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A critical review of criticality methods for a European Life Cycle Sustainability Assessment

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Abstract

The beginning of the 21st century is marked by the fourth industrial revolution, which could be a great opportunity for a sustainable technological transformation. The key role of these technologies in the development of a more sustainable future implies the need for the evaluation and monitoring of both supply risks as well as environmental and social impacts of a number of raw materials in the supply chain. These raw materials that are important to the economy and might be under supply risk are referred to as Critical Raw Materials (CRMs) in the EU. The integration of Life Cycle Sustainability Assessment (LCSA) - well established for sustainability evaluation - and Criticality Assessment (CA) – increasingly used as governance tool - is therefore consequent to support decision-making regarding efficient use those natural resources.

Based on a critical review of CA methods within and outside the framework of an LCSA, this research aimed to investigate the compatibility of CA methods with the life-cycle approach. The methods range from specific CA methodologies (e.g., NRC (USA) and EC-CA (EU)) to the existing methods integrating CA and LCSA (e.g., ESSENZ and GeoPolRisk). The evaluation of the methods was based on a set of criteria (e.g., acceptance and credibility) and further analysis of compatibility with frameworks from ISO 14040-44 and UNEP-SETAC. The current challenges for integration in the field are identified, namely: interpretation of criticality within the three pillars of sustainability (social, economic or environmental); the incompatibility among inventories and the characterization of material's criticality; arbitrariness in the interpretation of what is "critical"; and the uncertainty intrinsic to CA models. Potential solutions towards the operationalization of criticality indicators in a product-oriented LCSA include the definition of the impact pathway of criticality in LCSA, the linkage of criticality indicators to product/technological flows, the use of intermediate indicators (supply risk and economic importance), the characterization of criticality at the normalization and weighting step, and addressing uncertainties in an LCSA. Further works of this research will explore the solutions proposed.

Keywords: Criticality assessment; raw materials; Life Cycle Sustainability Assessment; supply risk.

1. Introduction

Since the beginning of the 21st century, economies with high dependency on materials import (e.g. EU) have identified a potential risk of supply disruption of those raw materials that are important to sustain contemporary lifestyles and the prosperity of national and regional sectors, while transitioning towards sustainable development goals. These materials are referred to as Critical Raw Materials (CRMs) in the EU, but

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other names are also used (since "critical" is a context-dependent concept [1]).

A few examples of markets where CRMs are crucial include e-mobility, batteries, renewable energies, pharmaceuticals, aerospace, defense and digital applications [2]. The key role of these technologies in the development towards a more sustainable future implies the need for the evaluation and monitoring of both supply risks as well as environmental and social impacts of CRMs supply chain [3]. Hence, the continued development of analytical tools and Criticality Assessment (CA) methods to address these risks and impacts is also needed [4].

Criticality can be characterized from the perspective of trading relationships of a company [5] or country or region [6], or based on global availability [7, 8]. CA can also cover different time horizons, from the short (e.g. a few years) to the long term (a few decades) [6]. Besides, the existing methods and reports cover different dimensions (e.g. vulnerability and probability of supply disruption), consider different aspects (e.g. geopolitical, economic, social, environmental) and use different indicators (e.g. a country's concentration of mines and manufacturing) [9]. In the European policy context, the identification of CRMs is part of the strategies from the EU Raw Materials Initiative [10] to tackle the issue of sufficient access to raw materials. Relying on the criteria of economic importance and supply risk [11], 4 lists have been issued since 2011 that show an increasing number of CRMs for the EU: 14, 20, 27, and 30 CRMs, respectively [7, 12- 14].

Regarding other sustainability aspects of raw materials supply, an evaluation of CRMs could be part of the further development of the product environmental footprint (PEF) into a product sustainability footprint. In PEF [15], life cycle assessment (LCA) is used to support decision-making regarding the impact of products on the environment. A number of recent LCA studies evaluating the impacts of the raw material sector demonstrate the growing need of considering socio-economic and geopolitical aspects [16 – 22], including how they affect resource accessibility. Since it is beyond the scope of (environmental) LCA, integrating CA into Life Cycle Sustainability Assessment (LCSA) is the way forward [2].

In this research, a review of existing CA methods inside and outside the scope of LCSA was conducted (section 2.1). Relevant methods that can potentially be integrated into a European Life Cycle Sustainability Assessment (considering needs of adaptation) are evaluated (sections 2 and 3). The main objective of the research is to present recommendations for methodological developments for this integration, as part of the ORIENTING[1] project.

2. Methods and Materials

The research was based on a literature review to identify the currently used CA methods within and outside the scope of LCSA with a subsequent criteria-based evaluation of selected methods. This section presents the literature review procedure and the criteria used in the evaluation.

The ORIENTING project being funded by the European Commission, we adopt its definition of CRMs: "CRM are raw materials of high importance to the economy of the EU and whose supply is associated with high risk" [11]. Thus, the two main parameters to determine criticality are economic importance (EI) and supply risk (SR). Besides, the term "natural resources" in LCA encompasses land and sea area, energy sources, water, air, natural biomass (i.e., flora and fauna), minerals, fossil fuels, metallic ores, and nuclear ores [23]. Here, we address criticality of minerals, metals and other ores, as well as fossil fuels and natural biomass, such as on the EU CRMs list.

2.1. Literature review

The literature was identified through Web of science (WoS) and Google scholar (for literature related and unrelated to LC(S)A[2]) as well as Scopus (for literature related to LC(S)A). The following combination of strings were used for the research: "method" or "methodolog*" or "indicator*" or "characterization factor*"; and ("criticality" and "material*") or "critical raw material*" or "supply risk"; and (for the LC(S)A-related method) "LCA" or "Life cycle assessment" or "Life cycle analysis" or "LCSA" or "Life cycle sustainability assessment" or "LCIA" or "Life cycle impact assessment". All references published since 2006 were considered at first.

The search of Criticality-LCSA-related literature (done by mid-April 2021) on Scopus and WoS returned a list of, respectively, 65 and 68 journal articles and reviews. Among those, 44 results were duplicates. By analyzing abstract, introduction and conclusions, the literature prioritized included- conceptually or methodologically- supply risk (and economic importance [3]) indicators and LC(S)A methods/approaches, while both are analyzed and discussed in the results. Only review papers and papers presenting methodological proposals and/or advances were further considered. From this screening, 25 documents were selected for further analysis. To this list, four documents frequently cited [8, 20, 21, 24] and complementary to the conceptualization of the topic were added.

Where there was no immediate link to LC(S)A, the search performed by mid-March 2021 yielded 33 journal articles, reviews and reports. Three other publications could be identified from the review by Schrijvers et al. [9]. So, 36 documents were considered further.

To select the methods to be analyzed, the 65 documents were subjected to further criteria. Eleven review articles were excluded because they did not present specific methods that could be analyzed. Only those methods that have been used (e.g. [25]) or updated since 2015 were included. A total of

[1] Horizon 2020 Project, entitled "Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy" (GA number: 9582311). Website: https://orienting.eu/

[2] When referring to both LCA or LCSA, they are referred to here as LC(S)A.

[3] Economic importance only rarely appears explicitly within the LC(S)A+CA literature. Therefore, this was not used as an exclusion criterion.

seven methods were selected for evaluation. The methods are presented in section 3.

2.2. Set of criteria

The selected methods were evaluated according to a set of criteria based on the RACER methodology (Robust, Accepted, Credible, Easy and Relevant) [26], amended based on further frameworks (e.g. [28 – 33], among others). The set of criteria encompasses: *1. Stakeholder acceptance and credibility, 2. Applicability and complexity of methods/tools, 3. Transparency, 4. Scientific robustness, 5. Completeness and 6. Compatibility with life cycle approach*. Each of these headline criteria normally consisted of several sub-criteria.

Within the ORIENTING project, there was one default set of criteria and sub-criteria (followed by its description) for all method/approach evaluations with some topic-specific modifications (see footnote [1] for further information). During the evaluation, each sub-criterion was given a score between A and E, with "A" as the best possible/realistic answer and "E" as the worst one. A description of the meaning of the scores per sub-criterion was provided. The option of not applicable ("N/A") was also possible, which also includes "no sufficient evidence". The simple (unweighted) averaging of the sub-criteria scores results in the (aggregated) score for each criterion. Likewise, the method's overall score is obtained from the criteria scores. Certain aspects of the methods that help identify weaknesses and strengths and allow categorization of methods could not be consistently defined in the quantitative scale proposed (e.g., representation of indicators in a qualitative or semi-quantitative way). These were nevertheless considered, interpreted and discussed. A full description of the criteria is available in ORIENTING's deliverable, i.e. Bachmann et al. [33].

3. Criticality Assessment methods: description and evaluation

3.1. Description of the methods

The following criticality methods were selected:

- **National Research Council (NRC) methodology**: the NRC framework is based on a matrix of the raw materials' supply risk and impacts of supply restrictions. The supply risk is determined by different aspects of the availability of primary as well as secondary resources, regarding short or long term. The placement of raw materials in the matrix defines the degree of criticality [7];
- **European Commission's Criticality Assessment (EC-CA) methodology**: developed to assess the criticality of minerals, metals and other ores, fossil fuels and natural biomass for the EU, the EC-CA classifies raw materials according to thresholds for two indicators, i.e. supply risk and economic importance. The EC-CA is updated and used for the generation of CRMs list every three years. Results are compared to previous lists to analyze the key trends and identify potential risks. Besides, it is focused on the short term availability of CRMs [6, 11];
- **Yale methodology**: developed by Graedel et al. [25] to determine the criticality of metals (also adapted to identify the criticality of water or construction aggregates by [36, 37]). It is based on supply risk, environmental implications and vulnerability to supply restrictions. The method provides quantitative time-dependent results in form of a single score indicator (normalized and aggregated), also displayed in a 3-dimensional space graph. It addresses corporate, national and/or global levels, medium and long-term analysis [25];
- **British Geological Survey (BGS) methodology**: the methodology estimates the relative risk of supply of chemical elements, based on seven criteria (each scored 1 to 3). A supply risk index is obtained by adding all criteria score values and normalizing the results. This provides a rank of 41 elements (or group of elements) considered of economic value by the BGS. It is intended to provide short-term supply risk indicators [36];
- **Japan's Resource Strategy (NEDO)**: it evaluates strategic minerals according to supply risk, price risk, demand risk, recycling restriction and potential usage restriction utilizing 12 indicators. Each indicator is scored from 0 to 3 points. Risk categories are weighted unequally such that the maximum total sum amounts to 32 points. Minerals with 18 points or higher are classified as "strategic". Both short- and long-term scores can be provided [37].
- **ESSENZ**: the method quantifies 19 resource efficiency indicators, from which eleven concern geopolitical and socioeconomic accessibility constraints (e.g., the country concentration of reserves and mine production, political stability, among others). After quantification, indicators are divided by a target value above which accessibility constraints are assumed to occur. This distance-to-target (DtT) ratio is normalized by the global production of the respective resource. Finally, the normalized DtT factors are scaled to a range based on the largest production volume considered. The method provides information about the medium- and long-term availability of resources and is suitable for decision-making at a product system's level (from a life cycle perspective) [8];
- **GeoPolRisk**: first proposed by Gemechu et al. [38], the method produces an import-based indicator for the geopolitical supply risk of resources in LCSA. The supply risk of raw materials is primarily determined by the perspective of the resource-demanding country, considering the import share of the demanding country from the supplying country, the global share of a supplying country in the production of a certain commodity and the geopolitical stability of that country. An extension of the method includes a more comprehensive analysis of the supply chain (i.e. including multiple stages of raw materials production), and the consideration of vulnerability to supply restriction (i.e. economic importance, substitutability and recyclability measurements). It aims to provide information at a product system's level [5, 41, 42].

3.2. Criteria-based evaluation

The methods were evaluated according to their characteristics, documentation and data available. Table 1 shows the results of the evaluation for the six criteria presented in section 2. A full description of the evaluation of criteria and sub-criteria is available in ORIENTING's deliverable [33].

Almost all analyzed methods for the assessment of criticality were relatively high scored, i.e., between A and B, except for NRC scoring C+ due specifically to a lack of transparency and robustness of methodological assumptions and data (based on the documentation retrieved in the literature review). The highest score (A) has resulted for EC-CA and GeoPolRisk, mainly due to transparency, completeness and easiness of applicability. Considering the purpose of the integration of criticality into LCSA, three key features are highlighted here: operationality (addressed by criteria 2 and 6), as well as alignment with the European Commission's criticality initiative (addressed within criterion 1). For operationality in terms of applicability, EC-CA, GeoPolRisk and the Japanese NEDO assessment rank highest (A+). The two methods developed in an LCSA context, i.e., GeoPolRisk and ESSENZ, score highest (B+) for compatibility with the life cycle approach (including aspects of operationality). When it comes to acceptance by (EU) policymakers, only EC-CA is assigned the highest score (A). Except for GeoPolRisk, all methods overlap at least with one sustainability pillar (issue of potential double-counting). Also, in terms of scientific robustness, the most promising methods are GeoPolRisk (A), closely followed by ESSENZ and Yale method (A-). Regarding this criterion, the EC-CA scored B+ due to the subjectivity of both thresholds and methodological choices.

The evaluation has two main limitations: 1) the arbitrariness of the mathematical procedure for arriving at one overall evaluation score (simple unweighted average), and 2) the arbitrariness intrinsic to the evaluators' interpretation of the criteria. Despite that, the results indicate that EC-CA and/or GeoPolRisk are the two most relevant approaches in terms of development and context of usage. They will be further investigated with the aim to integrate raw materials' criticality into a European LCSA framework.

4. Criticality assessment and the LCSA framework

There is no scientific consensus on best practice how to evaluate criticality neither in general nor from a product life cycle perspective [9]. There is, however, a general agreement that material criticality is not part of environmental LCA. The authors that have attempted to draft the relationship of criticality parameters to the LCSA domains conclude that CA can have elements connectable to all three, i.e. environmental (e.g. mineral and metal resource depletion and impacts on ecosystems quality), economic (e.g. economic importance due to percent of revenue impacted and cost increases) and social (e.g. geopolitical issues such as corruption and political stability, and labor conditions such as fair salary and health and safety). In this sense, according to some researchers, CA could be part of a more encompassing LCSA [20, 25, 41, 40, 43]. However, it is also important to highlight that the LCA methodological steps have given rise to divergent arguments in the literature. For Sonnemann et al. [18], the LCA-related elements in different CA methods are the depletion indicators and the inventory itself. Following the same reasoning, Mancini et al. [1] argue that criticality aspects could be better introduced as (environmental) LCA due to the use of biophysical elementary flows in the LCI, despite the socio-economic aspects. These are rather technical arguments regarding LCA practices. They are relevant to the operationalization of criticality indicators in LCSA, but should not restrict the understanding of what these indicators aim to convey.

At the bottom line, the main question is: What does one seek to evaluate in terms of criticality in general and in the context of an LCSA specifically? In this research, only supply risk methods have been included in the evaluation. Sonderegger et al. [20] argue that, for the time being, supply risks have only been assessed at the midpoint level. When assessed at the endpoint level, they suggest evaluating "impaired product functions" and "additional costs of production". This points to economic implications, suggesting to assess criticality as part of the economic sustainability pillar.

If criticality was to be evaluated as part of the economic pillar, another implication would be that the formula LCSA = environmental LCA + social LCA + LCC [44, 45] would no longer hold, given that criticality would not be expressed as costs (alone). Bachmann [44] already pointed at this shortcoming: the different building blocks of this equation do not exactly match the three pillars of sustainability. As an alternative, Bachmann [44] suggested distinguishing at endpoint impact (or Area of Protection) level[4] (modified):

Table 1. Overview on the scoring of the different material criticality

#	Criterion	NRC	EC-CA	Yale	UK GS	NEDO	ESSENZ	GeoPolRisk
	Source	[7]	[6], [11]	[27],[35],[36]	[36]	[37]	[8]	[38]–[40]
	Overall Score	**C+**	**A**	**A-**	**B**	**B+**	**B+**	**A**
1	Stakeholder acceptance, credibility and suitability	B-	A+	A	B	B	B	B
2	Applicability / Complexity	C+	A+	B	A	A+	B+	A+
3	Transparency	C	A+	A	B	B+	B+	A
4	Scientific robustness	C	B+	A-	C+	B	A-	A
5	Completeness	B	A+	A	A	A	B-	A+
6	Compatibility with life-cycle approach	C+	C+	C+	C+	C+	B+	B+

[4] noting that a distinction at inventory level is also possible, as e.g. suggested by Mancini et al. [1] and largely, but somewhat inconsistently applied by current environmental LCAs

"ecosystem (nature)-related LCA" + "economic LCA" + "social LCA" (including human health impacts). How criticality fits into this framework needs further reflection.

Beyond these conceptual questions, other practical issues of the integration of CA to LCSA were identified. First, as stated in Cimprich et al. [41], LCIA methods provide characterization factors (CF) that are applied (only) to elementary flows as contained in the life cycle inventory. According to ISO 14040 [45], "elementary flows" are the flows that cross the boundary between the product system and the environment. They may relate to the use of resources (e.g. ores) or to releases (e.g. CO_2 equivalent emissions). Regarding criticality, only the aspect "use of resources" is relevant. In contrast to resource use impact assessments in LCA, criticality methods usually consider socio-economic aspects e.g. geopolitical situations [28], which are driven by society. Therefore, criticality's CFs are a function of the entire value chain of a raw material, from extraction and processing to assembling. This means that criticality might characterize the supply risk of relevant flows other than the elementary flows, such as the supply risk differentiation in the EC-CA of raw materials at the extraction stage and processing stage [6]. Besides, the composition of resources in an ore is different to the raw materials after processing [46]. Rather, CFs for criticality methods would need to be applied (also) to intermediate flows [41]. Therefore, an obstacle to the implementation of criticality assessments in an LC(S)A framework is that intermediate flows, notably in the background system, cannot be used as elementary flows, i.e., for the multiplication with the characterization factors because the pathway is not adequately reflected in the elementary flows.

The second potential issue regarding the use of existing CA methods to be integrated into LCSA is the use of thresholds. CAs classify a raw material as "critical" either when the indicator exceeds a threshold [11, 39] or relating the indicators to targets elicited in surveys [26, 34, 38, 39]. The "criticality area" (or range) represents an element of arbitrariness [1], either based on the opinion of experts or the comparison among materials analyzed. That can be a source of uncertainty to the CA given that "critical" becomes a relative concept subjected to the questions: to whom?; where?; and when? [47]. In addition, ISO 14040 requires to preferably base decisions within an LCA on natural science as one of the main principles [45]. ISO 14044 further recommends minimizing value-choices in characterization models [48]. In this sense, methods just as the EC-CA that involve the use of subjective elements (thresholds, targets and/or weights) need adaptation. As already proposed by Mancini et al. [1] and Tran et al. [49], the creation of CFs from results of CA indicators before applying thresholds, such as to the SR and EI from EC-CA [6], could be a potential solution. The use of thresholds as normalization or weighting factors for the interpretation of results was not yet explored but could also represent a solution (e.g. computing the two indicators that the EC-CA relies upon without thresholds by default and then allowing the use of thresholds/weighting factors as an optional element). CAs not (fully) belonging to the environmental domain, another question is whether the priority of the (natural) scientific approach of ISO 14040 actually applies.

The third practical issue concerns uncertainties in the CAs. In the EC-CA reports, data availability is explicitly addressed as an issue. According to European Commission [6], there is good coverage of publicly available data on global supply chains. However, there is a general lack of publicly available data on the market shares of raw materials and their substitutes. Generally, the lack of real-world data is filled by estimated values, which creates uncertainty. For example, some recycling rates (RR) to build the EU list of CRM are based on data from industry (e.g. aluminium RR are based on data from the European Aluminum association), while others rely on estimates (e.g. antimony RR are based on UNEP and Deloitte estimates) [6]. In the perspective of the integration of a criticality indicator into an operational LCSA framework, the uncertainty linked to the modelling data for the characterization of material criticality should be properly addressed. In this sense, the use of existing criticality indicators, e.g. SR and EI from the EC-CA, must address the consistency between the modelling data and inventory data.

5. Conclusion

A technological-driven, more sustainable and circular future implies the continued evaluation and monitoring of supply risks, environmental impacts and social implications of raw materials consumption. The integration of LCSA and CA approaches is therefore consequent to support decision-making regarding resource use. This research presented a literature review of the existing CA methods within and outside the field of LC(S)A. Relevant methods were evaluated against a comprehensive set of criteria.

The results show that EC-CA and GeoPolRisk are the most promising methods to be integrated into a European LCSA. Using these methods as a basis for the development of ORIENTING's LCSA framework is suggested, considering also the methodological development needs presented in section 4. This includes the definition of the impact pathway of criticality in LCSA, the proposed linkage of criticality indicators to product/technological flows in the LCI, the use of CF for intermediate indicators (SR and EI), the characterization of criticality at the normalization and weighting step, and addressing uncertainties due to LCIA modelling data.

Due to the diversity of CA approaches and interpretation of what "critical" means, there is an ongoing discussion about criticality methods relationship/harmonization by the International Round Table on Materials Criticality (IRTC) [9]. It is expected to provide clearer guidance on the common ground of criticality assessment. Beyond the guidelines from EC-CA, the IRTC's recommendation will be considered in the development of ORIENTING's LCSA framework, integrating CA.

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