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LIFE CYCLE SUSTAINABILITY ASSESSMENT

CriticS: a resource criticality characterization method for life cycle assessment considering stakeholders' perspectives

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Abstract

Purpose Assessing the supply risk of critical raw materials (CRMs) is crucial for supporting green transition strategies. Combining criticality assessment with life cycle sustainability assessment (LCSA) helps to link business actions to supply risks. However, these assessments are characterized by a variety in context, scope, and stakeholder influence, as well as a lack of method standardization. Currently, no operational quantitative method applied to LCSA includes diverse stakeholder perspectives.

Methods This study proposes a novel fit-for-purpose criticality assessment methodology leveraging existing criticality values from the study on CRMs from the European Commission (EC) while considering different stakeholder perspectives. In this research, several sets of characterization factors (CFs) are proposed, in which the values for supply risk and economic importance from the EC study on CRMs are combined in different ways, in some cases also with further parameters such as material prices. The methodology, called CriticS, guides stakeholders in defining the goal and scope, choosing sets of CFs, and operationalizing the assessment using a product's bill of materials (BoM) or its life cycle inventory (LCI). Specific sets of CFs are tested in a proof-of-concept case study of a laptop by using its BoM and LCI.

Results and discussion Supply risk and economic importance values were used to create 19 different sets of CFs. All sets of CFs of the CriticS are organized in a decision tree framework, helping stakeholders to select the most appropriate set of CFs that meets their needs. The CFs are linked to elementary flows in the ecoinvent® database, creating an operationalized model. The results of the proof-of-concept study highlight the benefits and the challenges in applying the CriticS methodology. These challenges are discussed, and potential solutions are identified.

Conclusions The results demonstrated the usefulness of the CriticS method with regard to the selection of the set of CFs using the decision tree, taking into account a given stakeholder's perspective. Future research should focus on refining the CF-elementary flow links, integrating CriticS into LCA software, and interpreting the results of the CriticS method together with those of life cycle sustainability assessment.

Keywords Critical raw materials (CRM) · Criticality assessment · Life cycle impact assessments (LCIA) · Characterization factors

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1 Introduction

Mitigating the risks of supply disruption is crucial for a green transition and the fourth industrial revolution. The acceleration of digitization and electrification, especially in view of sustainability goals, has intensified the need for scarce resources (Carrara et al. 2023). As the demand for those materials increases, so does the demand for studies on resource accessibility. That is, beyond the problem of resource availability, defined by Schulze et al. (2020) as "physical presence of a resource," raw materials are susceptible to environmental and socioeconomic conditions that also hamper their accessibility. Accessibility is defined as "the ability to make use of a resource" (Schulze et al. 2020). The accessibility can be limited by different causes from feasibility of exploration of reserves, concentration of mine production, price variation, political conflicts, and demand growth to the in-use materials in products in the technosphere (Berger et al. 2020; Dewulf et al. 2024).

Concerns about the reliability of supply chains and the accessibility of energy and mineral resources, particularly from certain regions, have been initially associated with times of war and national emergency (National Research Council, 2008). The term "critical material" first appeared in the US Strategic and Critical Materials Stock Piling Act of 1939 (National Research Council, 2008). Studies of Critical Raw Materials (CRMs) intensified after the second half of the twentieth century. While there is no standardized definition for CRMs or a generally accepted method for conducting criticality assessments (CAs), CRMs can be understood as raw materials that are critical for a specific entity at a given point in time and location according to measurable circumstances (Mancini et al. 2013). The study of criticality also includes the choice of the raw materials to be assessed, which in the literature can range from minerals and metals in most cases (Schrijvers et al. 2020b), to the study of biotic materials (Bach et al. 2017) or even water (Sonderegger et al. 2015).

In the European policy context, the European Commission's Criticality Assessment method (EC-CA) aims to identify CRMs for European Union (EU) member states. The EC-CA defines CRMs as "raw materials of high importance to the economy of the EU whose supply is associated with high risk" (European Commission 2017a). Following this two-dimensional definition, the EC-CA relies on the evaluation of economic importance (EI) and supply risk (SR) as the main criteria for assessing criticality (European Commission 2017a). The so-called "candidate" raw materials assessed by the EC include minerals (e.g., gypsum), metals (e.g., silver), and natural biomass (e.g., natural cork) (European Commission 2023a).

In a broader context, there is a link between the CRMs and achieving more sustainable development. The EC-CA is particularly used by the EC to identify risks that could affect the energy transition, where the increased production of electricity from renewable energy sources will require an additional supply of critical metals (Carrara et al. 2023). At the same time, strategies to promote a circular economy have a direct impact on the availability of both primary and secondary raw materials (Hackenhaar et al. 2024). Hence, there is a growing interest from the scientific, public, and private sectors in analyzing criticality together with sustainability. In this sense, the integration of CA into life cycle (sustainability) assessment (LCA and LCSA, henceforth referred to as LC(S)A) seems to be a good way forward. LCA is currently being used by various stakeholders for sustainable value chain management, and it is increasingly appearing in public policies, such as the corporate sustainability reporting directive (CSRD) (European Commission, 2022), and reporting guidelines in the private sector, such as the numerous initiatives led by the World Business Council for Sustainable Development.

To facilitate the integration of CA into LCSA, it is crucial to adopt a method with or adaptable to a life cycle perspective as CA methods are not necessarily designed for such a life cycle approach (Hackenhaar et al. 2022). This approach means going beyond the perspective of a company's production site to consider the functions and the impacts of the product throughout its entire life cycle, from raw material extraction to disposal or recycling, and its value chain (UNEP/SETAC 2011). This implies that the chosen CA methodology must be applicable to the functional unit and also to the entire life cycle of a given product, which would allow CA results to be analyzed alongside environmental, social, and economic impacts in LCSA (Hackenhaar et al. 2024). This is challenging given the lack of scientific consensus on the optimal approach to assessing criticality from both a macro-economic and from a product life cycle perspective (Schrijvers et al. 2020b). Hackenhaar et al. (2022) presented a detailed review and analysis on existing CA within and outside the context of LC(S)A. Two methods were considered promising for the purpose of a European LCSA methodology including criticality: EC-CA and GeoPolRisk. However, methodological challenges exist when applying the methods, which include the definition of scope and operationalization of the product's life cycle.

When analyzing criticality in LCA, Cimprich et al. (2019) argue that the Bill of Materials (BoM) of a product, production losses, and all other inventory flows in the Life Cycle Inventory (LCI) should be considered in order to capture criticality in both the product and the value chain. A BoM lists the names and amounts of the raw materials (or ingredients) required to manufacture a product (Zampori and Pant 2019). The BoM is part of the LCI which in turn includes all the necessary resources required in the life cycle (value chain) of the product including all releases (Zampori and Pant 2019). The review on mineral resources assessment from the Life Cycle Initiative (Sonderegger et al. 2020) identified a few well-established CA methods for products, namely, GeoPolRisk (Cimprich et al. 2019; Gemechu et al. 2015, 2016; Helbig et al. 2016; Santillán-Saldivar et al. 2021a, b, 2022), ESP (Schneider et al. 2014), and ESSENZ (Bach et al., 2016; Yavor et al. 2021). However, they do not immediately characterize background inventory flows occurring in the supply chains due to constraints in data availability and/or methodological choices (Cimprich et al. 2019). Mancini et al. (2018) and Tran et al. (2018), by contrast, propose characterization factors (CFs) based on SR and EI values from the EU CRM list applicable to both, the foreground and background, thereby identifying two key issues. First, Mancini et al. (2018) noted that the SR values used as CFs showed low variability, potentially masking relative differences between materials in terms of security of supply. The authors proposed several solutions, such as using exponentials to broaden the resulting values or normalizing indicators by market size or geological reserve data to account for variations in market and resource availability, respectively. Second, Tran et al. (2018) found inconsistencies in characterizing the criticality of a specific CRM when using LCI datasets from available LCA databases. These are often aggregated into ores with varying levels of purity or composition in nature. For instance, the EU's CRM study analyzed the criticality of "iron ore" with a dataset indicating 46% iron content in the ore. In response, Tran et al. (2018) proposed an adjustment factor of 2.17, considering that 2.17 kg of iron ore (according to the EU's CRM study) is required to produce 1 kg of iron according to the database. However, none of the above methodologies addresses criticality regarding the questions: for whom is the material critical?; where (i.e., in which geographical location) is the material critical?; and when (i.e. in which time span) does this criticality occur? (Mancini et al. 2013). The variability of existing criticality assessments reflects the context and scope dependency of the concept which is also influenced by the stakeholder concerned, the geographical coverage, and the timeframe of interest (Schrijvers et al. 2020b; Cimprich et al. 2023; Deteix et al. 2024).

Such as for LCA, it essential to CAs to clearly define the goal and scope of the study from the stakeholders' perspectives, including the geographical and temporal coverage of the assessment to ensure that the indicators appropriately reflect the specific geological, technological, geopolitical, social, and environmental factors relevant to the context of the study (Schrijvers et al. 2020b). As in social LCA, stakeholders, such as companies, consumers, workers, local communities, and policy makers, may be affected differently by potential supply constraints (Dewulf et al. 2015; Mancini et al. 2018). The analysis by Hool et al. (2023) of the European Critical Raw Materials Act (CRMA) (European Commission 2023b) illustrates how different stakeholders may be affected by criticality mitigating strategies. For example, in relation to the CRMA, Hool et al. (2023) found that opportunities for consumers include making responsible choices in terms of their environmental footprint (environmental concerns), but this may include the challenge of increased costs (economic concerns). On the other hand, for governments, there could be job creation and economic development (economic concerns), but also challenges in balancing environmental and social concerns (Hool et al. 2023). As a result, the CAs that emerge from different concerned stakeholders differ accordingly (Helbig et al. 2021). According to Helbig et al. (2021, pg. 345), "the aim should not be to establish uniform methodologies, as the objectives, scope and focus of different stakeholders differ in many ways." Rather, stakeholders would benefit from clear guidance on formulating objectives and scope, selecting indicators, and interpreting results (Schrijvers et al. 2020a). For this reason, the International Round Table on Materials Criticality (IRTC) has developed a qualitative tool[1] to help companies find the right strategies for building a resilient value chain depending on their questions. It allows a general study of material supply risks or an analysis of CRM for companies producing technologies (batteries and wind turbines) in specific sectors (transport and energy). However, the tool is currently limited to these few examples of sectors and technologies. These risks failing to consider all potential stakeholders interested in its use. Besides, to our knowledge, there is no operational quantitative method of criticality that includes different stakeholder perspectives and that could also be applied to LC(S)A.

The goal of this research is to develop a quantitative operational method to characterize criticality in LC(S)A for the European context while allowing for differing stakeholder perspectives. Extending the work by Mancini et al. (2018), this study introduces new indicators based on SR and/or EI values from the EC CRM methodology. Each indicator is computed with one set of CFs, differing in terms of if and how they combine the SR and EI parameters and potentially additional parameters such as material prices, considered relevant for the criticality concept definition to a given stakeholder. A decision tree organizes these sets of CFs in order for stakeholders to identify the criticality indicator that meets their needs. This paper presents the development of the criticality stakeholder-driven characterization methodology (CriticS) method, the sets of CFs, and the decision tree, as well as an operationalized

[1] IRCT Decision Tool: https://www.irtc-decision-tool.weloop.org/exploration

model using elementary flows from ecoinvent® database. The use of the decision tree and the chosen set of CFs is tested in a proof-of-concept case study of a laptop. This case study was selected due to recent reports of component shortages (Shah and McCornick 2021; Pachhandara 2022). The proof-of-concept model uses data from André et al. (2019) and Van Eygen et al. (2016). Furthermore, the sensitivity of choosing different sets of CFs is tested for both, the BoM and the LCI. The results are discussed and assessed against to the findings of Mancini et al. (2018). Finally, the proposed CriticS indicators—and other existing CA methodologies—are compared, thereby also reflecting on the potential to use the CriticS alongside LCSA.

2 Materials and methods

Following the principle of ease of application (Hackenhaar et al. 2024) and operationality (see ORIENTING, 2022), the CriticS is conceptualized as a life cycle impact assessment (LCIA) method. This means that the total criticality score of product "p" is obtained by first multiplying the natural resource flow "m" (from the LCI), "m" needed to deliver the functional unit (FU) by its criticality CFs and second summing these results for all "n" natural resources (Eq. 2).

$$Critically\ indicator_p = \sum_{m=1}^{n} total\ mass\ of\ resource_m \times CF_m \quad (1)$$

The following sections describe which natural resource flows are characterized, according to the scope of the criticality study (Sect. 2.1) and the scope of the CriticS methodology (Sect. 2.2). Section 2.3 describes the proof-of-concept case study.

2.1 Scope of a criticality study within LC(S)A

CAs often focus on quantifying criticality according to supply risk and/or vulnerability to supply disruption of each of the parts needed for a product (see Helbig et al. 2016; Carrara et al. 2023) or of the raw materials in general (i.e., not product-specific, see European Commission 2023a). A third alternative, taking a product life cycle perspective, is to evaluate the criticality of a product by accounting for the total quantified raw materials within its product system, including parts, consumable auxiliaries (such as fuels, lubricants, and process chemicals), capital assets (including machinery and infrastructure), and other necessary processes in the life cycle (Cimprich et al. 2019; Mancini et al. 2015; Tran et al. 2018; Santillán-Saldivar et al. 2022). The latter, a more holistic approach, is adopted in the CriticS. Since the CriticS is to be applied alongside LC(S)A, life cycle terminology for goal and scope definition is used here (ISO 2006).

As presented by Hackenhaar et al. (2024), the system boundary of an integrated sustainability assessment may differ for each of its methodological components (e.g., environmental, social, or economic) due to the intrinsic difference in the nature of the assessed domains. Therefore, the study of criticality may have a different scope than the other dimension(s) of LC(S)A. Nevertheless, they should rely on a consistent definition of the product system and its functionalities. Figure 1 summarizes the three potential system boundaries: (1) BoM, (2) cradle-to-gate life cycle, and (3) cradle-to-grave life cycle.

CAs are "outside-in" methods (Sonderegger et al. 2020), meaning that they measure the effects of the ecological and socio-economic conditions on a product system ("the

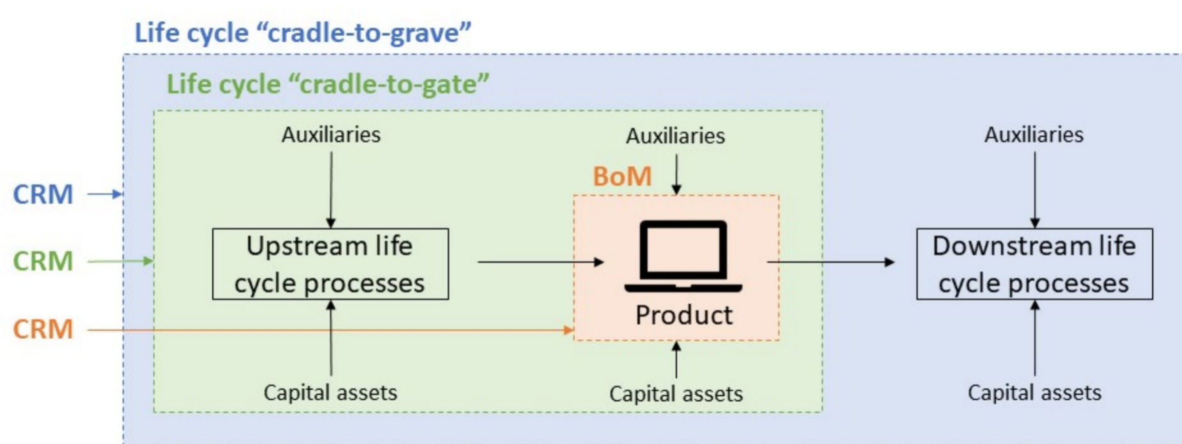

Fig. 1 Product system boundaries for identification of total criticality in LC(S)A. BoM: Bill of Materials; CRM: critical raw materials

environment affecting the product system"). In a narrow sense, the main concern is to secure the availability of raw materials needed for the product (good or service) under study. For that, the analysis of the BoM is sufficient. The study of the BoM is valuable information to estimate the direct risks for the manufacturer of a product. In this case, the total mass of materials "m" in Eq. 1 is the total material contained in the product "p."

In a broader sense, such as in LCA, the life cycle perspective of criticality enables to evaluate the supply risks linked to the utilities and auxiliaries used in the processes of the product's life cycle. This approach accounts for the indirect use of raw materials to produce, e.g., heat, power and electricity, facilities, fertilizer for agricultural goods, and/or packaging (ORIENTING 2024; Deteix et al. 2024). It also means accounting for the use of secondary raw materials (Santillán-Saldivar et al. 2021a), which are usually not shown separately in the BoM. Using the LCI facilitates the understanding of potential criticality risks in upstream or downstream processes in the product system (Helbig et al. 2016). A cradle-to-gate analysis is most common, but the analysis of the full life cycle ("cradle-to-grave"), or of a closed-loop ("cradle-to-cradle"), is also possible when relevant to the goal of the study and if the required data is available (e.g., regarding the collection, separation, and recycling of raw materials) (Hackenhaar et al. 2024). In both cases, the total mass of materials "m" in Eq. 1 is the total material inventoried which includes the total material contained in the product "p," and the indirect demand of materials for the utilities and auxiliaries. In this sense, the available LCI data may limit the scope of the criticality assessment.

The definition of the assessment scope is intimately related to the goal of the study. For instance, if the goal is to assess the potential risks associated with supply disruptions of materials incorporated in the end product, the scope can be limited to the BoM. Criticality results based on the BoM aim to provide product-specific recommendations in terms of product CRM content, including improving the design in a way that incorporates less CRMs, by, e.g., revising the secondary raw material content of CRM, diversifying suppliers, etc. Nevertheless, while a BoM may not be readily accessible, a bill of components is more commonly available. In this case, effective criticality mitigation strategies may require further detailed analysis of the supply chain. Alternatively, if the goal is to identify any conceivable supply risk within the supply chain that may impact the manufacturing process, the assessment should encompass all the relevant processes and required materials within the LCI leading up to that particular life cycle stage. In the end, criticality results based on the LCI can initiate broader risk mitigation actions, such as revision of secondary raw material processes within the product system, design for recycling and recovery of CRM, and/or adaptation through internalization of external processes, such as domestic recycling of materials (Santillan-Salvidar et al. 2021).

2.2 Characterization of criticality

2.2.1 The EC-CA method

The starting point for the development of the CriticS was the critical review of criticality methods done by Hackenhaar et al. (2022). Using a set of criteria and sub-criteria (see ORIENTING, 2021) such as "Stakeholder acceptance, credibility and suitability," "Applicability/Complexity," "Transparency," and "Compatibility with life-cycle approach," the EC-CA method was considered the most relevant and mature method to build the CriticS upon.

The EC-CA was created in response to the Raw Materials Initiative to assess criticality of raw materials important to the EU economy (European Commission 2008). The first list of CRMs was provided in 2011 (European Commission 2011) and it has undergone regular updates every three years since (European Commission 2014, 2017b, 2020a, 2023a). The core methodology was revised in 2017 with stakeholders being actively involved (Blengini et al. 2017). The two criteria of the methodology to determine criticality are the supply risk (SR) and economic importance (EI).

The SR of a raw material "m" indicates the risk of a disruption in the supply of "m." It is a dimensionless value calculated based on the import reliance of EU, concentration of primary supply from countries producing "m" and their governance performance. It proportionally accounts for the global suppliers and EU sourcing countries. Besides, SR is defined by also considering risk-mitigating factors, being both the recycling of "m" within the EU and potential substitute materials according to their market application (European Commission 2017a).

As explained in Sect. 2.1, vulnerability to supply disruption often accompanies SR indicators in CA. In the EC-CA, EI indicates the potential consequences to the EU economy associated to a potential supply disruption of "m". It is a dimensionless value calculated based on the share of end-use of "m" for different manufacturing sectors and the gross value added associated to each sector to EU economy. Similarly to SR, it considers potential substitute materials according to their market application (European Commission 2017a). According to the classification of Schrijvers et al. (2020a, b), the parameters used to EI (i.e., share of end-use products in different manufacturing sectors, gross added value, and potential substitute materials) indicate vulnerability. Hence, EI is further considered in the text analogous to vulnerability to supply disruption.

The values SR_m and EI_m are plotted in a chart (see Supplementary Information SI1 and European Commission 2020a), each indicator plotted on one axis. A given raw material "m" is considered critical if its SR_m and EI_m values reach or exceed pre-defined thresholds. These thresholds represent acceptable levels of SR and EI according to experts' opinions and are, respectively, 1 and 2.8 (dimensionless) (European Commission 2017a).

The CriticS uses the SR and EI values and additional information for 83 raw materials presented in the study of the EU CRMs list of 2020 (European Commission 2020a, b, c). They are used to calculate all sets of CFs. Extending the work of Mancini et al. (2018) and inspired by the work of Tran et al. (2018) and Santillán-Saldivar (2021b), CriticS explores how criticality differs when based on different mathematical combinations of these values, and how stakeholder views on criticality lead to preference for one or another. Table 1 shows the principles used to formulate sets of CFs according to the available information as well as the existing proposals in the literature (Mancini et al. 2018; Tran et al. 2018; adaptations from Santillán-Saldivar, 2021b).

2.2.2 Stakeholders' perspectives and principles

The EC-CA includes two elements that need further consideration for the conceptualization of the CriticS. First, the use of thresholds represents an element of subjectivity (Mancini et al. 2013), normally to be minimized in LCA (ISO 2006), that may or may not be supported by or acceptable for the stakeholders using the results. One of the consequences of using thresholds would be, for example, to include only those raw materials in the assessment that are considered critical according to the EU CRMs list (European Commission 2020a).

Second, as discussed by Hackenhaar et al. (2022, 2024), criticality cannot be evaluated by natural science alone as it is multidisciplinary. Elements considered in the assessment of criticality are diverse, such as geological concentration of materials, value added to the economy and geopolitical stability. In CriticS, we included the aspects 'subjectivity/stakeholder preferences' and 'multidisciplinarity,' by providing different sets of CFs, which are transparently described (see Sect. 3.1.1).

As criticality is a strategic outside-in method (see Sect. 2.1), the criticality indicator is recommended to be used for product and process design. Therefore, the target audiences for this methodology are LCA practitioners, researchers, technology developers, and potentially investors and retailers who are learning about criticality and/or are concerned about resource accessibility alongside other relevant sustainability topics. It is important to note that the user of the CriticS methodology is expected to have a basic understanding of resource criticality, in particular its key dimensions such as supply risk and vulnerability to supply disruption, as well as familiarity with factors that influence these parameters such as market dependence and geopolitical stability. This knowledge can either be derived from prior expertise or developed through an initial materiality assessment, as suggested by ORIENTING (2022), or introduced by the practitioner to stakeholders, e.g., during internal company stakeholder consultancy.

A decision tree is developed to guide the stakeholders to choose the most suitable set of CFs for their needs. The methodology (i.e., CFs and decision tree) is developed based on the central parameters identified in the literature on criticality assessment methodologies (Hackenhaar et al. 2022; Schrijvers et al. 2020a, b) and discussions with various stakeholders, including SMEs, LCSA, and criticality experts, within and outside the ORIENTING project context (see more details on the methodology development in SI2). The sets of CFs proposed here (according to Eq. 1 and including previous ones from Mancini et al. (2018) and Tran et al. (2018)) can be distinguished into three types: (i) SR, (ii) EI, and (iii) materials criticality, which combine the first two types of indicators. The description of the sets of CFs can be found in Sect. 3.1.1, while the decision tree is presented in Sect. 3.1.2.

2.2.3 Operationalization

To operationalize the CriticS method, one needs to map a given critical raw material to the elementary flows (EFLs). The classification and nomenclature of EFLs, however, vary among different databases (Edelen et al. 2018). For example, while in ecoinvent® uses "calcite, in ground," the corresponding EFL in the ILCD database is "calcium carbonate" (UNEP Life Cycle Initiative 2023). In this work, the widely known, commercial and comprehensive LCI database of ecoinvent® was chosen as a starting point to operationalize the CriticS method.

Based on the CRMs reports (European Commission 2020b, d), we identified a list of potential natural resources from which a given CRM could be obtained. The potential natural resources on this list were then mapped to one or more fitting elementary flows available in the ecoinvent® database up to version 3.8.

The CriticS applied to the proof-of-concept case study uses ecoinvent® v3.4, cut off by classification system model. While the full list of raw materials and their proposed correspondent EFL can be found in SI3, here, we highlight some of the characteristics and limitations of the mapping, using examples.

Some EFL in ecoinvent® versions before v3.8 were specified with different ore compositions from which the raw materials were retrieved. In these cases, all ore compositions were considered. That is the case, e.g., of copper, which has a total of 13 corresponding EFLs in the database. Thus, the inventory results presented for the case study includes the sum of all 13 inventoried EFLs.

Table 1 Principles for the formulation of the sets of characterization factors. Abbreviations: SR: supply risk; EI: economic importance; MP: market price of a raw material; P: total yearly production of a raw material; R: availability of resources in reserves; CRM: critical raw material;

Principles	Information	Type	Description
Mathematical combination	$\{SR_m; EI_m\}$	Multiplication ($a_m * b_m$)	When multiplied, both values contribute equally to the results; a low value of "a" decrease total value of criticality; therefore, trade-off is limited;
	$\{SR_m; MP_m\}$	Multiplication ($a_m * b_m$)	When multiplying supply risk and market price, products that contain higher market price materials are assigned more importance;
	$\{SR_m\}$	Exponential (a_m^x)	When applying exponential methods to supply risk data, potential points of concern are more effectively identified (Mancini et al. 2018);
	$\{SR_m; EI_m\}$	Pythagorean theorem ($\sqrt{(a_m^2 + b_m^2)}$)	If criticality is defined by the intersection of SR and EI values of a material "m" when plotted in a two-dimensional chart, then it can be represented as the vector whose magnitude is measured as the distance between the origin and the point determined by the values for SR and EI
Normalization	Thresholds $\{SR_m; EI_m; SR_{threshold}; EI_{threshold}\}$	($a_m/a_{threshold}$)	When normalized by the thresholds, SR and/or EI for the EU economy are assigned values relative to the thresholds stipulated; the use of thresholds is a means to consider limits stipulated by the EC (based on experts' opinion included in consultations) for SR[†)] and EI values for each of the materials;
	Market size $\{SR_m; P_m\}$	(a_m/b_m)	When normalized by total annual production, specialty materials having small markets are assigned more importance (Mancini et al. 2018)
	Availability of resources in natural reserves $\{SR_m; R_m\}$	(a_m/b_m)	When normalized by the total available natural resources, materials having smaller reserves are assigned more importance; this is done to include an element of resource depletion (Mancini et al. 2018)
	Maximum values {SR; EI}	(a_m/a_{max}); (b_m/b_{max})	Since SR and EI span different ranges of values. As a result, EI (currently reaching a value of more than 8) increases the criticality value more than SR (currently reaching a value of about 6 at most). When normalized to their maximum values, SR and/or EI are given comparable weight;
Cutting off	CRM $\{SR_m; EI_m; SR_{threshold}; EI_{threshold}\}$	Subtraction ($a_m - a_{thresholds}$)	Thresholds can assign no criticality (CF score = 0) to the materials that are not considered critical according to the EC-CA; the use of thresholds is a means to consider limits stipulated by the EC (based on experts' opinion included in consultations) for SR and EI values for each of the materials;
Classification according to thresholds	$\{SR_m; EI_m; SR_{threshold}; EI_{threshold}\}$	Binary	Depending on threshold information, different classes of raw materials can be distinguished; in binary classification, the CFs of CRMs are equal to 1 (noting that the scaling will take place through the respective masses involved) while the CFs of non-critical raw materials are equal to 0;
	$\{SR_m; EI_m; SR_{threshold}; EI_{threshold}\}$	Ternary	In ternary classification, raw materials whose SR and EI values are lower than the respective thresholds have CFs equal to 0[††)]; raw materials for which either SR or EI exceed the threshold are assigned CFs of 0.5; the CFs of the CRMs are greater 0.5;

[†]As explained in Sect. 2.2.1, the value of the threshold of SR is 1 in this study, according to the EU study on CRM of 2020. This means that the division by $SR_{thresholds}$ is irrelevant and does not change the value when considering SR alone. However, the value of the SR threshold could be subject to change in future updates of the EC-CA which is why the division is kept where appropriate[††]Assigning CFs of 0 to all non-critical raw materials also helps overcoming the issue that the list of raw materials in the EC-CA does not cover all raw materials covered in LCA databases: both, non-critical raw materials according to EC-CA and raw materials not covered by EC-CA are treated alike; *SR* supply risk, *EI* economic importance, *MP* market price of a raw material, *P* total yearly production of a raw material, *R* availability of resources in reserves, *CRM* critical raw material

Additionally, for raw materials characterized as "ores" or "rocks" by the EC (2020a), corrections based on the reasoning from Tran et al. (2018) are applied according to the ore content in the description of the ecoinvent® EFL nomenclature. This is the case only for "iron ore" and "phosphorus rock" (see further information in SI3).

Additionally, some materials as listed in the EC-CA report are overlapping. For example, this is the case for "aggregates," which includes both gravel and sand production (European Commission 2020b). Therefore, "aggregates" is represented by the EFL of both sand and gravel. The different sources of the materials were also considered according to the described analysis from the EC (2020b, c). That is the case for, e.g., "silica sand," which is described by the report as being sourced mainly from quartz crystals, but also from diatomite, tripoli, and perlite (European Commission 2020b). Diatomite and perlite are not available as EFL in the ecoinvent® database, while quartz is. The ecoinvent® database links the intermediate product "silica sand" in its background information with the EFL "gravel," wherefore it also includes "gravel, in ground." The same is valid for the description of "silicon metal" once the metallurgical-grade silicon is also obtained from the purification of quartz crystals (European Commission 2020c; IEA 2022).

Three candidate materials in the EC study could not be characterized because a mapping with ecoinvent® was not possible: hydrogen, phosphorus, and natural rubber. In the case of hydrogen, the element is obtained as a co-product from other production processes such as nuclear energy and water electrolysis (European Commission 2020a). Similarly, phosphorus criticality is calculated based on the isolated element (P_4), which is a co-product of electrothermal reducing furnaces (European Commission 2020a). In the case of natural rubber, no corresponding EFL was found in the database.

Note that substantial changes have been made in the nomenclature of EFLs in v3.8 according to the studies of the Global LCA Data Access (GLAD) network (further discussed in Sect. 4.3). In previous ecoinvent® versions, the natural resources were named according to their ore content. For example, in v3.4, iron could be found in the database as "Iron, 46% in ore, 25% in crude ore, in ground" and other ore compositions. In v3.8, it was simplified/unified into a single EFL called "Iron, in ore." To avoid any confusion, both types of nomenclature were considered in the mapping (see Sect. 3.1.3). In this paper, we tested the case study using ecoinvent® v3.4. Other versions of ecoinvent® and databases such as GaBi from Sphera have been tested in ORIENTING, the results of which can be found in the project report on case studies (ORIENTING 2024).

2.3 Proof-of-concept case study

A proof-of-concept case study was used to test the applicability of the CriticS model (method and characterized EFLs). To create a case comparable to Mancini et al. (2018), a laptop is analyzed with BoM and LCI based on the work of André et al. (2019) and Van Eygen et al. (2016). André et al. (2019) provide information and data on the BoM and LCI of the components in a typical second-hand laptop recovered by a Swedish company. Meanwhile, the study of Van Eygen et al. (2016) provides detailed BoM with the data on material inputs of laptops and on waste from electrical and electronic equipment in Belgium. The study of Van Eygen et al. (2016) describes the content of more than 20 minerals and metals and other materials such as plastics. Since neither of the studies provides a complete and detailed version of both the BoM and LCI, the information from both reference studies (Van Eygen et al. 2016; André et al. 2019) was adapted with complementary information to create the BoM and LCI for this study.

The laptop consists of several metal-rich components for which data was available: the casing, the liquid crystal display (LCD), the cables, and the printed circuit boards (PCBs). Battery, loudspeakers, camera, power cord, keyboard, and other components are not considered in this study. Detailed information regarding the BoM and LCI used in this study can be found in SI4. Table 2 shows the mass of minerals and metals for the laptop and per component. Barytes and limestone are grouped under "Industrial and construction minerals" because of their low mass in the total BoM. Gold, silver, and palladium are grouped under "Precious metals," following the classification of the EC (European Commission 2020a). The information about polymers content such as acrylonitrile butadiene styrene, polyethylene terephthalate, among others, can be found in SI4. They are disregarded here because they cannot be characterized by this version of the CriticS model.

Within this proof-of-concept case study, the goal is to evaluate the criticality of raw materials in a laptop that has an average lifespan of 3 years (based on the study of André et al. (2019). All sets of CFs were tested, but the results of only a few of them are presented here, illustrating the use of the decision tree (explained further in Sect. 2.2.2). Being based on different assumptions and perceptions, different sets of CFs will lead to different, non-comparable results. Nevertheless, the purpose of using different sets of CFs is to highlight the influence of taking different perspectives (and thus different sets of CFs) on the results in terms of criticality according to the decision tree.

Table 2 Bill of materials and components of the characterized minerals and metals in the proof-of-concept laptop study. Abbreviations: LCD: liquid crystal display; PCB: printed circuit boards. based on the work of André et al. (2019) and Van Eygen et al. (2016).

Minerals and metals	Cable (g)	PCB (g)	LCD (g)	Casing (g)	**Total mass of materials (g)**
Aluminum	-	31.84	52.81	36.40	121.05
Antimony	-	2.10	-	-	2.10
Copper	5.50	84.99	46.66	10.92	148.07
Iron ore	-	13.22	0.08	65.00	78.30
Magnesium	-	0.11	-	106.60	106.71
Nickel	-	2.05	-	-	2.05
Silicon metal	-	69.28	-	-	69.28
Tin	-	18.01	-	-	18.01
Titanium	-	0.00	30.80	-	30.80
Zinc	-	7.81	-	-	7.81
Industrial and construction minerals	-	21.53	-	-	21.53
Barytes	-	1.53	-	-	1.53
Limestone	-	20.00	-	-	20.00
Precious metals	-	0.49	-	-	0.49
Gold	-	0.06	-	-	0.06
Silver	-	0.21	-	-	0.21
Palladium	-	0.01	-	-	0.01
Total mass of components	5.50	251.21	130.34	218.92	605.98

LCD liquid crystal display, *PCB* printed circuit boardsBased on the work of André et al. (2019) and Van Eygen et al. (2016)

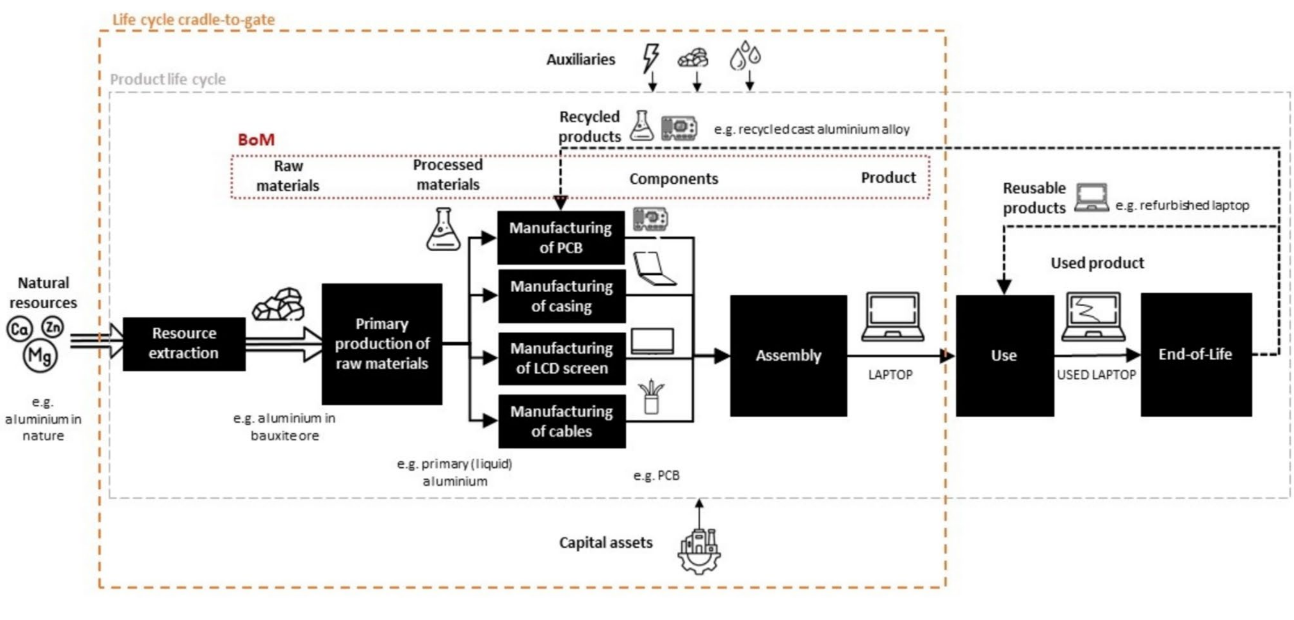

Fig. 2 Product system and the two alternative system boundaries in the proof-of-concept laptop study

From the three scope definitions stated in Sect. 2.1, two were analyzed: the BoM and the life cycle “cradle-to-gate” approach, shown in Fig. 2. The third scope was not considered due to data gaps regarding the use and EoL phase of the materials in the BoM.

Table 3 The 19 sets of characterization factors in the CriticS. Abbreviations: CF: characterization factor; SR: supply risk; EI: economic importance; P: total yearly production of a raw material; R: availability of resources in reserves; MP: market price of a raw material; CRM: critical raw material; USD: US American dollar

	CF detailed	Unit	Type	Reference
CF1	SR_m	(dimensionless)	SR	(European Commission 2020a, b)
CF2	SR_m^3	(dimensionless)	SR	(Mancini et al., 2018)
CF3	SR_m^6	(dimensionless)	SR	(Mancini et al., 2013)
CF4	SR_m/P_m	SR per ton commercialized	SR	(Mancini et al., 2013)
CF5	SR_m/R_m	SR per ton of available reserves	SR	(Mancini et al., 2013)
CF6	SR_m*MP_m	SR*USD/ton	SR	New proposal
CF7	$SR_m/SR_{threshold}$	(dimensionless)	SR	New proposal
CF8	EI_m	(dimensionless)	EI	(European Commission 2020a, b)
CF9	$EI_m/EI_{threshold}$	(dimensionless)	EI	New proposal
CF10	$SR_m * EI_m$	(dimensionless)	Materials criticality	(Tran et al. 2018)
CF11	$(SR_m\text{-}SR_{threshold}) * (EI_m\text{-}EI_{threshold})$ *CF = 0, when non-critical according to EC-CA*	(dimensionless)	Materials criticality	New proposal
CF12	$(SR_m/SR_{threshold})*(EI_m/EI_{threshold})$	(dimensionless)	Materials criticality	New proposal
CF13	$\sqrt{(SR_m^2+EI_m^2)}$	(dimensionless)	Materials criticality	New proposal
CF14	$\sqrt{((SR_m/SR_{max})^2+(EI_m/EI_{max})^2)}$	(dimensionless)	Materials criticality	New proposal
CF15	$\sqrt{((SR_m\text{-}SR_{threshold})^2+(EI_m\text{-}EI_{threshold})^2)}$ *CF = 0, when non-critical according to EC-CA*	(dimensionless)	Materials criticality	New proposal
CF16	"Binary" *CF = 1, when CRM according to EC-CA* *CF = 0, when non-critical according to EC-CA*	(dimensionless)	Materials criticality	New proposal
CF17	"Ternary" *CF = 1, when CRM according to EC-CA* *CF = 0.3, when the threshold for either EI or SR are exceeded* *CF = 0, when no threshold neither for EI nor for SR are exceeded*	(dimensionless)	Materials criticality	New proposal
CF18	"Ternary + Degree of criticality via subtraction of thresholds" like CF17, but CFs for CRMs are computed according to CF15	(dimensionless)	Materials criticality	New proposal
CF19	"Ternary + Degree of criticality via division by maximum value": like CF17, but CFs for CRMs are computed according to CF14	(dimensionless)	Materials criticality	New proposal

3 Results

3.1 Characterization model

3.1.1 Sets of CFs

The developed CriticS method includes 19 sets of CFs, listed in Table 3. They differ in terms of which parameter is used (SR and/or EI, their related thresholds, etc.) and how this is processed, based on the principles presented in Table 1 in Sect. 2.2.1. Note that further sets of CFs could have been developed by combining those principles.

CF1 to CF9 only consider either EI or SR, while CF10 to CF19 constitute materials criticality indicators in line with the EC-CA, presenting a single criticality score considering both SR and EI. Table 3 displays the sets according to their type: (i) SR, (ii) EI, and (iii) materials criticality. They are briefly described below.

CF1 simply uses the SR values from the EC-CA. The proposal of Mancini et al. (2018) to better visualize differences in the SR of materials by using exponentials of third and sixth order are, respectively, the sets CF2 and CF3. CF4 corresponds to the proposal of Mancini et al. (2018) to divide SR_m by the measure of the annual production (P) of the market of material "m" which allows assigning higher criticality to materials with smaller markets. Mancini et al. (2018) also proposed to assign higher criticality to materials with smaller reserves (CF5). In this regard, CF5 takes into account not only the socio-economic aspects of raw materials supply chains, but also issues related to resource depletion. Santillán-Saldivar (2021b) proposed to assign higher criticality to supply risk according to potential price variations, facing a supply disruption (e.g., due to natural disasters) by including price elasticity to the GeoPolRisk endpoint indicator. A similar but different approach is considered here, as the definition of price variation would require additional modeling that is outside the scope of CriticS. In CF6, the SR value of material "m" is multiplied by the market price of "m," assuming that the price of "m" in the year for which SR_m is calculated indicates a higher vulnerability to supply disruption, e.g., in terms of the cost of production of a product. The price values are considered for the year of 2020, in line with the SR values used in the methodology from the EC (2020). The market price values are retrieved from the EC CRM study factsheets (European Commission 2020b, c). The last set of CFs in the group of SR (CF7) considers that the degree of criticality of a material is relative to the SR threshold used in the EC-CA. The magnitude of those indicators is rescaled to criticality values considered "acceptable" according to experts consulted by the EC.

There are only two sets of CFs on the group based solely on EI. Indicators of vulnerability to supply disruption, here represented by EI, are less frequently used (alone) to represent criticality (Schrijvers et al. 2020b). Most often EI indicators are combined with supply risk indicators. Nevertheless, the CriticS method includes two related sets of CFs in order to represent vulnerability to supply disruption, which is, in a general consensus (Dewulf et al. 2016; Schrijvers et al. 2020b), an important criterion for determining criticality. CF8 simply uses the EI values from the EC-CA (in analogy to CF1). CF9, similar to CF7, considers that the degree of criticality of a material is relative to the EI threshold defined in the EC-CA.

The group of sets of CFs that combine SR and EI values starts with the proposal of Tran et al. (2018) that used the multiplication of SR and EI as indicator of criticality (CF10). Similar to Tran et al. (2018), CF11 multiplies SR with EI. There are two differences. First, only CRMs are assigned CFs larger than 0. Second, the values of SR and EI are rescaled by the subtraction of threshold values prior to multiplication. CF12 proposes an alternative to CF11, where all raw materials are considered, but normalized by the threshold values (division prior to multiplication).

CF13 to CF15 calculate criticality as a vector function of SR and EI using the Pythagorean theorem. CF13 considers the absolute values of SR and EI. CF14 normalizes the values by their maximum values such that EI and SR are given the same maximum weight (i.e., 1). The maximum values for SR and EI correspond respectively to 6.1 (for holmium, thulium, lutetium, and ytterbium), and 8.7 (for tungsten). CF15 incorporates the principle of CF14, i.e., only raw materials with values higher than the thresholds (i.e., CRMs) are considered and are thus rescaled.

CF16 to CF19 classify raw materials into different groups according to whether SR, EI, or both are beyond the threshold. The CFs according to CF16 assume only two values: 1 for CRMs, i.e., both SR and EI exceeding the respective thresholds, and 0 for materials that are not critical according to EC-CA. CF17 uses a similar reasoning, considering certain criticality for materials that exceed the threshold of one parameter—either SR or EI. Those materials are assigned a CF of 0.5. CF18 and CF19 are variants of CF17 by allowing CFs equal to as well as larger than 1 for CRMs: the CFs of the CRMs are calculated according to CF15 and CF14 for, respectively, CF18 and CF19.

These different mathematical combinations result in different criticality scores with differing most contributing raw materials. Because of the different principles followed, identifying the most appropriate set of CFs is subjective (e.g., depending on stakeholder preferences). To help in their selection, we propose a decision tree that subdivides the CFs into the three types of indicators (SR, EI, or material criticality indicators) and subsequently organize information in such a way to decide whether it is relevant or not for determining criticality.

3.1.2 Selecting the most appropriate set of CFs: Decision tree

Like in LC(S)A, the goal and scope of a CA needs to be defined. Likewise, the specific aspects of criticality that are of interest to the stakeholder using the results need to be identified. To aid in the process of selecting the most appropriate set of CFs, a decision tree has been created (Fig. 3). According to the definition of criticality in the EC-CA (see Sect. 2.2.1), a stakeholder's view on criticality is the starting point of the decision tree. If in line with EC-CA, both supply risk and vulnerability to supply disruption are considered. By contrast, stakeholders might prefer to analyze criticality only in view of supply risk or vulnerability to supply disruption.

Reasons to choose one set of CFs over the others vary. At the highest level, a stakeholder might prefer a purely economic perspective of criticality, therefore selecting an EI-based set of CFs. In this case, the gross value added of the materials on the EU market, reflecting their market value, would mainly drive the results. Another stakeholder might only be interested in the supply risks, choosing SR-based sets of CFs. If the study aims to consider both perspectives, materials criticality-based sets of CFs should be chosen. Two options exist: choosing a perspective that reflects the market price of the materials and its direct influence on the price of the product under study (i.e., combining SR with material price), or that reflects the value to the economy (i.e., combining EI and SR).

Subsequent questions concern the relevance of additional parameters, depending on the goal and scope. Elements taken from the EC-CA methodology and associated

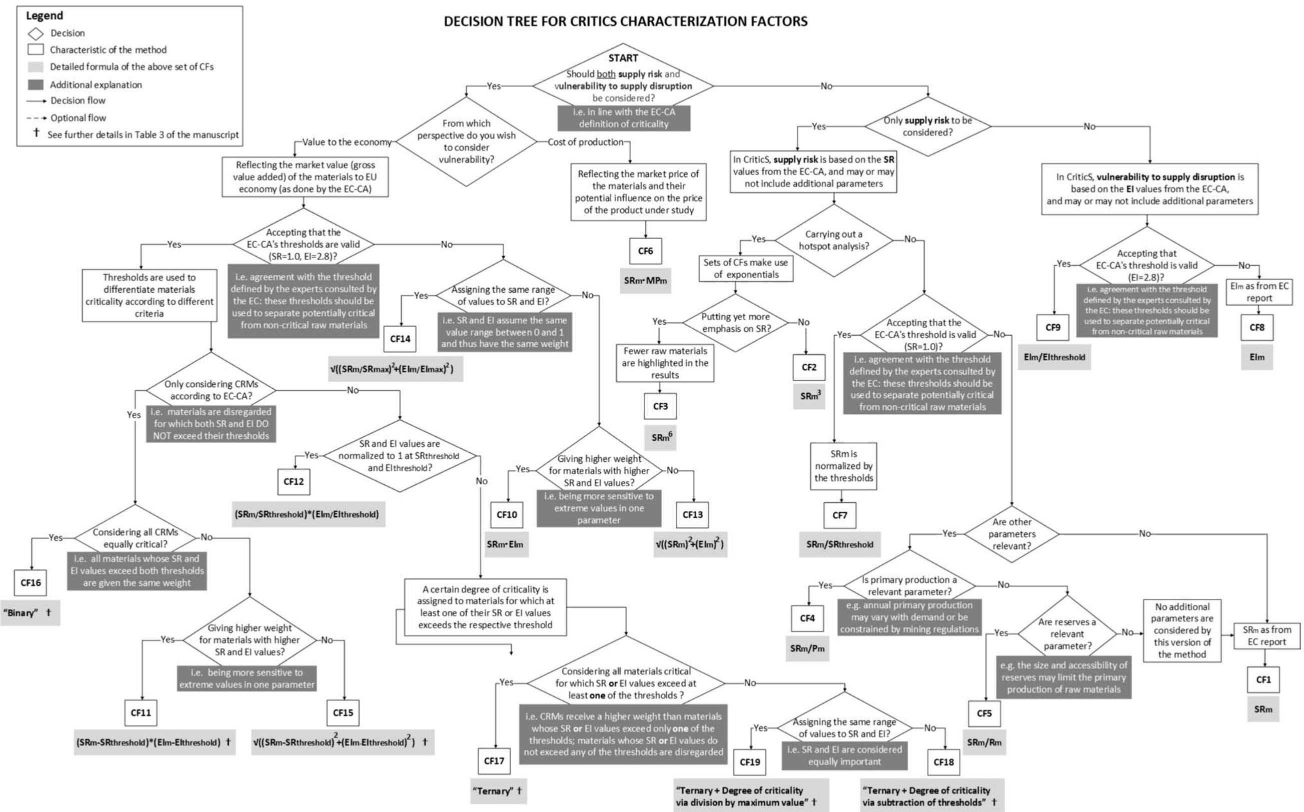

Fig. 3 Decision tree for criticality CFs

data are included as parameters (see Sect. 2.2.1), i.e., the EC thresholds identified by experts and the maximum values for SR and EI. A stakeholder might prefer to consider all the materials regardless of whether or not they are considered CRMs and, thus, prefer to disregard the EC-CA thresholds. The maximum values can be used to normalize the value ranges of SR and EI to between 0 and 1, giving them equal importance. In addition, some potentially relevant parameters are proposed: resource availability, market availability in terms of annual production (see Sect. 3.1.1). Further explanation of the questions and their aim can be found in SI5.

The questions of the decision tree help choosing the set of CFs according to the preferences of the targeted audience. For example, when stakeholders want to assess materials criticality in terms of both SR and EI, and the goal of the study is to identify potential bottlenecks in the supply chain including all raw materials, disregarding the thresholds and/or the maximum values of EI and SR, the decision tree will guide the user to CF13 ($\sqrt{(SR_m{}^2+EI_m{}^2)}$; see Sect. 3.2 for further explanations). It should be noted, however, that this approach focuses on criticality from the perspective of raw material content within the BoM and/or LCI. Bottlenecks specific to the product supply chain related to the disruptions in logistics or external systemic issues (e.g., the temporary disruption of a shipping route), are beyond the scope of a CA.

3.2 Case study

We tested the proposed CriticS model in a laptop case study (explained in Sect. 2.3). Figure 4(**a**) shows the BoM aggregated values, being (**a.1**) the total mass of raw materials in the proof-of-concept laptop, (**a.2**) the portion of raw materials in the BoM that are characterized by the method, i.e., excluding polymers, and (**a.3**) the same raw materials aggregated per laptop component. Figure 4(**b**) shows the criticality results of the BoM using CF13 (see choice reasoning in Sect. 3.1.2), relying on the most recent SR and EI data from 2020, (**b.1**) per raw material and (**b.2**) per laptop component.

The characterized raw materials (i.e., excluding the polymers) in the laptop constitute slightly less than half of the total mass of the product: 0.61 kg out of 1.35 kg. Among these materials, copper, aluminum, and magnesium are the most substantial contributors in terms of mass, followed by iron ore, silicon metal, titanium, industrial and construction minerals (here representing barytes and limestone), and tin. Other materials contribute less than 1% to the total mass of the laptop. Most of these materials are found in the PCB and casing, with a smaller portion present in the LCD.

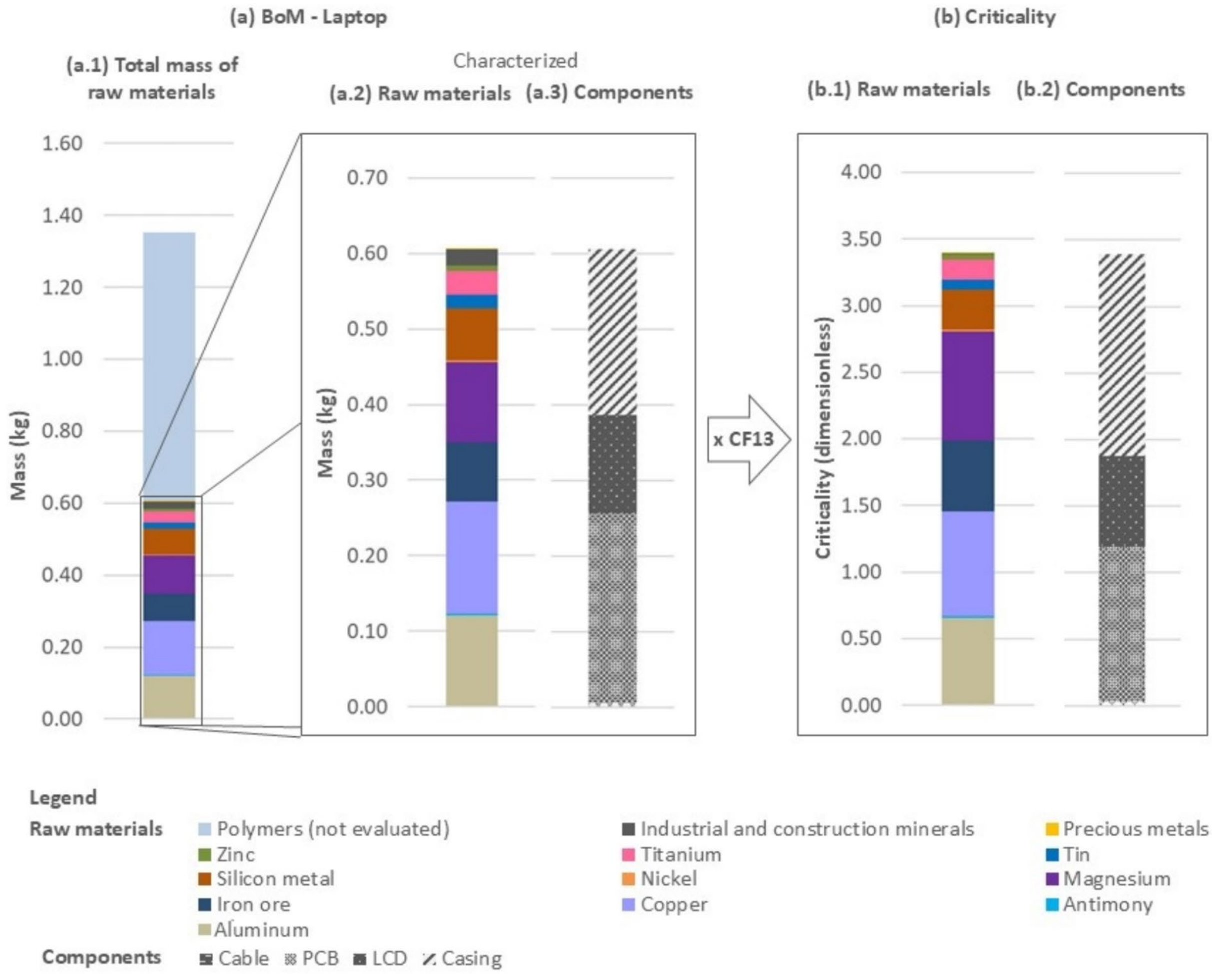

Fig. 4 The BoM of the proof-of-concept laptop (expressed in mass) and materials' criticality using CF13: (**a**) shows the BoM being (**a.1**) the total mass of raw materials in the laptop, (**a.2**) the portion of raw materials that are characterized by the method and (**a.3**) the values aggregated per component. (**b**) shows criticality results (**b.1**) per raw materials and (**b.2**) per component. Abbreviations: BoM: Bill of Materials; LCD: liquid crystal display; PCB: printed circuit boards

In terms of contribution, the criticality results per material shown in Fig. 4(b) do not appear to be very different from the total mass of the same materials shown in Fig. 4(a). Consequently, criticality results using CF13 were mostly sensitive to the mass of each material being present in the BoM. However, some shifts can be observed. For example, while copper contributes most in terms of mass, magnesium has the highest (characterized) criticality value. Within the characterized materials, the highest CFs of CF13 are magnesium (7.67 criticality score) and iron ore (6.82 criticality score). This explains their slightly higher contribution to the total criticality value when compared to their mass contribution and the contribution of other materials. The reverse is also true since the group of industrial and construction minerals shows a lower contribution to the total criticality score of a laptop, with barytes at 3.55 criticality CF13 score and limestone at 3.51 criticality CF13 score. Similar trends are observable in the analysis of components, where the higher content of critical materials such as iron ore, magnesium, and aluminum in the casing is shown in the higher contribution of the casing to total criticality.

Note that in this example the BoM is analyzed in terms of mass and mass contribution. However, it would also be possible to analyze the BoM in terms of, for example, material cost and cost contribution. The aggregation method used to analyze the BoM should be appropriate to the goal and scope of the study.

Furthermore, the effect of choosing eight different sets of CFs (1, 4, 5, 6, 8, 10, 13, and 16) on the criticality results of the laptop case study is explored to showcase the variety of parameters available in the CriticS. Figure 5 presents the materials' contribution to total criticality for (a) the BoM and (b) the LCI cradle-to-gate approach for each selected set of CFs. Raw materials contributing only little/marginally

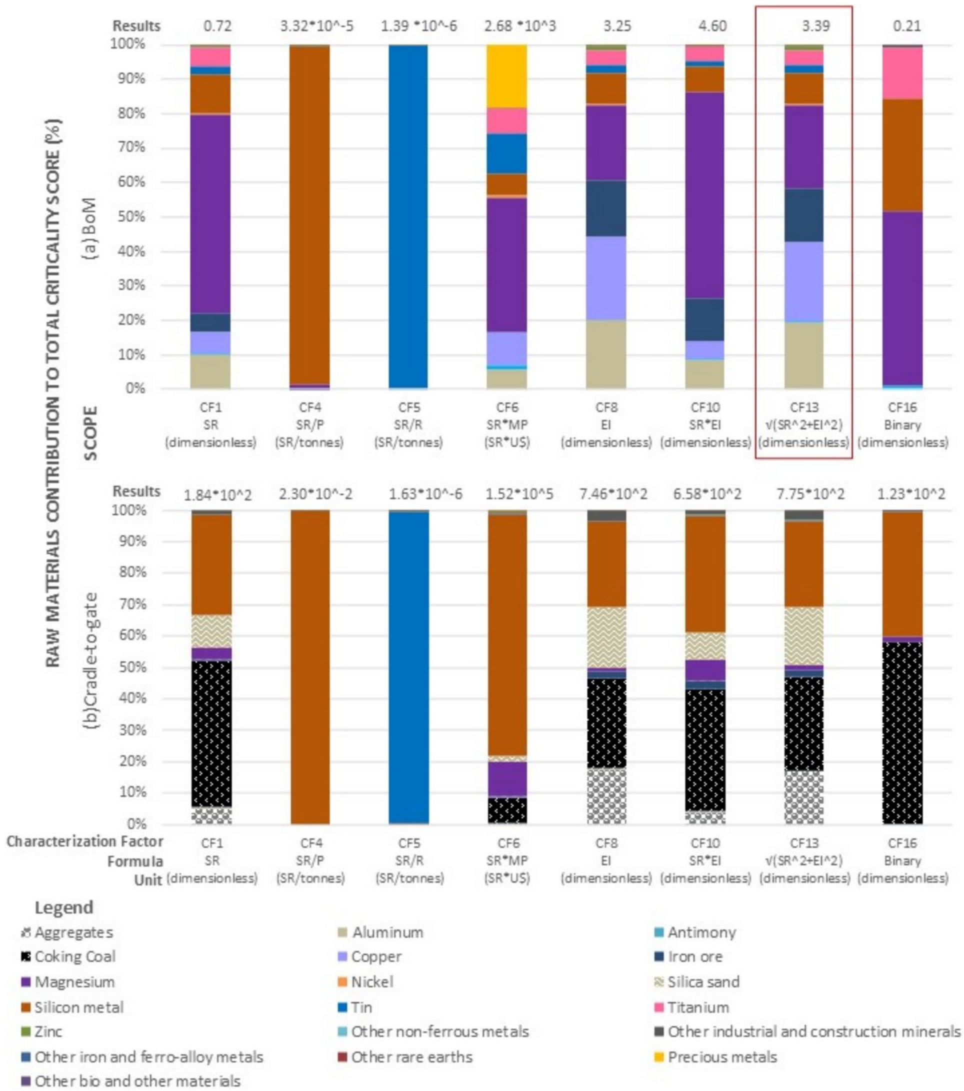

Fig. 5 Sensitivity analysis of results of criticality regarding different sets of CFs: (**5a**) shows the sensitivity of results of criticality for the BoM ; (**5b**) shows the sensitivity of results of criticality in a cradle-to-gate assessment using the LCI, similarly . Them red rectangle highlights the results previously presented and discussed (Figure 4). Abbreviations: BoM: Bill of Materials; CF: characterization factor; SR: supply risk; EI: economic importance; P: total yearly production of a raw material; R: availability of resources in reserves; MP: market price of a raw material; CRM: critical raw material; USD: US American dollar

are aggregated into groups following the classification of the European Commission study (European Commission 2020a), with the full list available in the SI3. Additional findings, including the absolute values of characterized LCI data and further insights into the results of alternative sets of CFs, can be explored in SI6.

For the results based on BoM (Fig. 5(a)), although copper is the most abundant mineral in the laptop (mass-based), it only appears as the most critical material when using CF8 and CF13. The results from both of these sets of CFs are similar even though CF8 only considers EI and CF13 both SR and EI according to the Pythagorean theorem. This is because most of the materials in the BoM are high in EI yet low in SR (see SI6). Similar observations apply to aluminum and iron ore (Fig. 5(a)). As previously discussed, among the characterized materials, these are the highest CFs in the set CF13, contributing to higher criticality alongside magnesium. However, neither copper, aluminum, nor iron ore are critical according to the EC study (2020). On the other hand, all exceed the threshold of EI. That is, CF13 also considers the unweighted values of both SR and EI to calculate criticality scores.

CF4 and CF5 stand out most from the other sets of CFs. Based on market production (CF4), silicon metal is considered to be the most critical material in the laptop. On the other hand, CF5 emphasizes the criticality risk of materials that are present only in small quantities in the LCI (less than 0.01%) but are relatively scarce in terms of reserves. In this case, the accessibility to reserves (CF5) indicates that tin might be the most critical material. The results from CF6 highlight the criticality of materials such as gold and palladium, besides magnesium due to their higher market prices. When only CRMs according to (European Commission 2020a) are characterized (in CF16), silicon metal and titanium also stand out.

Except for CA results based on CF4 and CF5, all other sets of CFs assign a higher value to magnesium. This is because magnesium has relatively high SR and EI values and the laptop contains considerable amounts of it. Magnesium is the third material in the laptop in weight and is present mainly in the casing (20.50% of casing weight).

The results based on the LCI cradle-to-gate approach (Fig. 5(b)) differ substantially from those of the BoM (Fig. 5(a)), except for CF4 and CF5. Out of the 80 characterized materials, the predominant materials in the inventory are coking coal (31%), aggregates (21%), silica sand (21%), and silicon metal (21%). The CA results align with the total mass of materials in the life cycle inventory. However, as highlighted in Sect. 3.1.3, aggregates, silica sand, and silicon metal are characterized by the EFL "gravel, in ground," indicating a potential double-counting in their relatively high contribution to almost all the tested sets of CFs. Nonetheless, considering the annual market production of specific raw materials, CF4 emphasizes the criticality of silicon metal over other materials. Similar trends apply to CF6, where the price of the raw materials is factored into the characterization of criticality, showing the highest criticality score for silicon metal, followed by magnesium and coking coal. The implications of the CA findings from both the BoM and LCI cradle-to-gate level are further discussed in Sect. 4.1.

4 Discussion and perspectives

4.1 The CA results and the limitations of the CriticS

4.1.1 Stakeholders' preferences and the scope of the study

The CriticS results help informing the strategic mitigation of supply risks according to different stakeholders' preferences. In the proof-of-concept study of a laptop, the preference of a stakeholder is chosen who aims to assess materials criticality in terms of both SR and EI, and who goal is to identify potential bottlenecks in the supply chain including all raw materials, irrespective of thresholds. For this stakeholder, the decision tree leads to CF13 ($\sqrt{(SR_m^2 + EI_m^2)}$). The findings from the analysis of the BoM for CF13 (as well as for CF8) show high sensitivity to the total mass of the materials in the product. The sensitivity analysis regarding the use of other sets of CFs show that the classification of criticality can vary significantly based on the preference of the stakeholder. However, this variation reflects the distinct aspects of criticality emphasized by each set of CFs, rather than constituting a direct comparison between them. The results should therefore be interpreted in the context of the choices and assumptions underlying a given set of CFs. In this sense, CriticS provides guidance for the definition of the goal and scope, selecting corresponding indicators and interpretation of the results, as put forward by Schrijvers et al. (2020a).

Regarding the definition of the scope of the assessment, the results show that an analysis at BoM level may overlook potential supply disruptions beyond the end product. In fact, recently, supply disruption has also been reported due to shipping freights, which had increased costs related to lower demand for energy and raw materials and ships unavailability (Khan et al. 2022). Although this specific case was not tackled by the proof-of-concept study, it shows the need for a more holistic approach. In this study, the analysis of the life cycle cradle-to-gate showed that there are components in the infrastructure, or the so-called capital assets, that are also critical for the supply chain of the laptops. Some modeling issues regarding the use of the LCI for CA that are not specific to the model of CriticS are discussed in Sect. 4.2.

It is also important to note that CriticS enables the characterization of about 80 raw materials studied by the EC-CA (European Commission 2020a). However, when deciding to use sets of CFs 11, 13, 15, 16, 17, 18, or 19, the number of raw materials to which a criticality value is assigned is more limited. Sets of CFs 11, 15, and 16 only consider CRMs according to the EU list (2020; see the list of materials in SI2). Sets of CFs 17, 18, and 19 imply that a raw material whose SR or EI values exceed at least one threshold is considered somewhat critical (i.e., less than the raw materials exceeding both thresholds). In fact, the laptop study (see Fig. 5) shows that aluminum, copper, iron ore, aggregates, and silica sand, that appear to be relevant to, e.g., CF 10 and CF13, do not contribute to total criticality in CF16 since these materials are not CRMs. It exemplifies how the preferences of stakeholders affect the CA results.

4.1.2 Issues with the EC-CA

There are inconsistencies and uncertainties related to the EC-CA method used for the CriticS. According to the European Commission (European Commission 2020a, b, pg. 21), "in general, there is good public data availability for global supply" but there is a "general difficulty obtaining public data on the shares of applications of materials, as well as their substitutes." Data for the CriticS method is obtained from reports and factsheets which are not fully transparent about the values used for the calculations. The results are often aggregated, e.g., by group of minerals such as bauxite and aluminum or phosphate rock and phosphorus. In this same example, the factsheets report only the price of phosphate rock (SCREEN 2023), while the price of the phosphorus commodities can be up to three times higher depending on its source (Brownlie et al. 2023). Additionally, as highlighted by Hackenhaar et al. (2022), the CA from EC-CA measures supply risks in the EC-CA framework for raw materials at both the extraction and processing stages (i.e., resources in the technosphere) while CriticS proposes the characterization of elementary flows (i.e., resources in nature). Therefore, the additional values regarding annual production, resource availability in nature and price of materials used in this research to calculate, respectively, CF4, CF5, and CF6 retrieved from the EC-CA studies might be inconsistent due to both the inaccessibility of the values used to calculate SR and EI as well as the discrepancy between, for instance, the resource price at different stages of the supply chain (i.e., in nature, extracted, and processed).

The list of candidate raw materials studied by the EC (2020) also includes materials with different levels of processing requirements, for which the results of the CA are presented together (European Commission 2020a). This was an issue in the example of bauxite and aluminum in the list of 2020. In the list of 2023 (European Commission 2023a), both are analyzed together as they are part of the same supply chain. We argue that the same should be done for silica sand and silicon metal, since the metallurgical-grade silicon is also obtained from the purification of quartz crystals (IEA 2022) (see Sect. 3.1.3).

4.1.3 Updating the CriticS

Although a new list of CRMs has been published in 2023 (European Commission 2023a), not all the factsheets on the candidate materials were available until recently, which is why we have used the publication from 2020 to derive the sets of CFs. However, the SI3 should be sufficient to enable future users of the method to update it if deemed relevant. The number of candidate raw materials has notably increased since the first version of the EU CRM list: from 43 in 2011 to 87 in 2023 (European Commission 2023a). Note that due to their strategic importance for the EU economy and the green transition, the EU CRM list 2023 (European Commission, 2023a) includes two so-called strategic raw materials, although they do not meet the CRM SR threshold: copper and nickel (European Commission, 2023a). Therefore, updating the CriticS method based on the latest list of CRMs would allow the characterization of more raw materials and would include copper and nickel in the calculation of a few sets of CFs where the classification “CRM” is determinant (i.e., CF11 and CF15 to CF19).

Updating the CriticS does not only concern the CFs but also the mapping between the CRMs and the datasets in the database used which can be ecoinvent® or other databases. We have used ecoinvent® database up to v3.8 in our mapping of the elementary flows, while in the meantime there is v3.10. Developments in ecoinvent® versions may resolve some of the inconsistencies mentioned throughout the text. Concerning interoperability, the CriticS model could be adapted using the GLAD network nomenclature repository (UNEP Life Cycle Initiative 2023). The repository contains EFL lists, mapping files and other resources from different databases including IDEA; ILCD-EF; ecoinvent®; FED-EFL. Moreover, the JRC provides a freely accessible tool named the GLAD mapper (Valente A et al. 2022) designed to aid in the creation of mapping files which could streamline the adaptation of the CriticS model.

4.2 CA using LCI: modelling issues beyond CriticS

4.2.1 Consideration of production losses within the scope of the study

Cimprich et al. (2019) also emphasize the importance of production losses. In LCA databases, production losses are usually systematically attributed to multi-output processes. For example, in the laptop case study, the life cycle inventory datasets for silica sand production indicate that 1.04 kg of sand is required for every 1 kg of silica sand produced. This implies at least 4% more raw material extraction than what is listed in the BoM. As highlighted in Sect. 3.2, the results are highly sensitive to the mass contribution of raw materials. That is, BoM analysis does not capture all the raw material extraction required for laptop production. Failure to consider losses or the total materials requirement can lead to a misinterpretation of the overall criticality of a product. That is possible with a life cycle analysis. Additionally, improved allocation for more accurate CA results, as well as for LCA results, could be achieved by tracking each material’s flows in the supply chains of the product system. This is currently not automated in LCA software, which means that additional modeling is necessary which could be facilitated, e.g., by the use of material flow analysis (Dewulf et al. 2015).

4.2.2 Treating capital assets/infrastructure separately

Mancini et al. (2018) identified clay as critical based on the cradle-to-gate assessment of a laptop because of its mass contribution to the total inventoried flows. However, clay is mainly used in the infrastructure datasets. In the discussion of their results, the authors argue that “clay is an abundant resource and evenly distributed in the world, with no concentration of suppliers in a given country” (Mancini et al. 2018). Therefore, Mancini et al. (2018) concluded that our CF4 and CF5 were more appropriate options for assessing resource availability in LCA. However, they disregarded the role of data treatment and modeling choices in the results that we deem more important as explained in the following paragraphs.

Similar to the clay findings of Mancini et al. (2018), gravel-related raw materials are important in our case study. According to our mapping, aggregates, silica sand and silicon metal are mainly modeled by the EFL “gravel, in ground” (see Sect. 3.1.3). The amount of “gravel, in ground” in the LCI is mainly connected to the infrastructure such as the facilities needed for each process. For example, in the LCD, 36.37% of the inventoried gravel is linked to the electronic component factory (infrastructure) while only 0.01% is linked to the production of dipropylene glycol monomethyl ether (intermediate product) which can later be found in the BoM of the laptop. In the casing, 1.37% of the inventoried gravel is related to production of diecast magnesium-alloy from which only 0.34% is linked to the production of ferrosilicon (also called silicon metal) which can also be found in the BoM of the laptop.

CA methods adapted to LCA, such as the CriticS, pose a challenge for both database developers and practitioners. Cimprich et al. (2019) recommended differentiating the life cycle processes between consumable auxiliaries and capital assets. While a software such as SimaPro has the option to "exclude infrastructure processes" for the calculation of results, this is not the case for openLCA. This means that the choice of software can influence how the results should be interpreted due to their limitations. That should be a point of attention to LCA practitioners and stakeholders when aiming at a life cycle approach differentiating criticality hotspots of "consumable auxiliaries" and the "capital assets."

4.3 Comparison to other CA methodologies

Being based on the EC-CA methodology and its available data (European Commission 2017b, 2020a, 2023), the number of characterized raw materials is limited in the CriticS. Besides, this also means that criticality scores are related to the EU economy. For the development of the CriticS, this EU-centric view was preferred. However, other criticality assessment methods aim at integrating aspects of LC(S)A from a broader perspective. They can cover broader scopes and thus present higher flexibility regarding regionalization of the CA, such as GeoPolRisk (Cimprich et al., 2019; Gemechu et al., 2015, 2016; Helbig et al. 2016; Santillán-Saldivar et al. 2021a, b, 2022) and ESSENZ (Bach et al., 2016; Yavor et al. 2021).

In general, the purpose of the CriticS differs from ESSENZ and GeoPolRisk. The difference with ESSENZ is clear: it is a CA method that includes LCIA impact categories as part of the environmental dimension of a sustainability-based CA. Hence, instead of a single score on criticality, ESSENZ is a methodology with 27 impact categories and indicators (Bach et al., 2016). The impact categories included are for example political stability and concentration of production, which are also implicitly included in the CriticS (i.e., they are included in the calculation of SR by the EC-CA). Despite the proven value of the method, it is arguable whether ESSENZ is a fit-for-purpose method to include in LCSAs due to the consideration of other social, environmental, and economic indicators which might overlap with other LCSA indicators (Hackenhaar et al. 2024). For example, ESSENZ includes climate change, eutrophication, acidification, ozone depletion, and smog as relevant environmental impacts related to resource efficiency. It is a suitable method for streamlining LCA impact categories for studies focusing on resource efficiency. However, it is limited for other goals. Socio-economic availability categories representing supply risk could be used as indicators of criticality in LCSA. However, unlike CriticS and GeoPolRisk that use LCI to characterize product criticality, ESSENZ requires the calculation of each of the indicators based on global, regional, or company data (Bach et al., 2016; Yavor et al. 2021). Therefore, additional resources are needed when applying the method.

On the other hand, similar to the CriticS, GeoPolRisk was designed to fit LC(S)A studies as an impact assessment method with CFs. The first comprehensive version of the GeoPolRisk (Gemechu et al., 2015, 2016) covers similar but fewer subparameters for the calculation of supply risk CFs when compared to the CriticS and EC-CA. Later versions of the method include additional subparameters, such as supply chain bottlenecks (Helbig et al. 2016), economic importance and substitutability (Cimprich et al., 2019), recycling (Santillán-Saldivar et al. 2021a, b), and monetization of the GeoPolRisk indicator (Santillán-Saldivar et al. 2022). In this sense, the complexity for creating new CFs for the GeoPolRisk method depends on the version chosen.

Differences between GeoPolRisk and CriticS also include regionalization, since GeoPolRisk considers criticality of raw materials on the global market. In contrast, CriticS potentially considers criticality as a single score based on both EI and SR, and the different sets of CFs of CriticS take into account preferences and perspectives of different stakeholders. GeoPolRisk is a mainly based on SR-related parameters. Besides, the GeoPolRisk and ESSENZ methods currently do not incorporate background inventory flows due to constraints in data availability and/or methodological choices (Cimprich et al. 2019). The CriticS includes guidance on the definition of the scope and the discussion of the results. Section 4.1 shows methodological choices that enable the consideration of the background system. Therefore, the choice regarding the most appropriate methodology for an integrated assessment depends on the goal and scope of the study.

4.4 The integration of CA into LCSA

Although the aim of CriticS is to allow integration into LC(S)A, neither environmental, nor social, nor economic impacts were evaluated in this paper. While the focus of this study was to present and provide insights into the use of the CriticS, its possible integration into an overall LCSA was tested in the ORIENTING project (ORIENTING 2024) and discussed by Hackenhaar et al. (2024). Here, we discuss potential issues and assets of the use of the CriticS in this context.

Synergies in data collection is one of the main advantages of using the CriticS in an integrated assessment. For example, we proposed the use of the BoM and LCI data from LCA. Beyond LCA, relevant information on the geolocation, as well as the geopolitical and social risks inherent to the processes in the supply chain can be sourced from the metadata of the LCSA inventory or from the results of a social risk assessment. However, one should pay attention to methodological constraints as discussed in Sects. 4.1 and 4.2.

It is important to consider the potential synergies and trade-offs of strategies to mitigate criticality in relation to the sustainability impacts identified in the LCSA. As discussed in Sect. 2.2.1, CA examines the extent to which resource availability affects a product system based on multidisciplinary parameters (Sonderegger et al. 2020). Thus, criticality and LCSA results are interlinked and also vary over time (Hackenhaar et al. 2024). Therefore, the EU supply chain information used to model the CriticS CFs may differ from the product system analyzed in the LCSA, which potentially creates inconsistencies. This reinforces the relevance of integrated data collection from an early stage in the assessment (Hackenhaar et al. 2024). Particular attention has been paid to avoid double counting with environmental, social, and/or economic indicators in the development and use of the sets of CFs. For example, the impact category ‘resource depletion’ in LCA when accounting for the available reserve, is also considered in CF5. However, the results of resource depletion potential aim at indicating “how resource use contribute to depletion of reserve” while CF5 aims at indicating “how the size of reserves may affect the availability of resources.” Thus, no double-counting issues should arise from the consideration of this CF alongside resource depletion.

4.5 Perspectives

The above discussion suggests a trade-off between the ease of use of CA as an LCIA indicator and the modeling challenges of using the CriticS. Therefore, future research and tool development should focus on the main issues raised above and summarized here. Firstly, improving the links between characterized flows and CFs by mapping of LCI elementary flows, or, alternatively, characterizing intermediate/product flows to avoid double-counting. Secondly, facilitating data treatment and modeling choices, for example through integrated material flow analysis (MFA) modeling and potentially also within the LCA software. Thirdly, applying the decision tree in a case study with an active involvement of stakeholders in order to test its usability and limitations, as well as to improve it. Finally, testing the CriticS model in an LCSA study, exploring the synergies and trade-offs between criticality and sustainability.

5 Conclusions

While seeking to move towards a more sustainable development, the increasing use of minerals and metals in key economic sectors such as energy and industry exacerbates the challenges of resource accessibility. This interconnectedness of the issues is the reason why an increasing number of studies link raw material criticality and LC(S)A. To meet this demand, we propose a novel fit-for-purpose methodology.

This paper presents the criticality assessment methodology “CriticS” that provides several sets of CFs with different combinations of values for SR and EI taken from the EC study on CRMs (European Commission 2020a) which in some cases are complemented by further parameters. CriticS implementation is supported by a decision tree to guide stakeholders in selecting the most appropriate set of CFs according to their own understanding of criticality and the chosen goal and scope of the study. It is noted that the system boundary of a CA can be different from that of an LC(S)A. Nevertheless, the use of inventories based on either the analysis of the BoM or the life cycle—in a cradle-to-gate approach—has been validated. Furthermore, the CriticS method has been developed to be used with elementary flows from the LCI ecoinvent® database.

Some of the developed sets of CFs were tested in a proof-of-concept case study of a laptop by using its BoM. First, the decision tree was used to select the most appropriate set of CFs. In this specific case study, the chosen set of CFs was CF13 ($\sqrt{(SR_m^2 + EI_m^2)}$). The analysis based on CF13 showed that magnesium—the third most important raw material by mass in the laptop—was the most critical material in the product under the given assumptions. Second, the sensitivity of the CA results was analyzed by testing further sets of CFs. This analysis showed similarities and differences regarding the most critical raw materials depending on the chosen set of CFs. Third, the differences in the CA results were analyzed by changing the scope of the assessment to a cradle-to-gate life cycle approach. The results showed the dominance of raw materials in capital goods (e.g., factories) and support services (e.g., energy production). It also revealed inconsistencies in the model with respect to the links of the CriticS model to the ecoinvent® database, modeling choices, data treatment, and constraints related to the EC-CA methodology.

The results demonstrated the applicability of the methodology in terms of defining the scope of the analysis and the selection and use of a given set of CFs. However, the sensitivity of the results to modeling choices and data treatment is also highlighted. Future research should focus on refining the links between the flows characterized and the CFs, further guiding the operationalization of integrated models through LCA software and testing the application of the methodology alongside LCSA.

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Data availability The authors declare that the data supporting the calculations and findings of this study are available within the article or supporting information.

Declarations

Competing interests The authors declare no competing interests.

References

André H, Ljunggren Söderman M, Nordelöf A (2019) Resource and environmental impacts of using second-hand laptop computers: a case study of commercial reuse. Waste Manage 88:268–279. https://doi.org/10.1016/j.wasman.2019.03.050

Bach V, Berger M, Henßler M, Kirchner M, Leiser S, Mohr L, Rother E, Ruhland K, Schneider L, Tikana L, Volkhausen W, Walachowicz F, Finkbeiner M (2016) Integrated method to assess resource efficiency – ESSENZ. J Clean Prod 137:118–130. https://doi.org/10.1016/j.jclepro.2016.07.077

Bach V, Berger M, Finogenova N, Finkbeiner M (2017) Assessing the availability of terrestrial biotic materials in product systems (BIRD). Sustainability (Switzerland) 9:. https://doi.org/10.3390/su9010137

Berger M, Sonderegger T, Alvarenga R, Bach V, Cimprich A, Dewulf J, Frischknecht R, Guinée J, Helbig C, Huppertz T, Jolliet O, Motoshita M, Northey S, Peña CA, Rugani B, Sahnoune A, Schrijvers D, Schulze R, Sonnemann G, Valero A, Weidema B, Young SB (2020) Mineral resources in life cycle impact assessment: part II – recommendations on application-dependent use of existing methods and on future method development needs. Int J Life Cycle Assess 25(4):798–813. https://doi.org/10.1007/s11367-020-01737-5

Blengini GA, Nuss P, Dewulf J et al (2017) EU methodology for critical raw materials assessment: policy needs and proposed solutions for incremental improvements. Resour Policy 53:12–19. https://doi.org/10.1016/j.resourpol.2017.05.008

Brownlie WJ, Sutton MA, Cordell D, et al (2023) Phosphorus price spikes: a wake-up call for phosphorus resilience. *Frontiers in Sustainable Food Systems*, 7. https://doi.org/10.3389/fsufs.2023.1088776

Carrara S, Bobba S, Blagoeva D et al (2023). Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU a Foresight Study. https://doi.org/10.2760/386650

Cimprich A, Bach V, Helbig C et al (2019) Raw material criticality assessment as a complement to environmental life cycle assessment: examining methods for product-level supply risk assessment. J Ind Ecol 23:1226–1236. https://doi.org/10.1111/jiec.12865

Cimprich A, Young SB, Schrijvers D et al (2023) The role of industrial actors in the circular economy for critical raw materials: a framework with case studies across a range of industries. Miner Econ 36:301–319. https://doi.org/10.1007/s13563-022-00304-8

Deteix L, Salou T, Loiseau E (2024) Implementation of resource supply risk characterisation factors in the life cycle assessment of food products: application to contrasting bread supply chains. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-023-02276-5

Dewulf J, Mancini L, Blengini GA et al (2015) Toward an overall analytical framework for the integrated sustainability assessment of the production and supply of raw materials and primary energy carriers. J Ind Ecol 19:963–977. https://doi.org/10.1111/jiec.12289

Dewulf J, Blengini GA, Pennington D et al (2016) Criticality on the international scene: quo vadis? Resour Policy 50:169–176. https://doi.org/10.1016/j.resourpol.2016.09.008

Dewulf J, Beylot A, Monfort D, Lai F, Santillan-Saldivar J , Muller S, Mathieux F (2024). Contribution to inaccessibility as resource impact method: a base for sustainable resource management along the life cycle. Resources, Conservation and Recycling, 202. https://doi.org/10.1016/j.resconrec.2023.107363

Edelen A, Ingwersen WW, Rodríguez C et al (2018) Critical review of elementary flows in LCA data. Int J Life Cycle Assess 23:1261–1273. https://doi.org/10.1007/s11367-017-1354-3

European Commission (2008) The raw materials initiative — meeting our critical needs for growth and jobs in Europe. COM(2008) 699 final. In: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0699:FIN:en:PDF

European Commission (2011) Tackling the challenges in commodity markets and on raw materials. COM(2011) 25 final. In: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A52011AE1177

European Commission (2014) On the review of the list of critical raw materials for the EU and the implementation of the raw materials initiative. Official Journal of the European Union COM(2014) 297 final. In: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52014DC0297

European Commission (2017a) Methodology for establishing the EU list of critical raw materials. Publications Office of the European Union 1–25. https://doi.org/10.2873/769526
European Commission (2017b) Communication from the Commission to the European Parliament, the Council, the European Economic and social committee and the committee of the regions on the 2017 list of critical raw materials for the EU. Official Journal of the European Union COM(2017):8. In: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2017:0490:FIN
European Commission (2020a) Study on the EU's list of critical raw materials (2020). Non-Critical Raw Materials Factsheets. https://doi.org/10.2873/587825
European Commission (2020b) Study on the Review of the List of Critical Raw Materials - Critical Raw Materials Factsheets. https://doi.org/10.2873/92480
European Commission (2020c) Study on the EU's list of critical raw materials (2020). https://doi.org/10.2873/11619?urlappend=%3Fref%3DPDF&jav=VoR&rel=cite-as
European Commision (2022). Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting. In: http://data.europa.eu/eli/dir/2022/2464/oj
European Commission (2023a) Study on the critical raw materials for the EU 2023 final report. https://doi.org/10.2873/725585
European Commission (2023b) European Critical Raw Materials Act. In: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661
Hackenhaar IC, Alvarenga RAF, Bachmann TM, et al (2022) A critical review of criticality methods for a European life cycle sustainability assessment. In: Procedia CIRP. Elsevier B.V., pp 428–433. https://doi.org/10.1016/j.procir.2022.02.071
Hackenhaar IC, Moraga G, Thomassen G et al (2024) A comprehensive framework covering life cycle sustainability assessment, resource circularity and criticality. Sustain Prod Consum 45:509–524. https://doi.org/10.1016/j.spc.2024.01.018
Helbig C, Gemechu ED, Pillain B et al (2016) Extending the geopolitical supply risk indicator: application of life cycle sustainability assessment to the petrochemical supply chain of polyacrylonitrile-based carbon fibers. J Clean Prod 137:1170–1178. https://doi.org/10.1016/j.jclepro.2016.07.214
Helbig C, Schrijvers D, Hool A (2021) Selecting and prioritizing material resources by criticality assessments. One Earth 4:339–345. https://doi.org/10.1016/j.oneear.2021.02.006
Hool A, Helbig C, Wierink G (2023) Challenges and opportunities of the European Critical Raw Materials Act. Miner Econ. https://doi.org/10.1007/s13563-023-00394-y
IEA, International Energy Agency (2022) Special report on solar PV global supply chains. Retrieved from https://www.iea.org/reports/solar-pv-global-supply-chains
Ioannidou D, Heeren N, Sonnemann G, Habert G (2019) The future in and of criticality assessments. J Ind Ecol 23:751–766. https://doi.org/10.1111/jiec.12834
ISO (2006) ISO 14040:2006 Environmental management — life cycle assessment — principles and framework. ISO - International Organization for Standardization
Khan K, Su CW, Khurshid A, Umar M (2022) The dynamic interaction between COVID-19 and shipping freight rates: a quantile on quantile analysis. European Transport Research Review 14:. https://doi.org/10.1186/s12544-022-00566-x
Mancini L, De CC, Pennington D (2013). Security of Supply and Scarcity of Raw Materials: towards a Methodological Framework for Sustainability Assessment. https://doi.org/10.2788/94926
Mancini L, Benini L, Sala S (2015) Resource footprint of Europe: complementarity of material flow analysis and life cycle assessment for policy support. Environ Sci Policy 54:367–376. https://doi.org/10.1016/j.envsci.2015.07.025
Mancini L, Benini L, Sala S (2018) Characterization of raw materials based on supply risk indicators for Europe. Int J Life Cycle Assess 23:726–738. https://doi.org/10.1007/s11367-016-1137-2
ORIENTING (2021) (D1.4) Critical evaluation of material criticality and product-related circularity approaches. Authors: T. M. Bachmann, I. C. Hackenhaar, R. Horn, M. Charter, F. Gehring, R. Graf, S. Huysveld, R. A. F. Alvarenga, M. Cordella, F. Riva, J. van der Kamp. https://orienting.eu/publications/
ORIENTING (2022) (D2.3) LCSA methodology to be implemented in WP4 demonstrations. Authors: H.Pihkola, M. Cordella, K. Behm, R. Horn, A. Zamagni, L. Zanchi, R. Harmens, T. Sonderegger, E. Cadena Martinez, T. M. Bachmann, J. van der Kamp, M. Bianchi, F. Riva, D. Fehrenbach, G. Moraga, I. C. Hackenhaar, L. Sanchez Moreno, M. Isasa, S. E. Taelman, L. Kujanpää, L. Boone, M. Goedkoop, P. Saling, M. Charter, E. Paronen, J. Dewulf. https://orienting.eu/publications/
ORIENTING (2024) (D4.3) Report on orienting LCSA demonstration results. https://orienting.eu/publications/
Pachhandara N (2022) Impacts of the global chip shortage and how to prepare as the backlog stabilizes. Forbes. In: https://www.forbes.com/councils/forbestechcouncil/2022/05/19/impacts-of-the-global-chip-shortage-and-how-to-prepare-as-the-backlog-stabilizes/
Santillán-Saldivar J, Cimprich A, Shaikh N et al (2021a) How recycling mitigates supply risks of critical raw materials: extension of the geopolitical supply risk methodology applied to information and communication technologies in the European Union. Resour Conserv Recycl 164:105108. https://doi.org/10.1016/j.resconrec.2020.105108
Santillán-Saldivar J, Gaugler T, Helbig C et al (2021b) Design of an endpoint indicator for mineral resource supply risks in life cycle sustainability assessment: the case of Li-ion batteries. J Ind Ecol 25:1051–1062. https://doi.org/10.1111/jiec.13094
Santillán-Saldivar J, Gemechu E, Muller S et al (2022) An improved resource midpoint characterization method for supply risk of resources: integrated assessment of Li-ion batteries. Int J Life Cycle Assess 27:457–468. https://doi.org/10.1007/s11367-022-02027-y
Schneider L, Berger M, Schüler-Hainsch E et al (2014) The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. Int J Life Cycle Assess 19(3):601–610. https://doi.org/10.1007/s11367-013-0666-1
Schrijvers D, Blengini GA, Cimprich A et al (2020a). IRTC-Business Workshop Summary: Identifying Risks in Industry Supply Chains. https://doi.org/10.13140/RG.2.2.10892.33929
Schrijvers D, Hool A, Blengini GA, et al (2020b) A review of methods and data to determine raw material criticality. Resour Conserv Recycl 155. https://doi.org/10.1016/j.resconrec.2019.104617
Schulze R, Guinée J, van Oers L, Alvarenga R, Dewulf J, Drielsma J (2020) Abiotic resource use in life cycle impact assessment—part II – linking perspectives and modelling concepts. Resour Conserv Recycl 155:104595. https://doi.org/10.1016/j.resconrec.2019.104595
SCREEN (2023) Factsheets updates based on the EU factsheets 2020 - phosphate rock and phosphorus. In : https://scrreen.eu/wp-content/uploads/2023/03/SCRREEN2_factsheets_REE-EUROSTAT.pdf
Shah A, McCornick J (2021) CIOs say PC shipments are delayed by months. The Wall Street Journal. In: https://www.wsj.com/articles/cios-say-pc-shipments-are-delayed-by-months-11630445133
Sonderegger T, Pfister S, Hellweg S (2015) Criticality of water: aligning water and mineral resources assessment. Environ Sci Technol 49:12315–12323. https://doi.org/10.1021/acs.est.5b02982

Sonderegger T, Berger M, Alvarenga R et al (2020) Mineral resources in life cycle impact assessment—part I: a critical review of existing methods. Int J Life Cycle Assess 25:784–797. https://doi.org/10.1007/s11367-020-01736-6

Tran HP, Schaubroeck T, Swart P et al (2018) Recycling portable alkaline/ZnC batteries for a circular economy: an assessment of natural resource consumption from a life cycle and criticality perspective. Resour Conserv Recycl 135:265–278. https://doi.org/10.1016/j.resconrec.2017.08.018

UNEP/SETAC (2011) Towards a life cycle sustainability assessment. ISBN: 978–92–807–3175–0

UNEP Life Cycle Initiative (2023) GLAD elementary flow resources. In: https://github.com/UNEP-Economy-Division/GLAD-ElementaryFlowResources

Valente A, Fazio S, Diaconu E (2022) User's instructions of GLAD Mapper. In: https://eplca.jrc.ec.europa.eu/permalink/GLAD_Mapper/GLAD_Instructions.pdf

Van Eygen E, De Meester S, Tran HP, Dewulf J (2016) Resource savings by urban mining: the case of desktop and laptop computers in Belgium. Resour Conserv Recycl 107:53–64. https://doi.org/10.1016/j.resconrec.2015.10.032

Yavor K M, Bach V, Finkbeiner M (2021) Adapting the ESSENZ method to assess company-specific criticality aspects. Resources, 10(6). https://doi.org/10.3390/resources10060056

Zampori L, Pant R (2019) Suggestions for updating the product environmental footprint (PEF) method. https://doi.org/10.2760/424613 . In: https://publications.jrc.ec.europa.eu/repository/handle/JRC115959