basis to promote the circular economy and having a long-term positive impact on society and the environment.

# 7 Design guidelines for environmental product design addressing criticality and circularity

This chapter serves as a addition to the chapters explaining and implementing the assessment methods. Its purpose is to provide a preliminary step towards the assessment methods. The topics presented in this chapter revolve around the question 'How should electronic components be designed to perform well in the assessment methods?'.

It therefore serves as a preparation for the product and components to be evaluated. On the other hand, it aims to make product designers aware of the issues of raw material criticality and product circularity. The requirements for electronic products and components will be clarified in order for them to excel in terms of their criticality and circularity performance.

The requirements represented in this chapter are also referred to as design guidelines. The challenge of designing for environmental performance lies in its complexity. Each product and its components may have different requirements for good environmental product design. Some parts are designed for short-term use, while others are intended to operate for many years or even decades. Each product must be considered on its individual characteristics. Therefor it is difficult to make general statements about how to ensure environmentally sound product design. The topic about individual assessment of each component or material has already been discussed in detail in the previous chapters. This chapter is essentially an extended summary of the work in which the findings are again structured and formulated but with a stronger emphasis on the phase before the assessment of criticality and circularity and the formulation of improvement strategies.

## 7.1 The need for individual component analysis

To achieve excellent environmental performance, a thorough analysis of the product or component is essential. Each product and its components have unique characteristics, including factors such as lifetime, context of use and composition of parts and assemblies. Assessment of these elements plays a key role in making informed design decisions during product development.

To improve raw material criticality performance, it is essential to start with a comprehensive understanding of the materials used in the product or component. Information on the materials used, especially in purchased parts, is traditionally unavailable. Without such material information, it is not possible to carry out assessments and formulate guidelines. The formulation of guidelines assumes that this knowledge is available.

In the product development process, it is advisable to start by identifying critical materials. These materials typically relate to electronic components, such as Rare Earth Elements (REE) and usual not to structural and packaging materials, such as plastics. The more information that is available about these materials, the more effective performance-enhancing strategies for criticality improvement can be defined.

Key information includes the origin and extraction conditions of the raw materials. Ideally, there should be a comprehensive review of the exact sourcing areas and on-site conditions for all materials. In addition, all materials should be analysed for substitutability, with a selection of alternative materials available in the event of unfavourable assessments. The depth and extent of such screening should be determined on a case-by-case basis, taking into account available data and feasibility. These information can be difficult to determine.

Another alternative worth exploring is the purchase of secondary raw materials or renewable materials. They offer several advantages over primary raw materials, including another way to obtain the material and a potentially related reduced risk of supply shortages. However, the suitability of secondary or renewable raw materials for specific applications should be carefully assessed.

Components containing several critical materials should ideally be designed to allow disassembly. Modular design enables lifespan extending strategies like repair, which is cost effective in case of valuable materials. Modular design also supports the recovery of materials at the end-of-life stage. Components with valuable materials are typically electronic component like Printed Circuit Boards (PCB).

In order to optimise the circularity performance of components, a clear understanding of the type and role of components in the product is essential. Different component types require different product development strategies depending on their use. Whether they are consumables, key functional components, non-replaceable parts, housing components or other. The value of components varies accordingly, with higher value components warranting value retention strategies.

Component lifetime is a critical factor in circularity. All components in the final product should aim for a harmonised lifetime. If this is not possible, strategies for managing component lifetime should be integrated into the product design, as discussed in the following section.

Regardless of the type of component, all must at least meet the standard of waste management strategies at the end of its life. Waste management strategies for the product should be considered during product development through design features such as easy disassembly of components, uniform materials within components or modular construction.

The summarised guidelines for the individual analysis of each component are presented in Table 7.1.

| Category | Guidelines to achieve good performance in criticality and circularity |
|---|---|
| Analysis of each component | All materials of the product and their components are known |
| | The regional origin of the materials is known |
| | The degradation conditions of the materials are known |
| | A screening of the substitutability of the materials has been made |
| | The option of using secondary materials has been analysed |
| | The components with the largest number of critical materials are known |
| | The components with the largest number of critical materials are modularly designed |
| | The predicted lifetimes of all components are known |
| | The lifetimes of all components are harmonized |
| | All components have a waste management strategy |

Table 7.1: Guidelines for the individual analysis of each component

## 7.2 Strategies for the improvement of criticality and circularity

In the product development process it is crucial to be aware of the tools available to influence the performance of component criticality and circularity. For criticality this primarily involves knowledge of critical materials, while for circularity R-imperatives serve as the basis for component design decisions.

To improve the criticality of a product or component, it is essential to start with an understanding of the materials in the product. Based on this knowledge, strategies for substitutions should be established. These substitutions may involve materials or material suppliers. This means having alternatives for the materials used in the product. These pre-established substitution strategies can be used in the event of supply shortages. In general questions such as "Where can the material be sourced if the preferred supplier is unavailable?" and "What can the material be substituted with?" should always have answers to improve the criticality strategies.

The more information available on the criticality of individual materials, the more specific the strategies can become, focusing on individual materials. The more critical a material, the earlier in the product development process substitution strategies should be developed. Lists of critical materials such as the EU CRM[158] or the USGS CML[159] can be helpful references.

The ability to control circularity has been introduced in this work with the concept of the 10R framework. A detailed description of the concept can be found in Chapter 3.3.3. The concept is based on the premise that R-imperatives can be used to retain the value of components during their use, also termed as Value Retention Options (ROs).[160] Product designers can implement these ROs through

158. European Commission et al., *Study on the EU's list of critical raw materials (2023) : Final Report*.
159. U.S. Geological Survey, *Mineral commodity summaries 2023: U.S. Geological Survey*.
160. Reike, Vermeulen, and Witjes, "The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options," p.253.

product design strategies within the components. Not all ROs are relevant for every component, as their applicability varies depending on the requirements of the component.
It is important to note that for achieving a good circularity the minimum requirement during product development is to establish an appropriate waste management strategy for each component. In the context of the 10R framework, these are referred to as long loop ROs, which include recycling, recovery and re-mining. These options causes the highest value reduction and should therefore be considered as preferred ROs for less valuable components. An example of such components are the plastic housings of electronic components.
Other ROs should be used for more valuable components. The role of ROs is to ensure that the value of the component is maintained over time. This may involve components of the PCB that can be easily disconnected and replaced via connectors in the event of a malfunction, thus maintaining the functionality of the entire component.

The strategies for improving criticality and circularity are deliberately broad, as different component types have unique requirements and implementation options. It is in the responsibility of the designer to implement these strategies effectively. It is neither feasible nor practical to implement all strategies for every component. Therefore, the next section focuses on how to select the most appropriate strategies.

The summarised guidelines for improvement strategies related to criticality and circularity are presented in Table 7.2.

| Category | Guidelines to achieve good performance in criticality and circularity |
|---|---|
| Strategies to improve criticality and circularity | Any relevant material can be sourced by an alternative in case of failure of the preferred supplier |
| | If necessary, relevant materials can be replaced by alternative materials |
| | For each component, a strategy for setting the minimum requirement of a long loop RO is developed |
| | For more valuable components, strategies to implement ROs with a higher increase of circularity are developed |

Table 7.2: Guidelines for improvement strategies of criticality and circularity

It is not advisable to implement all criticality and circularity improvement strategies for every component from the beginning of product development. It is essential to identify and understand the most critical materials or components of the products through analysis and to determine why they are critical. Based on this understanding, the most efficient improvement strategies can be developed. Efficiency of strategies refers to the balance between benefits and efforts.
The assessment methods for criticality and circularity developed in this work should provide a tool

for evaluating the most efficient strategies. If design guidelines are established prior to the assessment such as during the product development phase, only more general strategies can be defined. Depending on the level of detail of information and understanding of the materials and components of the product, strategies can also be refined.

In general, it is important to protect and design valuable materials or components to ensure their longevity throughout the product life cycle and to facilitate efficient recovery at the end-of-life stage. Conversely, less valuable materials or components should be designed for effective recovery through waste management strategies. A factor to be considered in the formulation of all design strategies is the feasibility of the requirements, which is the responsibility of the designer.

The formulated design guidelines should be seen as a precursor to the evaluation methods for criticality and circularity. It is essential to know and understand the product and its components, including the identification of valuable materials and components. For all materials and components, appropriate waste management strategies must be in place to avoid waste.

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# Appendix

## A.1 Table of countries indicator calculation of the criticality assessment tool

| # | Countries (ISO 3166) | WGI 2021 scaled (0-10)[a] | WGI 2021 risk score (0-100%)[c] | HDI 2021 score (0-100%)[b] | HDI 2021 risk score (0-100%)[c] |
|---|---|---|---|---|---|
| 1 | Afghanistan | 8,18 | 86,8% | 47,8% | 78,3% |
| 2 | Albania | 5,07 | 47,1% | 79,6% | 9,5% |
| 3 | Algeria | 6,72 | 68,2% | 74,5% | 11,1% |
| 4 | American Samoa | 3,07 | 21,6% | | |
| 5 | Andorra | 2,15 | 9,8% | 85,8% | 37,8% |
| 6 | Angola | 6,87 | 70,1% | 58,6% | 69,0% |
| 7 | Anguilla | 3,23 | 23,6% | | |
| 8 | Antigua and Barbuda | 4,08 | 34,5% | 78,8% | 9,8% |
| 9 | Argentina | 5,11 | 47,6% | 84,2% | 39,8% |
| 10 | Armenia | 5,35 | 50,7% | 75,9% | 10,7% |
| 11 | Aruba | 2,59 | 15,5% | | |
| 12 | Australia | 1,92 | 6,9% | 95,1% | 26,1% |
| 13 | Austria | 2,1 | 9,2% | 91,6% | 30,5% |
| 14 | Azerbaijan | 6,39 | 64,0% | 74,5% | 11,1% |
| 15 | Bahamas | 3,77 | 30,5% | 81,2% | 43,5% |
| 16 | Bahrain | 5,33 | 50,4% | 87,5% | 35,6% |
| 17 | Bangladesh | 6,63 | 67,0% | 66,1% | 56,5% |
| 18 | Barbados | 3,3 | 24,5% | 79,0% | 9,7% |
| 19 | Belarus | 6,17 | 61,2% | 80,8% | 44,0% |
| 20 | Belgium | 2,59 | 15,5% | 93,7% | 27,9% |
| 21 | Belize | 5,53 | 53,0% | 68,3% | 52,8% |
| 22 | Benin | 5,64 | 54,4% | 52,5% | 76,1% |
| 23 | Bermuda | 2,84 | 18,6% | | |
| 24 | Bhutan | 3,92 | 32,4% | 66,6% | 55,7% |
| 25 | Bolivia | 6,26 | 62,3% | 69,2% | 51,3% |
| 26 | Bosnia and Herzegovina | 5,75 | 55,8% | 78,0% | 10,0% |
| 27 | Botswana | 3,81 | 31,0% | 69,3% | 51,2% |
| 28 | Brazil | 5,4 | 51,3% | 75,4% | 10,8% |
| 29 | Brunei Darussalam | 3,77 | 30,5% | 82,9% | 41,4% |
| 30 | Bulgaria | 4,59 | 41,0% | 79,5% | 9,5% |
| 31 | Burkina Faso | 5,94 | 58,2% | 44,9% | 79,6% |
| 32 | Burundi | 7,81 | 82,1% | 42,6% | 80,6% |
| 33 | Cambodia | 6,54 | 65,9% | 59,3% | 67,8% |
| 34 | Cameroon | 7,11 | 73,2% | 57,6% | 70,7% |
| 35 | Canada | 1,79 | 5,2% | 93,6% | 28,0% |
| 36 | Cape Verde | 3,97 | 33,1% | 66,2% | 56,3% |
| 37 | Cayman Islands | 3,29 | 24,4% | | |
| 38 | Central African Republic | 8,13 | 86,2% | 40,4% | 81,6% |
| 39 | Chad | 7,71 | 80,8% | 39,4% | 82,1% |
| 40 | Chile | 3,08 | 21,7% | 85,5% | 38,1% |

| # | Countries (ISO 3166) | WGI 2021 scaled (0-10)[a] | WGI 2021 risk score (0-100%)[c] | HDI 2021 score (0-100%)[b] | HDI 2021 risk score (0-100%)[c] |
|---|---|---|---|---|---|
| 41 | China | 5,68 | 54,9% | 76,8% | 10,4% |
| 42 | Colombia | 5,33 | 50,4% | 75,2% | 10,9% |
| 43 | Comoros | 6,77 | 68,8% | 55,8% | 73,7% |
| 44 | Congo | 7,3 | 75,6% | 57,1% | 71,5% |
| 45 | Congo, D.R. | 8,22 | 87,4% | 47,9% | 78,2% |
| 46 | Cook Islands | 2,93 | 19,8% | | |
| 47 | Costa Rica | 3,78 | 30,7% | 80,9% | 43,9% |
| 48 | Cote d'Ivoire | 6,1 | 60,3% | 55,0% | 75,0% |
| 49 | Croatia | 4,12 | 35,0% | 85,8% | 37,8% |
| 50 | Cuba | 5,91 | 57,9% | 76,4% | 10,5% |
| 51 | Cyprus | 3,39 | 25,7% | 89,6% | 33,0% |
| 52 | Czechia | 3,09 | 21,8% | 88,9% | 33,9% |
| 53 | Denmark | 1,65 | 3,4% | 94,8% | 26,5% |
| 54 | Djibouti | 6,69 | 67,8% | 50,9% | 76,9% |
| 55 | Dominica | 3,93 | 32,6% | 72,0% | 11,9% |
| 56 | Dominican Republic | 5,4 | 51,3% | 76,7% | 10,4% |
| 57 | Ecuador | 5,94 | 58,2% | 74,0% | 11,3% |
| 58 | Egypt | 6,7 | 67,9% | 73,1% | 11,5% |
| 59 | El Salvador | 5,59 | 53,8% | 67,5% | 54,2% |
| 60 | Equatorial Guinea | 7,71 | 80,8% | 59,6% | 67,3% |
| 61 | Eritrea | 8,24 | 87,6% | 49,2% | 77,6% |
| 62 | Estonia | 2,55 | 14,9% | 89,0% | 33,8% |
| 63 | Ethiopia | 6,75 | 68,6% | 49,8% | 77,4% |
| 64 | Fiji | 4,66 | 41,9% | 73,0% | 11,6% |
| 65 | Finland | 1,47 | 1,1% | 94,0% | 27,5% |
| 66 | France | 2,82 | 18,4% | 90,3% | 32,1% |
| 67 | French Guiana | 2,83 | 18,5% | | |
| 68 | Gabon | 6,46 | 64,9% | 70,6% | 12,3% |
| 69 | Gambia | 5,93 | 58,1% | 50,0% | 77,3% |
| 70 | Georgia | 4,15 | 35,4% | 80,2% | 44,8% |
| 71 | Germany | 2,07 | 8,8% | 94,2% | 27,3% |
| 72 | Ghana | 4,92 | 45,2% | 63,2% | 61,3% |
| 73 | Greece | 4,45 | 39,2% | 88,7% | 34,1% |
| 74 | Greenland | 2,25 | 11,1% | | |
| 75 | Grenada | 4,29 | 37,2% | 79,5% | 9,5% |
| 76 | Guam | 3,41 | 25,9% | | |
| 77 | Guatemala | 6,22 | 61,8% | 62,7% | 62,2% |
| 78 | Guinea | 6,81 | 69,3% | 46,5% | 78,9% |
| 79 | Guinea-Bissau | 7,27 | 75,2% | 48,3% | 78,0% |
| 80 | Guyana | 5,45 | 52,0% | 71,4% | 12,1% |
| 81 | Haiti | 7,39 | 76,8% | 53,5% | 75,7% |
| 82 | Honduras | 6,3 | 62,8% | 62,1% | 63,2% |
| 83 | Hong Kong | 2,36 | 12,5% | 95,2% | 26,0% |
| 84 | Hungary | 4,03 | 33,8% | 84,6% | 39,3% |

| # | Countries (ISO 3166) | WGI 2021 scaled (0-10)[a] | WGI 2021 risk score (0-100%)[c] | HDI 2021 score (0-100%)[b] | HDI 2021 risk score (0-100%)[c] |
|---|---|---|---|---|---|
| 85 | Iceland | 1,95 | 7,3% | 95,9% | 25,1% |
| 86 | India | 5,27 | 49,7% | 63,3% | 61,2% |
| 87 | Indonesia | 5,32 | 50,3% | 70,5% | 12,3% |
| 88 | Iran | 7,04 | 72,3% | 77,4% | 10,2% |
| 89 | Iraq | 8,01 | 84,7% | 68,6% | 52,3% |
| 90 | Ireland | 2,24 | 11,0% | 94,5% | 26,9% |
| 91 | Israel | 3,58 | 28,1% | 91,9% | 30,1% |
| 92 | Italy | 3,95 | 32,8% | 89,5% | 33,1% |
| 93 | Jamaica | 4,59 | 41,0% | 70,9% | 12,2% |
| 94 | Japan | 2,31 | 11,9% | 92,5% | 29,4% |
| 95 | Jersey | 2,52 | 14,6% | | |
| 96 | Jordan | 5,17 | 48,4% | 72,0% | 11,9% |
| 97 | Kazakhstan | 5,72 | 55,4% | 81,1% | 43,6% |
| 98 | Kenya | 6,13 | 60,7% | 57,5% | 70,8% |
| 99 | Kiribati | 4,34 | 37,8% | 62,4% | 62,7% |
| 100 | Korea, North | 8,25 | 87,7% | | |
| 101 | Korea, South | 3,23 | 23,6% | 92,5% | 29,4% |
| 102 | Kosovo | 5,67 | 54,8% | | |
| 103 | Kuwait | 5,22 | 49,0% | 83,1% | 41,1% |
| 104 | Kyrgyzstan | 6,3 | 62,8% | 69,2% | 51,3% |
| 105 | Laos | 6,49 | 65,3% | 60,7% | 65,5% |
| 106 | Latvia | 3,37 | 25,4% | 86,3% | 37,1% |
| 107 | Lebanon | 6,76 | 68,7% | 70,6% | 12,3% |
| 108 | Lesotho | 5,66 | 54,7% | 51,4% | 76,6% |
| 109 | Liberia | 6,49 | 65,3% | 48,1% | 78,1% |
| 110 | Libya | 8,83 | 95,1% | 71,8% | 11,9% |
| 111 | Liechtenstein | 1,74 | 4,6% | 93,5% | 28,1% |
| 112 | Lithuania | 3,13 | 22,3% | 87,5% | 35,6% |
| 113 | Luxembourg | 1,61 | 2,9% | 93,0% | 28,8% |
| 114 | Macau | 3,1 | 22,0% | | |
| 115 | Madagascar | 6,46 | 64,9% | 50,1% | 77,2% |
| 116 | Malawi | 5,94 | 58,2% | 51,2% | 76,7% |
| 117 | Malaysia | 4,21 | 36,1% | 80,3% | 44,6% |
| 118 | Maldives | 5,73 | 55,6% | 74,7% | 11,0% |
| 119 | Mali | 6,84 | 69,7% | 42,8% | 80,5% |
| 120 | Malta | 3,02 | 20,9% | 91,8% | 30,3% |
| 121 | Marshall Islands | 5,3 | 50,1% | 63,9% | 60,2% |
| 122 | Martinique | 3,01 | 20,8% | | |
| 123 | Mauritania | 6,46 | 64,9% | 55,6% | 74,0% |
| 124 | Mauritius | 3,43 | 26,2% | 80,2% | 44,8% |
| 125 | Mexico | 5,7 | 55,2% | 75,8% | 10,7% |
| 126 | Micronesia | 4,37 | 38,2% | 62,8% | 62,0% |
| 127 | Moldova | 5,7 | 55,2% | 76,7% | 10,4% |
| 128 | Monaco | 2,93 | 19,8% | | |

| # | Countries (ISO 3166) | WGI 2021 scaled (0-10)[a] | WGI 2021 risk score (0-100%)[c] | HDI 2021 score (0-100%)[b] | HDI 2021 risk score (0-100%)[c] |
|---|---|---|---|---|---|
| 129 | Mongolia | 4,97 | 45,8% | 73,9% | 11,3% |
| 130 | Montenegro | 4,8 | 43,7% | 83,2% | 41,0% |
| 131 | Morocco | 5,57 | 53,5% | 68,3% | 52,8% |
| 132 | Mozambique | 6,61 | 66,8% | 44,6% | 79,7% |
| 133 | Myanmar | 6,84 | 69,7% | 58,5% | 69,2% |
| 134 | Namibia | 4,4 | 38,6% | 61,5% | 64,2% |
| 135 | Nauru | 5,21 | 48,9% | | |
| 136 | Nepal | 6,21 | 61,7% | 60,2% | 66,3% |
| 137 | Netherlands | 1,71 | 4,2% | 94,1% | 27,4% |
| 138 | New Zealand | 1,38 | 0,0% | 93,7% | 27,9% |
| 139 | Nicaragua | 6,61 | 66,8% | 66,7% | 55,5% |
| 140 | Niger | 6,5 | 65,4% | 40,0% | 81,8% |
| 141 | Nigeria | 7,09 | 72,9% | 53,5% | 75,7% |
| 142 | Niue | 2,44 | 13,5% | | |
| 143 | North Macedonia | 5,05 | 46,9% | 77,0% | 10,3% |
| 144 | Norway | 1,43 | 0,6% | 96,1% | 24,9% |
| 145 | Oman | 4,7 | 42,4% | 81,6% | 43,0% |
| 146 | Pakistan | 6,95 | 71,1% | 54,4% | 75,3% |
| 147 | Palau | 4,52 | 40,1% | 76,7% | 10,4% |
| 148 | Panama | 4,77 | 43,3% | 80,5% | 44,4% |
| 149 | Papua New Guinea | 6,18 | 61,3% | 55,8% | 73,7% |
| 150 | Paraguay | 5,73 | 55,6% | 71,7% | 12,0% |
| 151 | Peru | 5,2 | 48,8% | 76,2% | 10,6% |
| 152 | Philippines | 5,66 | 54,7% | 69,9% | 50,2% |
| 153 | Poland | 3,7 | 29,6% | 87,6% | 35,5% |
| 154 | Portugal | 2,9 | 19,4% | 86,6% | 36,8% |
| 155 | Puerto Rico | 4,22 | 36,3% | | |
| 156 | Qatar | 4,18 | 35,8% | 85,5% | 38,1% |
| 157 | Reunion | 3,35 | 25,2% | | |
| 158 | Romania | 4,5 | 39,8% | 82,1% | 42,4% |
| 159 | Russia | 6,29 | 62,7% | 82,2% | 42,3% |
| 160 | Rwanda | 5,01 | 46,4% | 53,4% | 75,7% |
| 161 | Saint Kitts and Nevis | 3,83 | 31,3% | 77,7% | 10,1% |
| 162 | Saint Lucia | 3,85 | 31,5% | 71,5% | 12,0% |
| 163 | Saint Vincent and the Grenadines | 3,83 | 31,3% | 75,1% | 10,9% |
| 164 | Samoa | 3,74 | 30,1% | 70,7% | 12,3% |
| 165 | San Marino | 2,96 | 20,2% | 85,3% | 38,4% |
| 166 | Sao Tome and Principe | 5,46 | 52,1% | 61,8% | 63,7% |
| 167 | Saudi Arabia | 5,49 | 52,5% | 87,5% | 35,6% |
| 168 | Senegal | 5,12 | 47,8% | 51,1% | 76,8% |
| 169 | Serbia | 5,11 | 47,6% | 80,2% | 44,8% |
| 170 | Seychelles | 4,23 | 36,4% | 78,5% | 9,8% |
| 171 | Sierra Leone | 6,2 | 61,6% | 47,7% | 78,3% |

| # | Countries (ISO 3166) | WGI 2021 scaled (0-10)[a] | WGI 2021 risk score (0-100%)[c] | HDI 2021 score (0-100%)[b] | HDI 2021 risk score (0-100%)[c] |
|---|---|---|---|---|---|
| 172 | Singapore | 1,75 | 4,7% | 93,9% | 27,6% |
| 173 | Slovakia | 3,68 | 29,4% | 84,8% | 39,0% |
| 174 | Slovenia | 3,12 | 22,2% | 91,8% | 30,3% |
| 175 | Solomon Islands | 5,38 | 51,1% | 56,4% | 72,7% |
| 176 | Somalia | 9,21 | 100,0% | | |
| 177 | South Africa | 4,69 | 42,3% | 71,3% | 12,1% |
| 178 | South Sudan | 9,14 | 99,1% | 38,5% | 82,5% |
| 179 | Spain | 3,34 | 25,0% | 90,5% | 31,9% |
| 180 | Sri Lanka | 5,25 | 49,4% | 78,2% | 9,9% |
| 181 | Sudan | 8,12 | 86,1% | 50,8% | 76,9% |
| 182 | Suriname | 5,35 | 50,7% | 73,0% | 11,6% |
| 183 | Swaziland | 6,25 | 62,2% | | |
| 184 | Sweden | 1,65 | 3,4% | 94,7% | 26,6% |
| 185 | Switzerland | 1,49 | 1,4% | 96,2% | 24,8% |
| 186 | Syria | 8,97 | 96,9% | 57,7% | 70,5% |
| 187 | Taiwan | 2,73 | 17,2% | | |
| 188 | Tajikistan | 7,33 | 76,0% | 68,5% | 52,5% |
| 189 | Tanzania | 6,05 | 59,6% | 54,9% | 75,0% |
| 190 | Thailand | 5,51 | 52,7% | 80,0% | 45,0% |
| 191 | Timor-Leste | 5,96 | 58,5% | 60,7% | 65,5% |
| 192 | Togo | 6,49 | 65,3% | 53,9% | 75,5% |
| 193 | Tonga | 4,58 | 40,9% | 74,5% | 11,1% |
| 194 | Trinidad and Tobago | 4,81 | 43,8% | 81,0% | 43,8% |
| 195 | Tunisia | 5,43 | 51,7% | 73,1% | 11,5% |
| 196 | Türkiye | 5,93 | 58,1% | 83,8% | 40,3% |
| 197 | Turkmenistan | 7,82 | 82,2% | 74,5% | 11,1% |
| 198 | Tuvalu | 4,4 | 38,6% | 64,1% | 59,8% |
| 199 | Uganda | 6,2 | 61,6% | 52,5% | 76,1% |
| 200 | Ukraine | 6,29 | 62,7% | 77,3% | 10,2% |
| 201 | United Arab Emirates | 3,7 | 29,6% | 91,1% | 31,1% |
| 202 | United Kingdom | 2,25 | 11,1% | 92,9% | 28,9% |
| 203 | United States | 2,68 | 16,6% | 92,1% | 29,9% |
| 204 | Uruguay | 3,23 | 23,6% | 80,9% | 43,9% |
| 205 | Uzbekistan | 6,97 | 71,4% | 72,7% | 11,7% |
| 206 | Vanuatu | 6,38 | 63,9% | 60,7% | 65,5% |
| 207 | Venezuela | 8,38 | 89,4% | 69,1% | 51,5% |
| 208 | Vietnam | 5,69 | 55,0% | 70,3% | 12,4% |
| 209 | Virgin Islands (U.S.) | 3,27 | 24,1% | | |
| 210 | Yemen | 8,89 | 95,9% | 45,5% | 79,3% |
| 211 | Zambia | 5,83 | 56,8% | 56,5% | 72,5% |
| 212 | Zimbabwe | 7,42 | 77,1% | 59,3% | 67,8% |

[a]: Study on the EU's list of Critical Raw Materials 2023: annex9; s.119
[b]: https://hdr.undp.org/data-center/documentation-and-downloads Accessed on 28.03.2023
[c]: Own Table of Top 5 Global Producer (Table 7.2)

## A.2 Table of the EU-CRM Top 5 global production countries

| # | Material | Main global producer #1 | Share #1 | Main global producer #2 | Share #2 | Main global producer #3 | Share #3 | Main global producer #4 | Share #4 | Main global producer #5 | Share #5 | Other producer | Weighted WGI in % | Weighted HDI in % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aggregates | | | | | | | | | | | | | |
| 2 | Aluminium/bauxite | Australia | 28,4% | China | 20,8% | Guinea | 17,9% | Brazil | 10,4% | India | 6,8% | 15,7% | 40,9% | 34,4% |
| 3 | Antimony | China | 56,4% | Tajikistan | 20,3% | Russia | 11,6% | Myanmar | 2,9% | Türkiye | 2,5% | 6,3% | 61,0% | 26,1% |
| 4 | Arsenic * | China | 44,0% | Peru | 40,0% | Morocco | 12,0% | | | | | 4,0% | 52,2% | 15,8% |
| 5 | Baryte | China | 31,5% | India | 25,1% | Morocco | 8,9% | Iran | 6,6% | Kazakhstan | 6,5% | 21,4% | 54,6% | 34,1% |
| 6 | Bentonite | China | 26,6% | United States | 20,7% | India | 16,5% | Türkiye | 7,4% | Greece | 5,6% | 23,2% | 42,6% | 31,2% |
| 7 | Beryllium | United States | 67,3% | China | 26,0% | Mozambique | 3,6% | Brazil | 1,5% | Uganda | 0,6% | 1,0% | 29,3% | 26,6% |
| 8 | Bismuth * | China | 68,0% | Vietnam | 17,0% | Japan | 5,0% | Mexico | 3,0% | | | 7,0% | 52,6% | 11,8% |
| 9 | Boron/Borate | Türkiye | 48,4% | United States | 24,9% | Chile | 10,7% | Bolivia | 5,2% | China | 3,5% | 7,3% | 42,9% | 36,7% |
| 10 | Cadmium ** | China | 41,7% | Korea, South | 16,7% | Japan | 7,9% | Canada | 7,5% | Kazakhstan | 5,0% | 21,3% | 39,3% | 20,1% |
| 11 | Chromium | South Africa | 55,5% | Kazakhstan | 15,7% | India | 12,4% | Türkiye | 3,8% | Finland | 3,4% | 9,2% | 44,7% | 26,0% |
| 12 | Cobalt | Congo, D.R. | 62,8% | Russia | 6,6% | Canada | 4,1% | Australia | 3,9% | China | 3,8% | 18,8% | 75,8% | 67,1% |
| 13 | Coking coal | China | 52,7% | Australia | 18,2% | Russia | 8,8% | United States | 5,9% | India | 4,1% | 10,3% | 43,2% | 20,3% |
| 14 | Copper | Chile | 27,7% | Peru | 11,5% | China | 8,4% | Congo, D.R. | 6,4% | United States | 6,2% | 39,8% | 38,0% | 32,4% |
| 15 | Diatomite | United States | 36,3% | China | 17,4% | Türkiye | 7,2% | Mexico | 5,7% | Denmark | 5,0% | 28,4% | 32,2% | 24,4% |
| 16 | Feldspar | Türkiye | 31,8% | India | 19,8% | China | 7,7% | Italy | 6,9% | Iran | 5,0% | 28,8% | 54,0% | 40,0% |
| 17 | Fluorspar | China | 55,6% | Mexico | 20,5% | Mongolia | 7,4% | Vietnam | 3,4% | South Africa | 3,1% | 10,0% | 53,8% | 10,7% |
| 18 | Gallium * | China | 94,0% | Ukraine | 2,0% | Russia | 2,0% | | | | | 2,0% | 55,2% | 11,0% |
| 19 | Germanium * | China | 90,0% | Russia | 5,0% | Japan | 2,0% | United States | 2,0% | Ukraine | 1,0% | 0,0% | 53,8% | 12,7% |
| 20 | Gold | China | 12,3% | Australia | 9,4% | Russia | 8,6% | United States | 6,6% | Canada | 5,5% | 57,6% | 33,4% | 25,7% |
| 21 | Gypsum | United States | 13,2% | China | 12,9% | Iran | 9,3% | Spain | 6,8% | Thailand | 6,7% | 51,1% | 43,4% | 23,3% |
| 22 | Hafnium * | France | 49,0% | United States | 44,0% | China | 3,0% | Russia | 3,0% | | | 1,0% | 20,0% | 30,8% |
| 23 | Helium * | United States | 56,0% | Qatar | 30,0% | Algeria | 8,0% | Australia | 3,0% | Russia | 2,0% | 1,0% | 27,2% | 31,0% |
| 24 | HREE | | | | | | | | | | | | | |
| 25 | HREE Dysprosium | China | 84,4% | Myanmar | 9,3% | Russia | 1,9% | Thailand | 1,3% | India | 1,2% | 1,9% | 56,4% | 17,6% |
| 26 | HREE Erbium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 27 | HREE Europium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 28 | HREE Gadolinium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 29 | HREE Holmium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 30 | HREE Lutetium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 31 | HREE Terbium | China | 84,4% | Myanmar | 9,3% | Russia | 1,9% | Thailand | 1,3% | India | 1,2% | 1,9% | 56,4% | 17,6% |
| 32 | HREE Thulium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 33 | HREE Ytterbium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 34 | HREE Yttrium | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 35 | Hydrogen | United States | 22,2% | Russia | 17,5% | Iran | 5,9% | Canada | 4,4% | Qatar | 4,3% | 45,7% | 38,1% | 32,2% |
| 36 | Indium * | China | 50,0% | Korea, South | 26,0% | Japan | 8,0% | Canada | 8,0% | France | 4,0% | 4,0% | 37,2% | 19,5% |
| 37 | Iron ore | Australia | 36,6% | Brazil | 17,8% | China | 14,5% | India | 8,7% | Russia | 4,2% | 18,2% | 32,5% | 24,6% |
| 38 | Kaolin clay | Ukraine | 24,2% | China | 17,6% | Türkiye | 14,7% | India | 13,7% | Germany | 10,2% | 19,6% | 51,1% | 26,6% |
| 39 | Krypton | | | | | | | | | | | | | |

| # | Material | | Main global producer #1 | Share #1 | Main global producer #2 | Share #2 | Main global producer #3 | Share #3 | Main global producer #4 | Share #4 | Main global producer #5 | Share #5 | Other producer | Weighted WGI in % | Weighted HDI in % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | Lead | | China | 43,4% | Australia | 9,8% | United States | 6,4% | Peru | 6,3% | Mexico | 5,8% | 28,3% | 44,4% | 14,3% |
| 41 | Limestone | | Türkiye | 18,5% | Spain | 15,5% | Italy | 11,9% | United Kingdom | 10,1% | Germany | 9,3% | 34,7% | 31,4% | 33,4% |
| 42 | Lithium | | Australia | 53,0% | Chile | 24,1% | China | 10,2% | Argentina | 7,9% | Zimbabwe | 1,3% | 3,5% | 20,0% | 29,1% |
| 43 | LREE | | | | | | | | | | | | | | |
| 44 | LREE Cerium | | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 45 | LREE Lanthanum | | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 46 | LREE Neodymium | | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 47 | LREE Praseodymium | | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 48 | LREE Samarium | | China | 68,3% | Australia | 9,9% | United States | 9,2% | Myanmar | 7,5% | Russia | 1,5% | 3,6% | 47,6% | 18,9% |
| 49 | Magnesite | | China | 66,0% | Türkiye | 7,1% | Brazil | 6,4% | Russia | 4,6% | Slovakia | 3,2% | 12,7% | 54,4% | 15,6% |
| 50 | Magnesium | * | China | 91,0% | United States | 3,0% | Israel | 2,0% | | | | | 4,0% | 53,2% | 11,4% |
| 51 | Manganese | | South Africa | 29,3% | Australia | 16,3% | Gabon | 14,4% | China | 8,9% | Ghana | 6,4% | 24,7% | 40,7% | 19,2% |
| 52 | Molybdenum | | China | 38,3% | Chile | 21,3% | United States | 15,4% | Peru | 10,5% | Mexico | 6,4% | 8,1% | 40,1% | 20,1% |
| 53 | Natural cork | | Portugal | 48,1% | Spain | 31,5% | Morocco | 6,0% | Algeria | 5,1% | Tunisia | 3,6% | 5,7% | 27,3% | 33,8% |
| 54 | Natural graphite | | China | 66,7% | Brazil | 7,5% | Mozambique | 5,4% | India | 5,1% | Korea, North | 4,6% | 10,7% | 56,7% | 17,0% |
| 55 | Natural Rubber | | Thailand | 32,2% | Indonesia | 24,0% | Vietnam | 7,8% | India | 6,6% | China | 5,5% | 23,9% | 52,1% | 30,3% |
| 56 | Natural Teak wood | | Myanmar | 47,5% | Indonesia | 34,4% | India | 17,4% | Thailand | 0,6% | | | 0,1% | 59,5% | 48,1% |
| 57 | Neon | | | | | | | | | | | | | | |
| 58 | Nickel | | Indonesia | 26,3% | Philippines | 14,0% | Russia | 9,9% | Canada | 8,5% | Australia | 7,5% | 33,8% | 42,4% | 28,4% |
| 59 | Niobium | | Brazil | 91,8% | Canada | 6,6% | Russia | 0,6% | Congo, D.R. | 0,6% | Rwanda | 0,2% | 0,2% | 48,6% | 12,7% |
| 60 | Perlite | | China | 29,9% | Türkiye | 23,9% | Greece | 17,3% | United States | 11,2% | Iran | 10,7% | 7,0% | 50,2% | 24,8% |
| 61 | PGM | | | | | | | | | | | | | | |
| 62 | PGM Iridium | * | South Africa | 93,5% | Zimbabwe | 4,9% | | | | | | | 1,6% | 44,0% | 14,9% |
| 63 | PGM Palladium | * | Russia | 40,0% | South Africa | 36,0% | Canada | 9,9% | | | | | 14,1% | 47,5% | 28,0% |
| 64 | PGM Platinum | * | South Africa | 70,8% | Russia | 12,0% | Zimbabwe | 8,0% | | | | | 9,2% | 48,0% | 21,0% |
| 65 | PGM Rhodium | * | South Africa | 81,0% | Russia | 10,0% | Zimbabwe | 6,0% | | | | | 3,0% | 46,5% | 18,7% |
| 66 | PGM Ruthenium | * | South Africa | 93,5% | Zimbabwe | 4,9% | | | | | | | 1,6% | 44,0% | 14,9% |
| 67 | Phosphate rock | | China | 43,6% | Morocco | 14,2% | United States | 9,5% | Russia | 6,9% | Peru | 5,0% | 20,8% | 50,4% | 23,1% |
| 68 | Phosphorus | * | China | 75,0% | United States | 10,0% | Vietnam | 9,0% | Kazakhstan | 6,0% | | | 0,0% | 51,1% | 14,5% |
| 69 | Potash | | Canada | 30,2% | Russia | 17,2% | Belarus | 16,8% | China | 13,3% | Germany | 6,6% | 15,9% | 36,3% | 31,3% |
| 70 | Rhenium | * | China | 49,0% | United States | 19,0% | Poland | 15,0% | | | | | 17,0% | 41,6% | 19,4% |
| 71 | Roundwood | | United States | 18,0% | China | 16,0% | Russia | 9,0% | Brazil | 7,0% | Canada | 7,0% | 43,0% | 37,5% | 23,8% |
| 72 | Sapele wood | | Cameroon | 52,3% | Congo | 21,8% | Gabon | 8,7% | Congo, D.R. | 5,8% | Equatorial Guinea | 3,8% | 7,6% | 74,2% | 65,7% |
| 73 | Scandium | * | China | 66,0% | Russia | 23,0% | Ukraine | 7,0% | Kazakhstan | 1,0% | | | 3,0% | 57,3% | 18,3% |

| # | Material | | Main global producer #1 | Share #1 | Main global producer #2 | Share #2 | Main global producer #3 | Share #3 | Main global producer #4 | Share #4 | Main global producer #5 | Share #5 | Other producer | Weighted WGI in % | Weighted HDI in % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74 | Selenium | ** | China | 33,2% | Japan | 27,5% | Germany | 10,7% | Belgium | 7,1% | Russia | 5,4% | 16,1% | 32,1% | 22,3% |
| 75 | Silica | | United States | 41,0% | China | 8,4% | India | 5,0% | Türkiye | 4,4% | Germany | 4,4% | 36,8% | 26,7% | 30,3% |
| 76 | Silicon metal | * | China | 77,0% | Brazil | 7,0% | Norway | 6,0% | France | 4,0% | Russia | 2,0% | 4,0% | 49,9% | 12,9% |
| 77 | Silver | | Mexico | 24,3% | Peru | 14,2% | China | 12,8% | Chile | 5,2% | Russia | 5,1% | 38,4% | 51,4% | 15,5% |
| 78 | Strontium | | Iran | 37,5% | Spain | 34,2% | China | 16,4% | Mexico | 11,2% | Argentina | 0,7% | 0,0% | 51,2% | 17,9% |
| 79 | Sulphur | ** | China | 22,0% | United States | 10,5% | Russia | 8,9% | Saudi Arabia | 8,5% | United Arab Emirates | 7,3% | 42,8% | 45,5% | 25,3% |
| 80 | Talc | | India | 21,9% | China | 19,5% | Brazil | 9,6% | United States | 8,1% | Korea, South | 5,7% | 35,2% | 45,1% | 31,7% |
| 81 | Tantalum | | Congo, D.R. | 35,4% | Rwanda | 17,3% | Brazil | 15,9% | Nigeria | 10,6% | China | 6,9% | 13,9% | 68,1% | 59,5% |
| 82 | Tellurium | * | China | 69,0% | Japan | 9,0% | Russia | 7,0% | Sweden | 7,0% | Canada | 4,0% | 4,0% | 45,6% | 16,4% |
| 83 | Tin | | China | 28,9% | Indonesia | 23,5% | Myanmar | 17,0% | Peru | 6,4% | Bolivia | 5,7% | 18,5% | 56,7% | 26,1% |
| 84 | Titanium | | China | 25,4% | South Africa | 13,1% | Australia | 12,1% | Mozambique | 10,1% | Canada | 7,6% | 31,7% | 40,2% | 25,7% |
| 85 | Titanium metal | | China | 25,4% | South Africa | 13,1% | Australia | 12,1% | Mozambique | 10,1% | Canada | 7,6% | 31,7% | 40,2% | 25,7% |
| 86 | Tungsten | | China | 82,6% | Vietnam | 6,4% | Russia | 2,7% | Bolivia | 1,4% | Rwanda | 1,2% | 5,7% | 55,1% | 12,9% |
| 87 | Vanadium | | China | 61,6% | Russia | 19,8% | South Africa | 10,6% | Brazil | 7,6% | India | 0,4% | 0,0% | 54,8% | 17,1% |
| 88 | Xenon | | | | | | | | | | | | | | |
| 89 | Zinc | | China | 31,6% | Peru | 11,6% | Australia | 9,1% | United States | 6,4% | India | 6,2% | 35,1% | 42,8% | 19,4% |
| 90 | Zirconium | | Australia | 33,6% | South Africa | 23,4% | Mozambique | 11,2% | China | 9,0% | Senegal | 5,5% | 17,3% | 33,0% | 31,1% |

General data source for main global producer: *Study on the EU's list of Critical Raw Materials 2023: annex7; p.81 (extraction stage)*
* EU-SCRREEN factsheet 2023 (Data of 2016-2020)
** United States Geological Survey (USGS), National Minerals Information Center

## A.3 Table of the criticality assessment tool risk score calculation

| # | Material (EU-CRM 2023) | Element symbol | HHI share of Global Production[a] | Concentration Risk (CR)[b] | Supply Risk (SR)[c] | Current Supply Risk (CSR)[b] | Future Demand 2020 (in tons)[d] | Future Demand 2030 (in tons)[d] | Future Demand 2050 (in tons)[d] | Future Demand Increase per year (2020-2030)[e] | Future Demand Increase per year (2030-2050)[e] | Future Demand Increase per year (2020-2050)[e] | FDI per year (2020-2050/ 2030-2050/ 2020-2030) | Future Demand Risk (FDR)[b] | Economic Importance (EI)[c] | Economic Risk of Importance (ERI)[b] | End of Life Recycling Input Rate (EoL-RIR)[f] | Recirculation Risk (RR)[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aggregates | - | | | 0,2 | 16% | | | | | | | | | 3,2 | 81% | 9% | 53% |
| 2 | Aluminium/Bauxite | Al | 3372 | 81% | 1,2 | 81% | 3238388 t | 12348545 t | 32640378 t | 14% | 5% | 8% | 8% | 65% | 5,8 | 88% | 32% | 23% |
| 3 | Antimony | Sb | 2887 | 78% | 1,8 | 83% | 454 t | 994 t | | 8% | | | 8% | 66% | 5,4 | 87% | 28% | 24% |
| 4 | Arsenic | As | 3663 | 82% | 1,9 | 84% | 28 t | 33 t | 815 t | 2% | 17% | 12% | 12% | 85% | 2,9 | 80% | 0% | 100% |
| 5 | Baryte | Ba | 1889 | 71% | 1,3 | 81% | 2642 t | 3084 t | | 2% | | | 2% | 33% | 3,5 | 82% | 0% | 100% |
| 6 | Bentonite | - | 1352 | 65% | 0,4 | 32% | | | | | | | | | 3,1 | 81% | 19% | 35% |
| 7 | Beryllium | Be | 4965 | 88% | 1,8 | 83% | 2 t | 2 t | | 1% | | | 1% | 32% | 5,4 | 87% | 0% | 100% |
| 8 | Bismuth | Bi | 5529 | 90% | 1,9 | 84% | 20 t | 24 t | | 2% | | | 2% | 34% | 5,7 | 88% | 0% | 100% |
| 9 | Boron/Borate | B | 3164 | 80% | 3,6 | 90% | 1186 t | 2257 t | 3391 t | 7% | 2% | 4% | 4% | 43% | 3,9 | 83% | 1% | 75% |
| 10 | Cadmium | Cd | 2100 | 73% | 0,2 | 16% | 955 t | 2038 t | 2436 t | 8% | 1% | 3% | 3% | 41% | 4,1 | 84% | 30% | 23% |
| 11 | Chromium | Cr | 3096 | 79% | 0,7 | 56% | 116665 t | 204333 t | 375230 t | 6% | 3% | 4% | 4% | 45% | 7,2 | 92% | 21% | 32% |
| 12 | Cobalt | Co | 4876 | 87% | 2,8 | 87% | 43487 t | 330857 t | 577773 t | 22% | 3% | 9% | 9% | 70% | 6,8 | 91% | 22% | 30% |
| 13 | Coking coal | - | 3350 | 81% | 1,0 | 80% | | | | | | | | | 3,1 | 81% | 0% | 100% |
| 14 | Copper | Cu | 1097 | 61% | 0,1 | 8% | 1302150 t | 4831569 t | 12948951 t | 14% | 5% | 8% | 8% | 65% | 4,0 | 83% | 55% | 15% |
| 15 | Diatomite | - | 1869 | 71% | 0,3 | 24% | | | | | | | | | 2,3 | 58% | 4% | 67% |
| 16 | Feldspar | KAlSi3O8/ NaAlSi3O8/CaAl2Si2O8 | 1814 | 70% | 1,5 | 82% | | | | | | | | | 3,2 | 81% | 1% | 75% |
| 17 | Fluorspar | CaF2 | 4383 | 86% | 1,1 | 80% | 490 t | 9019 t | 43207 t | 34% | 8% | 16% | 16% | 100% | 3,8 | 83% | 1% | 75% |
| 18 | Gallium | Ga | 9368 | 99% | 3,9 | 92% | 66 t | 107 t | 1713 t | 5% | 15% | 11% | 11% | 82% | 3,7 | 83% | 0% | 100% |
| 19 | Germanium | Ge | 8658 | 97% | 1,8 | 83% | 2 t | 4 t | 106521 t | 7% | 66% | 43% | 43% | 100% | 3,6 | 82% | 2% | 72% |
| 20 | Gold | Au | 489 | 47% | 0,4 | 32% | 139 t | 199 t | | 4% | | | 4% | 43% | 2,4 | 62% | 5% | 64% |
| 21 | Gypsum | CaSO4·2H2O | 700 | 53% | 0,6 | 48% | | | | | | | | | 2,7 | 76% | 1% | 75% |
| 22 | Hafnium | Hf | | | 1,5 | 82% | 2 t | 2 t | | 1% | | | 1% | 32% | 4,3 | 84% | 0% | 100% |
| 23 | Helium | He | | | 1,2 | 81% | | | | | | | | | 2,9 | 80% | 2% | 72% |
| 24 | HREE | - | 4315 | 85% | 5,1 | 96% | | | | | | | | | 4,2 | 84% | 1% | 75% |
| 25 | HREE Dysprosium | Dy | | | 5,6 | 98% | 1420 t | 5135 t | 13348 t | 14% | 5% | 8% | 8% | 64% | 7,8 | 94% | | |
| 26 | HREE Erbium | Er | | | 5,6 | 98% | | | | | | | | | 3,5 | 82% | | |
| 27 | HREE Europium | Eu | | | 5,6 | 98% | 0 t | 0 t | | -1% | | | -1% | 19% | 3,3 | 81% | | |
| 28 | HREE Gadolinium | Gd | | | 3,3 | 89% | 26 t | 31 t | | 1% | | | 1% | 32% | 3,3 | 81% | | |
| 29 | HREE Holmium | Ho | | | 5,6 | 98% | | | | | | | | | 3,2 | 81% | | |
| 30 | HREE Lutetium | Lu | | | 5,6 | 98% | | | | | | | | | 5,0 | 86% | | |
| 31 | HREE Terbium | Tb | | | 4,9 | 96% | 462 t | 953 t | 1658 t | 8% | 3% | 4% | 4% | 47% | 6,4 | 90% | | |
| 32 | HREE Thulium | Tm | | | 5,6 | 98% | | | | | | | | | 3,2 | 81% | | |
| 33 | HREE Ytterbium | Yb | | | 5,6 | 98% | | | | | | | | | 3,2 | 81% | | |
| 34 | HREE Yttrium | Y | | | 3,5 | 90% | 1 t | 8 t | 188 t | 23% | 17% | 19% | 19% | 100% | 2,9 | 80% | | |
| 35 | Hydrogen | H | | | 0,5 | 40% | | | | | | | | | 2,9 | 80% | 0% | 100% |
| 36 | Indium | In | 3997 | 84% | 0,6 | 48% | 113 t | 193 t | 1683 t | 6% | 11% | 9% | 9% | 72% | 2,6 | 71% | 1% | 75% |
| 37 | Iron ore | Fe | 1883 | 71% | 0,5 | 40% | 4125327 t | 8152156 t | 18378106 t | 7% | 4% | 5% | 5% | 51% | 7,2 | 92% | 31% | 23% |
| 38 | Kaolin clay | Al4[(OH)8\|Si4O10] | 979 | 59% | 0,8 | 64% | | | | | | | | | 2,8 | 80% | 31% | 23% |
| 39 | Krypton | Kr | | | 0,7 | 56% | | | | | | | | | 3,3 | 81% | 0% | 100% |
| 40 | Lead | Pb | 2097 | 73% | 0,1 | 8% | 7976 t | 15440 t | 16574 t | 7% | 0% | 2% | 2% | 37% | 4,2 | 84% | 83% | 6% |
| 41 | Limestone | CaCO3 | | | 0,3 | 24% | | | | | | | | | 3,6 | 82% | 1% | 75% |

| # | Material (EU-CRM 2023) | Element symbol | HHI share of Global Production[a] | Concentration Risk (CR)[b] | Supply Risk (SR)[c] | Current Supply Risk (CSR)[b] | Future Demand 2020 (in tons)[d] | Future Demand 2030 (in tons)[d] | Future Demand 2050 (in tons)[d] | Future Demand Increase per year (2020-2030)[e] | Future Demand Increase per year (2030-2050)[e] | Future Demand Increase per year (2020-2050)[e] | FDI per year (2020-2050/ 2030-2050/ 2020-2030) | Future Demand Risk (FDR)[b] | Economic Importance (EI)[c] | Economic Risk of Importance (ERI)[b] | End of Life Recycling Input Rate (EoL-RIR)[f] | Recirculation Risk (RR)[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42 | Lithium | Li | 3380 | 81% | 1,9 | 84% | 23927 t | 358912 t | 1504044 t | 31% | 7% | 15% | 15% | 99% | 3,9 | 83% | 0% | 100% |
| 43 | LREE | - | 4315 | 85% | 3,7 | 91% | | | | | | | | | 5,9 | 89% | 1% | 75% |
| 44 | LREE Cerium | Ce | | | 4,0 | 92% | 86 t | 102 t | | 2% | | | 2% | 34% | 4,9 | 86% | | |
| 45 | LREE Lanthanum | La | | | 3,5 | 90% | | 53 t | 1169 t | | 17% | | 17% | 100% | 2,9 | 80% | | |
| 46 | LREE Neodymium | Nd | | | 4,5 | 94% | 13298 t | 43829 t | 107653 t | 13% | 5% | 7% | 7% | 61% | 7,2 | 92% | | |
| 47 | LREE Praseodymium | Pr | | | 3,2 | 89% | 1961 t | 4181 t | 7497 t | 8% | 3% | 5% | 5% | 48% | 7,0 | 92% | | |
| 48 | LREE Samarium | Sm | | | 3,5 | 90% | | | | | | | | | 7,7 | 94% | | |
| 49 | Magnesite | Mg[CO3] | 4273 | 85% | 0,6 | 48% | | | | | | | | | 3,6 | 82% | 2% | 72% |
| 50 | Magnesium | Mg | | | 4,1 | 92% | 68857 t | 78378 t | | 1% | | | 1% | 32% | 7,4 | 93% | 13% | 45% |
| 51 | Manganese | Mn | 1862 | 71% | 1,2 | 81% | 217842 t | 580590 t | 1063516 t | 10% | 3% | 5% | 5% | 52% | 6,9 | 91% | 9% | 53% |
| 52 | Molybdenum | Mo | 2266 | 74% | 0,8 | 64% | 23211 t | 42175 t | 75945 t | 6% | 3% | 4% | 4% | 45% | 6,7 | 91% | 30% | 23% |
| 53 | Natural cork | - | | | 0,9 | 72% | | | | | | | | | 1,7 | 31% | 8% | 56% |
| 54 | Natural graphite | C | 4154 | 85% | 1,8 | 83% | 167695 t | 2899279 t | 13066259 t | 33% | 8% | 16% | 16% | 100% | 3,4 | 82% | 3% | 69% |
| 55 | Natural Rubber | - | | | 0,9 | 72% | | | | | | | | | 6,0 | 89% | 2% | 72% |
| 56 | Natural teak wood | - | | | 1,7 | 83% | | | | | | | | | 2,4 | 62% | 5% | 64% |
| 57 | Neon | Ne | | | 0,7 | 56% | | | | | | | | | 3,1 | 81% | 0% | 100% |
| 58 | Nickel | Ni | 2110 | 73% | 0,5 | 40% | 205614 t | 1756761 t | 6707958 t | 24% | 7% | 12% | 12% | 87% | 5,7 | 88% | 16% | 40% |
| 59 | Niobium | Nb | 8595 | 97% | 4,4 | 94% | 13 t | 15 t | | 1% | | | 1% | 32% | 6,5 | 90% | 0% | 100% |
| 60 | Perlite | - | 2781 | 78% | 0,8 | 64% | | | | | | | | | 2,5 | 67% | 42% | 19% |
| 61 | PGM | - | | | 2,7 | 87% | | | | | | | | | 7,1 | 92% | 12% | 47% |
| 62 | PGM Iridium | Ir | | | 3,9 | 92% | | 23 t | 52 t | | 4% | | 4% | 46% | 6,4 | 90% | | |
| 63 | PGM Palladium | Pd | 3250 | 80% | 1,5 | 82% | 26 t | 59 t | 41 t | 8% | -2% | 1% | 1% | 32% | 8,1 | 95% | | |
| 64 | PGM Platinum | Pt | 5690 | 90% | 2,1 | 85% | 2 t | 28 t | 173 t | 32% | 10% | 17% | 17% | 100% | 6,9 | 91% | | |
| 65 | PGM Rhodium | Rh | 7352 | 95% | 2,4 | 86% | | | | | | | | | 8,6 | 96% | | |
| 66 | PGM Ruthenium | Ru | | | 3,8 | 91% | 0 t | 5 t | 13 t | 32% | 5% | 13% | 13% | 92% | 5,5 | 88% | | |
| 67 | Phosphate rock | - | 2133 | 73% | 1,0 | 80% | | | | | | | | | 6,4 | 90% | 0% | 100% |
| 68 | Phosphorus | P | | | 3,3 | 89% | 8893 t | 946698 t | 5577609 t | 59% | 9% | 24% | 24% | 100% | 4,7 | 85% | 0% | 100% |
| 69 | Potash | KCl | 1775 | 70% | 0,7 | 56% | | | | | | | | | 6,2 | 89% | 0% | 100% |
| 70 | Rhenium | Re | 2753 | 77% | 0,5 | 40% | | | | | | | | | 2,3 | 58% | 50% | 17% |
| 71 | Roundwood | - | | | 0,1 | 8% | | | | | | | | | 1,2 | 9% | 20% | 33% |
| 72 | Sapele wood | - | | | 1,3 | 81% | | | | | | | | | 1,6 | 27% | 7% | 58% |
| 73 | Scandium | Sc | | | 2,4 | 86% | | | | | | | | | 3,7 | 83% | 0% | 100% |
| 74 | Selenium | Se | 2004 | 72% | 0,3 | 24% | 102 t | 202 t | 242 t | 7% | 1% | 3% | 3% | 40% | 4,8 | 86% | 1% | 75% |
| 75 | Silica | SiO2 | | | 0,3 | 24% | | | | | | | | | 3,1 | 81% | 1% | 75% |
| 76 | Silicon metal | Si | | | 1,4 | 82% | 691721 t | 1360540 t | 1491646 t | 7% | 0% | 3% | 3% | 38% | 4,9 | 86% | 0% | 100% |
| 77 | Silver | Ag | 1087 | 61% | 0,8 | 64% | 6327 t | 12488 t | 13812 t | 7% | 1% | 3% | 3% | 38% | 4,6 | 85% | 4% | 67% |
| 78 | Strontium | Sr | | | 2,6 | 86% | 2025 t | 2340 t | | 1% | | | 1% | 32% | 6,5 | 90% | 0% | 100% |
| 79 | Sulphur | S | 835 | 57% | 0,3 | 24% | | | | | | | | | 5,0 | 86% | 0% | 100% |
| 80 | Talc | H2Mg3(SiO3)4 | 1028 | 60% | 0,2 | 16% | | | | | | | | | 3,3 | 81% | 16% | 40% |
| 81 | Tantalum | Ta | 1658 | 69% | 1,3 | 81% | 346 t | 410 t | | 2% | | | 2% | 34% | 4,8 | 86% | 1% | 75% |
| 82 | Tellurium | Te | 5410 | 89% | 0,3 | 24% | 1362 t | 2922 t | 3507 t | 8% | 1% | 3% | 3% | 41% | 3,8 | 83% | 1% | 75% |
| 83 | Tin | Sn | 1690 | 69% | 0,9 | 72% | 15674 t | 28769 t | 27623 t | 6% | 0% | 2% | 2% | 35% | 4,5 | 85% | 31% | 23% |
| 84 | Titanium | Ti | 1598 | 68% | 0,5 | 40% | 1457 t | 2069 t | | 4% | | | 4% | 43% | 5,4 | 87% | 1% | 75% |
| 85 | Titanium metal | Ti | 1598 | 68% | 1,6 | 82% | 1457 t | 2069 t | | 4% | | | 4% | 43% | 6,3 | 90% | 1% | 75% |
| 86 | Tungsten | W | 6203 | 92% | 1,2 | 81% | 769 t | 888 t | | 1% | | | 1% | 32% | 8,7 | 96% | 42% | 19% |
| 87 | Vanadium | V | 4605 | 86% | 2,3 | 85% | 64 t | 94 t | | 4% | | | 4% | 44% | 3,9 | 83% | 6% | 61% |

| # | Material (EU-CRM 2023) | Element symbol | HHI share of Global Production[a] | Concentration Risk (CR)[b] | Supply Risk (SR)[c] | Current Supply Risk (CSR)[b] | Future Demand 2020 (in tons)[d] | Future Demand 2030 (in tons)[d] | Future Demand 2050 (in tons)[d] | Future Demand Increase per year (2020-2030)[e] | Future Demand Increase per year (2030-2050)[e] | Future Demand Increase per year (2020-2050)[e] | FDI per year (2020-2050/ 2030-2050/ 2020-2030) | Future Demand Risk (FDR)[b] | Economic Importance (EI)[c] | Economic Risk of Importance (ERI)[b] | End of Life Recycling Input Rate (EoL-RIR)[f] | Recirculation Risk (RR)[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 88 | Xenon | Xe | | | 0,8 | 64% | | | | | | | | | 3,1 | 81% | 0% | 100% |
| 89 | Zinc | Zn | 1418 | 66% | 0,2 | 16% | 1054177 t | 1790472 t | 3573324 t | 5% | 4% | 4% | 4% | 46% | 4,8 | 86% | 34% | 22% |
| 90 | Zirconium | Zr | 2191 | 73% | 0,8 | 64% | 134 t | 10837 t | 37658 t | 55% | 6% | 21% | 21% | 100% | 3,5 | 82% | 12% | 47% |

[a]: World Mining Data 2021: table 6.5
[b]: Kolotzek2018- supplemental materials: tableS7; p.18
[c]: Study on the EU's list of Critical Raw Materials 2023: annex 2; p.54
[d]: EU-A foresight study 2023 - supplemental material
[e]: Calculation of the average annual growth rate
[f]: Study on the EU's list of Critical Raw Materials 2023: annex 11; p.119

## A.4 Table of the risk categories results of all EU-CRM 2023

| # | Material (EU-CRM 2023)[a] | Element symbol[f] | Classification[b] | Sub-classification[b] | By-Product Risk (BPR)[c] | Concentration Risk (CR)[d] | Policy Stability Risk (PSR)[e] | Social Stability Risk (SSR)[e] | Current Supply Risk (CSR)[d] | Future Demand Risk (FDR)[d] | Economic Risk of Importance (ERI)[d] | Recirculation Risk (RR)[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aggregates | - | Non-metallic minerals | Construction materials | | | | | 16% | | 81% | 53% |
| 2 | Aluminium/Bauxite | Al | Metallic minerals and metals | Non-ferrous base metals | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% |
| 3 | Antimony | Sb | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 80% | 78% | 61% | 26% | 83% | 66% | 87% | 24% |
| 4 | Arsenic | As | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 92% | 82% | 52% | 16% | 84% | 85% | 80% | 100% |
| 5 | Baryte | $BaSO_4$ | Non-metallic minerals | Industrial minerals | 2% | 71% | 55% | 34% | 81% | 33% | 82% | 100% |
| 6 | Bentonite | - | Non-metallic minerals | Industrial minerals | | 65% | 43% | 31% | 32% | | 81% | 35% |
| 7 | Beryllium | Be | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 11% | 88% | 29% | 27% | 83% | 32% | 87% | 100% |
| 8 | Bismuth | Bi | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 90% | 90% | 53% | 12% | 84% | 34% | 88% | 100% |
| 9 | Boron/Borate | B | Non-metallic minerals | Industrial minerals | 0% | 80% | 43% | 37% | 90% | 43% | 83% | 75% |
| 10 | Cadmium | Cd | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 73% | 39% | 20% | 16% | 41% | 84% | 23% |
| 11 | Chromium | Cr | Metallic minerals and metals | Ferro-alloy metals | 2% | 79% | 45% | 26% | 56% | 45% | 92% | 32% |
| 12 | Cobalt | Co | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 85% | 87% | 76% | 67% | 87% | 70% | 91% | 30% |
| 13 | Coking coal | C | other | other | | 81% | 43% | 20% | 80% | | 81% | 100% |
| 14 | Copper | Cu | Metallic minerals and metals | Non-ferrous base metals | 9% | 61% | 38% | 32% | 8% | 65% | 83% | 15% |
| 15 | Diatomite | - | Non-metallic minerals | Industrial minerals | | 71% | 32% | 24% | 24% | | 58% | 67% |
| 16 | Feldspar | $AT_4O_8$ | Non-metallic minerals | Industrial minerals | | 70% | 54% | 40% | 82% | | 81% | 75% |
| 17 | Fluorspar | $CaF_2$ | Non-metallic minerals | Industrial minerals | | 86% | 54% | 11% | 80% | 100% | 83% | 75% |
| 18 | Gallium | Ga | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 99% | 55% | 11% | 92% | 82% | 83% | 100% |
| 19 | Germanium | Ge | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 97% | 54% | 13% | 83% | 100% | 82% | 72% |
| 20 | Gold | Au | Metallic minerals and metals | Precious metals | 14% | 47% | 33% | 26% | 32% | 43% | 62% | 64% |
| 21 | Gypsum | $CaSO_4{\cdot}2H_2O$ | Non-metallic minerals | Construction materials | | 53% | 43% | 23% | 48% | | 76% | 75% |
| 22 | Hafnium | Hf | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | | 20% | 31% | 82% | 32% | 84% | 100% |
| 23 | Helium | He | Non-metallic minerals | Noble gas | | | 27% | 31% | 81% | | 80% | 72% |
| 24 | HREE | - | Metallic minerals and metals | Rare earths | | 85% | | | 96% | | 84% | 75% |
| 25 | HREE Dysprosium | Dy | Metallic minerals and metals | Rare earths | 100% | | 56% | 18% | 98% | 64% | 94% | |
| 26 | HREE Erbium | Er | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 98% | | 82% | |
| 27 | HREE Europium | Eu | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 98% | 19% | 81% | |

## A.4 Table of the risk categories results of all EU-CRM 2023

| # | Material (EU-CRM 2023)[a] | Element symbol[f] | Classification[b] | Sub-classification[b] | By-Product Risk (BPR)[c] | Concentration Risk (CR)[d] | Policy Stability Risk (PSR)[e] | Social Stability Risk (SSR)[e] | Current Supply Risk (CSR)[d] | Future Demand Risk (FDR)[d] | Economic Risk of Importance (ERI)[d] | Recirculation Risk (RR)[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | HREE Gadolinium | Gd | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 89% | 32% | 81% | |
| 29 | HREE Holmium | Ho | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 98% | | 81% | |
| 30 | HREE Lutetium | Lu | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 98% | | 86% | |
| 31 | HREE Terbium | Tb | Metallic minerals and metals | Rare earths | 100% | | 56% | 18% | 96% | 47% | 90% | |
| 32 | HREE Thulium | Tm | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 98% | | 81% | |
| 33 | HREE Ytterbium | Yb | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 98% | | 81% | |
| 34 | HREE Yttrium | Y | Metallic minerals and metals | Rare earths | 29% | | 48% | 19% | 90% | 100% | 80% | |
| 35 | Hydrogen | H | Non-metallic minerals | Industrial minerals | | | 38% | 32% | 40% | | 80% | 100% |
| 36 | Indium | In | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 84% | 37% | 19% | 48% | 72% | 71% | 75% |
| 37 | Iron ore | Fe | Metallic minerals and metals | Iron & steel | 1% | 71% | 32% | 25% | 40% | 51% | 92% | 23% |
| 38 | Kaolin clay | $Al_4[(OH)_8\|Si_4O_{10}]$ | Non-metallic minerals | Industrial minerals | | 59% | 51% | 27% | 64% | | 80% | 23% |
| 39 | Krypton | Kr | Non-metallic minerals | Noble gas | | | | | 56% | | 81% | 100% |
| 40 | Lead | Pb | Metallic minerals and metals | Non-ferrous base metals | 10% | 73% | 44% | 14% | 8% | 37% | 84% | 6% |
| 41 | Limestone | $CaCO_3$ | Non-metallic minerals | Industrial minerals | | | 31% | 33% | 24% | | 82% | 75% |
| 42 | Lithium | Li | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 52% | 81% | 20% | 29% | 84% | 99% | 83% | 100% |
| 43 | LREE | - | Metallic minerals and metals | Rare earths | | 85% | | | 91% | | 89% | 75% |
| 44 | LREE Cerium | Ce | Metallic minerals and metals | Rare earths | 73% | | 48% | 19% | 92% | 34% | 86% | |
| 45 | LREE Lanthanum | La | Metallic minerals and metals | Rare earths | 93% | | 48% | 19% | 90% | 100% | 80% | |
| 46 | LREE Neodymium | Nd | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 94% | 61% | 92% | |
| 47 | LREE Praseodymium | Pr | Metallic minerals and metals | Rare earths | 100% | | 48% | 19% | 89% | 48% | 92% | |
| 48 | LREE Samarium | Sm | Metallic minerals and metals | Rare earths | 82% | | 48% | 19% | 90% | | 94% | |
| 49 | Magnesite | $Mg[CO_3]$ | Non-metallic minerals | Industrial minerals | | 85% | 54% | 16% | 48% | | 82% | 72% |
| 50 | Magnesium | Mg | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 5% | | 53% | 11% | 92% | 32% | 93% | 45% |
| 51 | Manganese | Mn | Metallic minerals and metals | Ferro-alloy metals | 3% | 71% | 41% | 19% | 81% | 52% | 91% | 53% |
| 52 | Molybdenum | Mo | Metallic minerals and metals | Ferro-alloy metals | 46% | 74% | 40% | 20% | 64% | 45% | 91% | 23% |
| 53 | Natural cork | - | Biotic materials | Biotic materials | | | 27% | 34% | 72% | | 31% | 56% |
| 54 | Natural graphite | C | Non-metallic minerals | Industrial minerals | | 85% | 57% | 17% | 83% | 100% | 82% | 69% |
| 55 | Natural rubber | - | Biotic materials | Biotic materials | | | 52% | 30% | 72% | | 89% | 72% |
| 56 | Natural teak wood | - | Biotic materials | Biotic materials | | | 59% | 48% | 83% | | 62% | 64% |
| 57 | Neon | Ne | Non-metallic minerals | Noble gas | | | | | 56% | | 81% | 100% |
| 58 | Nickel | Ni | Metallic minerals and metals | Non-ferrous base metals | 2% | 73% | 42% | 28% | 40% | 87% | 88% | 40% |
| 59 | Niobium | Nb | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 2% | 97% | 49% | 13% | 94% | 32% | 90% | 100% |
| 60 | Perlite | - | Non-metallic minerals | Industrial minerals | | 78% | 50% | 25% | 64% | | 67% | 19% |
| 61 | PGM | - | Metallic minerals and metals | Precious metals | | | | | 87% | | 92% | 47% |

## A.4 Table of the risk categories results of all EU-CRM 2023

| # | Material (EU-CRM 2023)[a] | Element symbol[f] | Classification[b] | Sub-classification[b] | By-Product Risk (BPR)[c] | Concentration Risk (CR)[d] | Policy Stability Risk (PSR)[e] | Social Stability Risk (SSR)[e] | Current Supply Risk (CSR)[d] | Future Demand Risk (FDR)[d] | Economic Risk of Importance (ERI)[d] | Recirculation Risk (RR)[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 62 | PGM Iridium | Ir | Metallic minerals and metals | Precious metals | 100% | | 44% | 15% | 92% | 46% | 90% | |
| 63 | PGM Palladium | Pd | Metallic minerals and metals | Precious metals | 97% | 80% | 48% | 28% | 82% | 32% | 95% | |
| 64 | PGM Platinum | Pt | Metallic minerals and metals | Precious metals | 16% | 90% | 48% | 21% | 85% | 100% | 91% | |
| 65 | PGM Rhodium | Rh | Metallic minerals and metals | Precious metals | 100% | 95% | 47% | 19% | 86% | | 96% | |
| 66 | PGM Ruthenium | Ru | Metallic minerals and metals | Precious metals | 100% | | 44% | 15% | 91% | 92% | 88% | |
| 67 | Phosphate rock | - | Non-metallic minerals | Industrial minerals | | 73% | 50% | 23% | 80% | | 90% | 100% |
| 68 | Phosphorus | P | Non-metallic minerals | Industrial minerals | | | 51% | 15% | 89% | 100% | 85% | 100% |
| 69 | Potash | KCl | Non-metallic minerals | Industrial minerals | | 70% | 36% | 31% | 56% | | 89% | 100% |
| 70 | Rhenium | Re | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 77% | 42% | 19% | 40% | | 58% | 17% |
| 71 | Roundwood | - | Biotic materials | Biotic materials | | | 38% | 24% | 8% | | 9% | 33% |
| 72 | Sapele wood | - | Biotic materials | Biotic materials | | | 74% | 66% | 81% | | 27% | 58% |
| 73 | Scandium | Sc | Metallic minerals and metals | Rare earths | 100% | | 57% | 18% | 86% | | 83% | 100% |
| 74 | Selenium | Se | other | other | 100% | 72% | 32% | 22% | 24% | 40% | 86% | 75% |
| 75 | Silica | $SiO_2$ | Non-metallic minerals | Industrial minerals | | | 27% | 30% | 24% | | 81% | 75% |
| 76 | Silicon metal | Si | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | | | 50% | 13% | 82% | 38% | 86% | 100% |
| 77 | Silver | Ag | Metallic minerals and metals | Precious metals | 71% | 61% | 51% | 16% | 64% | 38% | 85% | 67% |
| 78 | Strontium | Sr | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 0% | | 51% | 18% | 86% | 32% | 90% | 100% |
| 79 | Sulphur | S | Non-metallic minerals | Industrial minerals | | 57% | 46% | 25% | 24% | | 86% | 100% |
| 80 | Talc | $Mg_3Si_4O_{10}(OH)_2$ | Non-metallic minerals | Industrial minerals | | 60% | 45% | 32% | 16% | | 81% | 40% |
| 81 | Tantalum | Ta | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 28% | 69% | 68% | 60% | 81% | 34% | 86% | 75% |
| 82 | Tellurium | Te | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 89% | 46% | 16% | 24% | 41% | 83% | 75% |
| 83 | Tin | Sn | Metallic minerals and metals | Non-ferrous base metals | 3% | 69% | 57% | 26% | 72% | 35% | 85% | 23% |
| 84 | Titanium | Ti | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 0% | 68% | 40% | 26% | 40% | 43% | 87% | 75% |
| 85 | Titanium metal | | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 0% | 68% | 40% | 26% | 82% | 43% | 90% | 75% |
| 86 | Tungsten | W | Metallic minerals and metals | Ferro-alloy metals | | 92% | 55% | 13% | 81% | 32% | 96% | 19% |
| 87 | Vanadium | V | Metallic minerals and metals | Ferro-alloy metals | 82% | 86% | 55% | 17% | 85% | 44% | 83% | 61% |
| 88 | Xenon | Xe | Non-metallic minerals | Noble gas | | | | | 64% | | 81% | 100% |
| 89 | Zinc | Zn | Metallic minerals and metals | Non-ferrous base metals | 10% | 66% | 43% | 19% | 16% | 46% | 86% | 22% |
| 90 | Zirconium | Zr | Metallic minerals and metals | High-tech and other non-ferrous metals and metalloids | 100% | 73% | 33% | 31% | 64% | 100% | 82% | 47% |

[a]: Study on the EU's list of Critical Raw Materials 2023
[b]: 3rd Raw Materials Scoreboard 2021: p.7
[c]: Nassar et al. 2015: fig.1; p.2
[d]: Own table of risk score calculation (Table 7.3)
[e]: Own table of Top 5 Global Producer (Table 7.2)
[f]: https://www.consilium.europa.eu/en/infographics/critical-raw-materials/ (Accessed on 2023-07-04)

## A.5 Table of material input for the circularity assessment tool of the Fairphone 4

**Information: Values are taken from the sheet "Materials_inidcators". If there are no values for the sub-materials in the REE (HREE, LREE) or PGM groups, the more general values for the groups are used.**

| | | | |
|---|---|---|---|
| **Product:** | ***Fairphone 4*** | **Edited by:** *Thomas Mandl* | **Date:** *21.07.2023* **Version:** *1.0* |

**Very Low Risk** | **Low Risk** | **Medium Risk** | **High Risk** | **No Data available**

| # | Material | Assembly | Part | Element symbol | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aluminium/ Bauxite | Battery | Lithium-ion battery | | | | | | | | | | lithium-ion batteries |
| 2 | Carbon | Battery | Lithium-ion battery | | | | | | | | | | lithium-ion batteries |
| 3 | Cobalt | Battery | Lithium-ion battery | Co | 85% | 87% | 76% | 67% | 87% | 70% | 91% | 30% | lithium-ion batteries |
| 4 | Lithium | Battery | Lithium-ion battery | Li | 52% | 81% | 20% | 29% | 84% | 99% | 83% | 100% | lithium-ion batteries |
| 5 | Oxygen | Battery | Lithium-ion battery | | | | | | | | | | lithium-ion batteries |
| 6 | Bromine | Casing | Case | | | | | | | | | | plastics will also include flame retardant compounds, some of which contain bromine |
| 7 | Carbon | Casing | Case | | | | | | | | | | |
| 8 | Magnesium | Casing | Case | Mg | 5% | | 53% | 11% | 92% | 32% | 93% | 45% | |
| 9 | Nickel | Casing | Case | Ni | 2% | 73% | 42% | 28% | 40% | 87% | 88% | 40% | included to reduce electromagnetic interference |
| 10 | Antimony | Electronics | Chip | Sb | 80% | 78% | 61% | 26% | 83% | 66% | 87% | 24% | added to allow the chip to conduct electricity |
| 11 | Arsenic | Electronics | Chip | As | 92% | 82% | 52% | 16% | 84% | 85% | 80% | 100% | added to allow the chip to conduct electricity |
| 12 | Gallium | Electronics | Chip | Ga | 100% | 99% | 55% | 11% | 92% | 82% | 83% | 100% | added to allow the chip to conduct electricity |
| 13 | Oxygen | Electronics | Chip | | | | | | | | | | oxidised to produce non-conducting regions |
| 14 | Phosphorus | Electronics | Chip | P | | | 51% | 15% | 89% | 100% | 85% | 100% | added to allow the chip to conduct electricity |
| 15 | Silicon metal | Electronics | Chip | Si | | | 50% | 13% | 82% | 38% | 86% | 100% | manufacture the chip in the phone |
| 16 | Copper | Electronics | Microelectrical components | Cu | 9% | 61% | 38% | 32% | 8% | 65% | 83% | 15% | wiring, microelectrical components |
| 17 | Gold | Electronics | Microelectrical components | Au | 14% | 47% | 33% | 26% | 32% | 43% | 62% | 64% | microelectrical components |
| 18 | Silver | Electronics | Microelectrical components | Ag | 71% | 61% | 51% | 16% | 64% | 38% | 85% | 67% | microelectrical components |
| 19 | Tantalum | Electronics | Microelectrical components | Ta | 28% | 69% | 68% | 60% | 81% | 34% | 86% | 75% | micro-capacitors |
| 20 | HREE Gadolinium | Electronics | Microphone | Gd | 100% | 85% | 48% | 19% | 89% | 32% | 81% | 75% | magnets |
| 21 | LREE Neodymium | Electronics | Microphone | Nd | 100% | 85% | 48% | 19% | 94% | 61% | 92% | 75% | magnets |
| 22 | LREE Praseodymium | Electronics | Microphone | Pr | 100% | 85% | 48% | 19% | 89% | 48% | 92% | 75% | magnets |
| 23 | Nickel | Electronics | Microphone | Ni | 2% | 73% | 42% | 28% | 40% | 87% | 88% | 40% | other electrical connections |
| 24 | Lead | Electronics | Solder | Pb | 10% | 73% | 44% | 14% | 8% | 37% | 84% | 6% | used to solder electronics in the phone |
| 25 | Tin | Electronics | Solder | Sn | 3% | 69% | 57% | 26% | 72% | 35% | 85% | 23% | used to solder electronics in the phone |
| 26 | HREE Gadolinium | Electronics | Speakers | Gd | 100% | 85% | 48% | 19% | 89% | 32% | 81% | 75% | magnets |
| 27 | LREE Neodymium | Electronics | Speakers | Nd | 100% | 85% | 48% | 19% | 94% | 61% | 92% | 75% | magnets |
| 28 | LREE Praseodymium | Electronics | Speakers | Pr | 100% | 85% | 48% | 19% | 89% | 48% | 92% | 75% | magnets |
| 29 | HREE Dysprosium | Electronics | Vibration unit | Dy | 100% | 85% | 56% | 18% | 98% | 64% | 94% | 75% | |
| 30 | HREE Terbium | Electronics | Vibration unit | Tb | 100% | 85% | 56% | 18% | 96% | 47% | 90% | 75% | |
| 31 | LREE Neodymium | Electronics | Vibration unit | Nd | 100% | 85% | 48% | 19% | 94% | 61% | 92% | 75% | |
| 32 | Tungsten | Electronics | Vibration unit | W | | 92% | 55% | 13% | 81% | 32% | 96% | 19% | JRC and Fairphone FM(focus material) |
| 33 | HREE Dysprosium | Screen | Display | Dy | 100% | 85% | 56% | 18% | 98% | 64% | 94% | 75% | produce the colours in the smartphone's screen or reduce UV light penetration |
| 34 | HREE Europium | Screen | Display | Eu | 100% | 85% | 48% | 19% | 98% | 19% | 81% | 75% | produce the colours in the smartphone's screen or reduce UV light penetration |

| # | Material | Assembly | Part | Element symbol | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 35 | HREE Gadolinium | Screen | Display | Gd | 100% | 85% | 48% | 19% | 89% | 32% | 81% | 75% | produce the colours in the smartphone's screen or reduce UV light penetration |
| 36 | HREE Terbium | Screen | Display | Tb | 100% | 85% | 56% | 18% | 96% | 47% | 90% | 75% | produce the colours in the smartphone's screen or reduce UV light penetration |
| 37 | HREE Yttrium | Screen | Display | Y | 29% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | produce the colours in the smartphone's screen or reduce UV light penetration |
| 38 | LREE Lanthanum | Screen | Display | La | 93% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | produce the colours in the smartphone's screen or reduce UV light penetration |
| 39 | LREE Praseodymium | Screen | Display | Pr | 100% | 85% | 48% | 19% | 89% | 48% | 92% | 75% | produce the colours in the smartphone's screen or reduce UV light penetration |
| 40 | Aluminium/Bauxite | Screen | Glass | Al | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% | the glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al2O3) and silica (SiO2) |
| 41 | Oxygen | Screen | Glass | | | | | | | | | | the glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al2O3) and silica (SiO2) |
| 42 | Potassium | Screen | Glass | | | | | | | | | | the glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al2O3) and silica (SiO2) |
| 43 | Silicon metal | Screen | Glass | Si | | | 50% | 13% | 82% | 38% | 86% | 100% | the glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al2O3) and silica (SiO2) |
| 44 | Indium | Screen | Touchscreen | In | 100% | 84% | 37% | 19% | 48% | 72% | 71% | 75% | used in a transparent film in the screen that conducts electricity |
| 45 | Oxygen | Screen | Touchscreen | | | | | | | | | | used in a transparent film in the screen that conducts electricity |
| 46 | Tin | Screen | Touchscreen | Sn | 3% | 69% | 57% | 26% | 72% | 35% | 85% | 23% | used in a transparent film in the screen that conducts electricity |

Data for the Fairphone 4 Materials are taken from *Joint Research Center et. al 2020; Sánchez et. al 2022; https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/ (Accessed on 2023-07-21)*

## A.6 Table of unfiltered dashboard of all critical raw materials of the Fairphone 4

**Assembly**

| | |
|---|---|
| Battery | |
| Casing | |
| Electronics | |
| Screen | |

**Part**

| | | | |
|---|---|---|---|
| Case | Chip | Display | Glass |
| Lithium-ion battery | Microelectrical co... | Microphone | Solder |
| Speakers | Touchscreen | Vibration unit | |

**Materials**

| | | | |
|---|---|---|---|
| Aluminium/Bauxite | Antimony | Arsenic | Bromine |
| Carbon | Cobalt | Copper | Gallium |
| Gold | HREE Dysprosium | HREE Europium | HREE Gadolinium |
| HREE Terbium | HREE Yttrium | Indium | Lead |
| Lithium | LREE Lanthanum | LREE Neodymium | LREE Praseody... |
| Magnesium | Nickel | Oxygen | Phosphorus |
| Potassium | Silicon metal | Silver | Tantalum |
| Tin | Tungsten | | |

**Very Low Risk**
**Low Risk**
**Medium Risk**
**High Risk**
**No Data available**

| **Product:** | ***Fairphone 4*** | **Edited by:** Thomas Mandl | **Date:** *21.07.2023* **Version:** *1.0* |
|---|---|---|---|

| Materials | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Average |
|---|---|---|---|---|---|---|---|---|---|
| Aluminium/Bauxite | 0% | 81% | 41% | 34% | 81% | 65% | 88% | 23% | 52% |
| Antimony | 80% | 78% | 61% | 26% | 83% | 66% | 87% | 24% | 63% |
| Arsenic | 92% | 82% | 52% | 16% | 84% | 85% | 80% | 100% | 74% |
| Bromine | | | | | | | | | |
| Carbon | | | | | | | | | |
| Cobalt | 85% | 87% | 76% | 67% | 87% | 70% | 91% | 30% | 74% |
| Copper | 9% | 61% | 38% | 32% | 8% | 65% | 83% | 15% | 39% |
| Gallium | 100% | 99% | 55% | 11% | 92% | 82% | 83% | 100% | 78% |
| Gold | 14% | 47% | 33% | 26% | 32% | 43% | 62% | 64% | 40% |
| HREE Dysprosium | 100% | 85% | 56% | 18% | 98% | 64% | 94% | 75% | 74% |
| HREE Europium | 100% | 85% | 48% | 19% | 98% | 19% | 81% | 75% | 66% |
| HREE Gadolinium | 100% | 85% | 48% | 19% | 89% | 32% | 81% | 75% | 66% |
| HREE Terbium | 100% | 85% | 56% | 18% | 96% | 47% | 90% | 75% | 71% |
| HREE Yttrium | 29% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | 66% |
| Indium | 100% | 84% | 37% | 19% | 48% | 72% | 71% | 75% | 63% |
| Lead | 10% | 73% | 44% | 14% | 8% | 37% | 84% | 6% | 35% |
| Lithium | 52% | 81% | 20% | 29% | 84% | 99% | 83% | 100% | 68% |
| LREE Lanthanum | 93% | 85% | 48% | 19% | 90% | 100% | 80% | 75% | 74% |
| LREE Neodymium | 100% | 85% | 48% | 19% | 94% | 61% | 92% | 75% | 72% |
| LREE Praseodymium | 100% | 85% | 48% | 19% | 89% | 48% | 92% | 75% | 69% |
| Magnesium | 5% | | 53% | 11% | 92% | 32% | 93% | 45% | 47% |
| Nickel | 2% | 73% | 42% | 28% | 40% | 87% | 88% | 40% | 50% |
| Oxygen | | | | | | | | | |

## A.6 Table of unfiltered dashboard of all critical raw materials of the Fairphone 4

| Materials | By-Product Risk (BPR) | Concentration Risk (CR) | Policy Stability Risk (PSR) | Social Stability Risk (SSR) | Current Supply Risk (CSR) | Future Demand Risk (FDR) | Economic Risk of Importance (ERI) | Recirculation Risk (RR) | Average |
|---|---|---|---|---|---|---|---|---|---|
| Phosphorus | | | 51% | 15% | 89% | 100% | 85% | 100% | 73% |
| Potassium | | | | | | | | | |
| Silicon metal | | | 50% | 13% | 82% | 38% | 86% | 100% | 61% |
| Silver | 71% | 61% | 51% | 16% | 64% | 38% | 85% | 67% | 57% |
| Tantalum | 28% | 69% | 68% | 60% | 81% | 34% | 86% | 75% | 62% |
| Tin | 3% | 69% | 57% | 26% | 72% | 35% | 85% | 23% | 46% |
| Tungsten | | 92% | 55% | 13% | 81% | 32% | 96% | 19% | 55% |

## A.7 Table of completed circularity questionnaire for the Fairphone 4

The selection of statements was inspired by: *http://pilot.ecodesign.at | https://system.wesustain-esm.com/circularity-check | https://d4r-pilot.ecodesign.at | https://tools.katche.eu/strategist/evaluate*

| **Product:** | **Fairphone 4** | **Date:** | 21.07.2023 | **Edited by:** |
|---|---|---|---|---|
| | | **Version:** | 1.0 | Thomas Mandl |

**#0 General Questions**

| St. | Category | Statement | Answer | Comments | |
|---|---|---|---|---|---|
| 0.1 | LCA | The **most critical life cycle stages** in relation to the highest environmental impact *(e.g. GWP, can be calculated by an LCA, EPD, ...)* of the product are known. | yes | | |
| 0.2 | LCA | <u>If St.0.1 is answered "yes" continue with St.0.2:</u> How are the environmental **impacts of the following 4 life cycle stages divided** in relation to each other? *(the weighting of the 4 life cycle stages, 10 points in total are to be divided between them. The more points per stage are entered in the answer field, the more weight is given to the statements of this stage in the RO (Retention Option) evaluation. If every stage is equal important, answer "equal".)* | **life cycle stages weighted** | | |
| 0.2.1 | LCA | - Raw material extraction | 3,9 | The data for the weighting of the life cycle | |
| 0.2.2 | LCA | - Manufacturing | 3,9 | stages are adopted by the LCA of the | |
| 0.2.3 | LCA | - Distribution | 0,5 | Fairphone 4. The LCA was done by | |
| 0.2.4 | LCA | - Use | 1,7 | Frauenhofer IZM (Source 1) | |

**#1 Raw material extraction**

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, ...)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 1.1 | Material supply | The company **choose secondary/recycled raw materials** instead of primary raw materials in the procurement process. | yes | yes | Source 2; p.37 | R0 |
| 1.2 | Material selection | The product is revised with the aim of **replacing the primary raw materials** with secondary materials in the material selection process if possible. | yes | partially | Source 2; p.37 | R1 |
| 1.3 | Material selection | The company **choose renewable materials** *(wood, corn, rape, hemp...)* instead of materials of fossil origin in the material selection process. | no | | No sources found for the use of renewable materials in smartphones | R0, R1 |
| 1.4 | Material selection | There are fulfilled requirements *(internal regulations, ISO, DIN, VDI, ...)* to ensure that **toxic/ecotoxic** *(dioxine, PCB, PVC, ...)* **materials are excluded** from the product hindering late recycling. | yes | yes | Source 3 | R0 |
| 1.5 | Material selection | The product is revised with the aim of ensuring that all **materials are easy to separate with conventional recycling methods**. | yes | yes | 75 % of the materials can, in theory, be recycled (Source 4) | R7, R9 |
| 1.6 | Material data | There is **product specific information** *(list (BOM) of all raw materials in the product/parts, on an element basis, ...)* **available** to support end-of-life strategies. | yes | partially | List of 14 *Focus materials* (Source 2; p.33) | R7, R8, R9 |
| 1.7 | Material data | The **most valuable materials** *(critical in supply, most expensive, not reusable, ...)* of the product are **known**. | yes | yes | *Fair material sourcing initiative* for the *Focus materials* (Source 2; p.34) | R1, R2, R3 |
| 1.8 | Material Production | The **raw material demand** of the product *(through targeted design, integration of functions, ...)* is revised to a **minimum**. | partially | no | Weight Fairphone 3: 190 g<br>Weight Fairphone 4: 225 g<br>Higher raw material demand can be compensated by a longer lifetime | R1 |

**#2 Manufacturing**

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, ...)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 2.1 | Strategy | The customer has the option to **purchase only the use of the product** *(circular business model like "Product-as-a-Service")*. The **ownership** of the product **remains within the company**. | yes | yes | *Fairphone Easy* (only available in the Netherlands status 2023-06-26) | R2, R3, R4, R5, R6, R7, R8 |

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, …)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 2.2 | Strategy | The company **minimise packaging waste** *(returnable packaging, standard packaging like EPAL, reuse packaging, …)* of external parts. | | | No sources were found to answer the question | R1, R2 |
| 2.3 | Strategy | The product is revised with the aim of **reducing material diversity and avoid inseparable composite materials** in the manufacturing process. | yes | yes | 75 % of the materials can, in theory, be recycled (Source 4) | R7, R9 |
| 2.4 | Design-dismantle | The **housing** of the product can be **opened easily and damage-free** in order to access the internal components. | yes | yes | Source 5 | R2, R3, R4, R5 |
| 2.5 | Design-dismantle | The **housing** of the product can be **opened easily** *(and NOT damage-free)* in order to access the internal components. | yes | yes | Source 5 | R6, R7 |
| 2.6 | Design-dismantle | The **electronic modules** *(PCB, CPU, sensors, …)* of the product are designed with **detachable connections** *(plug-in connections)* instead of being soldered. | yes | yes | Source 5 | R2, R3, R4, R5, R6 |
| 2.7 | Durability | The **visual appearance** of the product is designed to be **durable** *(durable materials, replaceable housing design, timeless design, …)* .* | yes | partially | The visual appearance cannot be changed (different back covers,…) | R2, R4 |
| 2.8 | Durability | The parts of **non-dismountable modules** *(soldered components, battery packs, displays, …)* are designed to have a **similar lifespan**.* | yes | partially | The modules can be replaced as a whole, but there is no information about the lifespan of the part within the module | R2, R3 |
| 2.9 | Durability | The product has **at least a similar lifespan** compared to competitive/reference products.* | yes | yes | 5-year manufacturer warranty (Source 2 [p.18] | R2, R3, R4, R5, R6 |
| 2.10 | Durability | The product is designed to have **a longer lifespan** compared to competitive/reference products.* | yes | yes | The majority of smartphones are covered by a 2-year warranty by default (Source 6) | R2, R3, R4, R5, R6 |
| 2.11 | Durability | The product is designed to **provide functionality checks for consumable parts** (*software functionality check, wear indicators, main dimensions for proof of functionality, …*) .* | yes | no | No sources found for functionality checks | R2, R3, R4, R5, R6 |
| 2.12 | Production | The **waste generated in the production process is minimised** by environmentally sound strategies *(reuse, recycle, repurpose, recover, …)* . | | | No sources were found to answer the question | R2, R7, R8 |
| 2.13 | Return | There is a **return-system** (provide in-house or by third-party companies) to return used products directly **to the company** for a recirculation process. | yes | yes | Via the fairphone website (Source 7) | R2, R3, R4, R5, R6, R7, R8 |

* The Statements is identical to the "Durability" category statements in the "Use" life cycle stage, please answer both the same way.

**#3 Distribution**

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, …)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 3.1 | Packaging | The company **uses reusable/standard packaging** *(European Pallet Association (EPAL), Returnable Plastic Crates (RPCs), International Fruit and Vegetable Container (IFCO), …)* if possible. | partially | partially | "The packaging is optimized to use it as a package to send in an old device" (Source 8) | R2 |
| 3.2 | Packaging | The company choose **recycled/cascaded materials** instead of primary materials for packaging if possible. | yes | yes | Source 8 | R7 |
| 3.3 | Packaging | The packaging is revised with the aim of **reducing raw material input to a minimum** for packaging. | no | | The packaging is completely recycled (Source 8) | R1 |

## A.7 Table of completed circularity questionnaire for the Fairphone 4

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, …)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 3.4 | Packaging | There is information/instruction provided *(printed on the packaging, in the manual, …)* for the **ideal end-of-life strategies of the packaging** *(return, reuse, repurpose, recycle, recover...)*. | yes | yes | Source 7 | R2, R6, R7, R8 |
| 3.5 | Distribution | The $CO_2$ **emission** during the **distribution process** is reduced to a **minimum** *(prefer environmentally sound types of transport, short distribution routes, ...)* . | yes | no | No sources were found for actions to reduce emissions in the distribution process | R0, R1 |

**#4 Use**

| St. | Category | Statement | Relevant for Product? | Executed? | Optional comments/bottlenecks *(economic, technical, social, …)* | Relevant ROs |
|---|---|---|---|---|---|---|
| 4.1 | Strategy | The product was analysed with the aim of **detecting the most valuable parts** *(critical materials, high production effort, high costs, ...)* . **Actions** have been taken to design the parts circular *(modular, removable, extendable, upgradable, ...)* . | yes | no | Only F*ocus materials* are analysed (Source 2; p.33) | R2, R3, R4, R5, R6 |
| 4.2 | Durability | The **visual appearance** of the product is designed to be **durable** *(durable materials, replaceable housing design, timeless design, ...)* .* | yes | partially | The visual appearance cannot be changed (different back covers,...) | R2, R4 |
| 4.3 | Durability | The parts of **non-dismountable modules** *(soldered components, battery packs, displays, …)* are designed to have a **similar lifespan**.* | yes | partially | The modules can be replaced as a whole, but there is no information about the lifespan of the part within the module | R2, R3 |
| 4.4 | Durability | The product has **at least a similar lifespan** compared to competitive/reference products.* | yes | yes | 5-year manufacturer warranty (Source 2 [p.18] | R2, R3, R4, R5, R6 |
| 4.5 | Durability | The product is designed to have **a longer lifespan** compared to competitive/reference products.* | yes | yes | The majority of smartphones are covered by a 2-year warranty by default (Source 6) | R2, R3, R4, R5, R6 |
| 4.6 | Durability | The product is designed to **provided functionality checks for parts** (*software functionality check, wear indicators, main dimensions for proof of functionality, ...)* .* | yes | no | No sources found for functionality checks | R2, R3, R4, R5, R6 |
| 4.7 | User-durability | There is information/instruction provided for the **user** to carry out **services** *(repairs, maintenance, life-extending measures, ...)* **by his own.** | yes | yes | Source 9 | R2, R3 |
| 4.8 | User-durability | There are repair centres/services provided *(in-house or by third-party companies)* provided the **user** to carry out **services** *(for product repairs, maintenance, other life-extending actions, ...)* **externally**. | yes | yes | Source 9 | R2, R3 |
| 4.9 | User-durability | There are **spare parts/software updates provided** for a reasonable period of time (*in relation to the product lifetime)* . | yes | yes | for a minimum of 5 years (Source 2; p.74) | R2, R3, R4, R5 |
| 4.10 | Utilisation | The **material consumption** of the product in the **utilisation stage** is reduced to a **minimum** *(minimize consumption materials, use renewable consumption materials, closed cycles for process materials, avoid waste, reuse waste, ...)*. | yes | yes | Possibility to send back the old modules | R0, R1 |

* The Statements is identical to the "Durability" category statements in the "Manufacturing" life cycle stage, please answer both the same way.

Source 1: Sanchez et al. 2022: fig.1; p.12
Source 2: Fairphone Impact Report 2022
Source 3: https://support.fairphone.com/hc/en-us/articles/360018631398-Safety-and-Hazardous-Materials (Accessed on 2023-06-26)
Source 4: https://circular-iq.com/circular-economy-fairphone-successful-innovation/ (Accessed on 2023-06-26)
Source 5: https://www.ifixit.com/Device/Fairphone_4 (Accessed on 2023-06-26)
Source 6: https://www.fairphone.com/en/warranty/ (Accessed on 2023-06-26)
Source 7: https://shop.fairphone.com/recycle (Accessed on 2023-06-26)
Source 8: https://www.fairphone.com/de/legal/fairphone-4-tagline-explained/ (Accessed on 2023-06-26)
Source 9: https://support.fairphone.com/hc/en-us/articles/115001041206-Find-fix-an-Issue-Yourself (Accessed on 2023-06-26)