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Criticality on the international scene: Quo vadis?

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ABSTRACT

This paper brings a discussion on the current state-of-the-art in criticality assessment in an international context. It analyzes the status of resource criticality concepts and their calculation methods. The current practice often exhibits a common two-axis assessment framework but the way the two axes are further operationalized shows heterogeneous approaches. Apart from the two-axis as key element of criticality assessment, the scope of the materials, the role of substitution, the delineation of the supply chain and data, and indicator selection are addressed as key elements. The abovementioned criticality assessment practice is approached in function of the upcoming international debate on criticality. The paper tackles the role of criticality assessment in the context of the sustainability assessment toolbox and it proposes a clear distinction between criticality assessment and resilience to criticality. The insights offered in the paper may feed the international discussion in the identification of elements that may be harmonized and elements that may be better left open in function of the particular application.

1. Introduction

The criticality concept for raw materials has seen a growing interest in the last decade, with the majority of studies carried out in Europe and the United States (Erdmann and Graedel, 2011; Buijs et al., 2012; Sonnemann et al., 2015; Graedel and Reck, 2016). Much of the work deals with metals and metalloids. However, non-food and non-energy bio-based raw materials have also been included, e.g., by the assessments of the European Commission (EC, 2010, 2014) and recently even water (Sonderegger et al., 2015). Criticality as concept for raw materials has been interpreted differently. Erdmann and Graedel (2011) state that “raw material criticality seeks to capture both the supply risks on the one hand and the vulnerability of a system to a potential supply disruption on the other”. Looking across the different approaches, the largest divergence seems in the definition of the economic system (both geographically and user-specifically) for which a stable and secure supply of raw materials is to be assured. Here, the economic systems to protect ranges from a single corporation (Duclos et al., 2010), to a sector or a few selected technologies of strategic importance (sector-specific criticality assessment) (Moss et al., 2013a , 2013b; USDOE, 2010, 2011), to entire national/regional economies (economy-wide criticality assessment) (EC, 2010, 2014; NRC, 2008; Graedel et al., 2015; BGS, 2012; Achzet et al., 2011; Coulomb et al., 2015; NSTC, 2016; Skirrow et al., 2013), and the world (global criticality assessment) (Graedel et al., 2015). Furthermore, the number of materials covered in criticality assessments ranges in scope from a single element (Rosenau-Tornow et al., 2009), to less than 5 metals belonging to the same geological family (Nassar et al., 2012; 2015a, , 2015) or used in similar end-use applications (Nuss et al., 2014; Harper et al., 2015b), to more than sixty raw materials, embracing and tying to encompass a large and diverse number of non-fuel, non-food mineral and biotic raw materials (EC, 2010, 2014). While the materials of interest are determined by the goal and scope of the assessment, we note that a desirable aspect of criticality determinations includes the applicability of the methodology to a wide range of materials (Graedel and Reck, 2016).

Criticality assessments have been around for a while, e.g. the term “critical and strategic material” has been in use in the US since 1939 as part of the original stockpile legislation and further reported in the 1950–1980s (Charles River Associates, 1982; Committee on the Technical Aspects of Critical and Strategic Materials, 1977; Paley et al., 1952). But the current approaches of criticality assessment in the last decade and the growing international attention lack an international forum that specifically intends to converge the criticality

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praxis, as is taking place for other assessment tools, e.g. Life Cycle Assessment (LCA) with activities by UNEP (United Nations Environmental Program), SETAC (Society of Environmental Toxicology and Chemistry), and ISO (International Organization for Standardization). The goal of this paper is to provide some perspective on the current state of practice in order to determine where there is convergence and divergence in criticality assessment methods. This paper may in the long-run serve as input to the international scene to discuss if international convergence to a uniform methodology is feasible and, if so, to identify which aspects may be harmonized and which may better be left open in function of the particular application.

In the next section convergence and divergence on the various aspects of the generally practiced two-axis approach are discussed. Subsequently, both axes (i.e. risk or likelihood of supply disruption and economic importance or vulnerability to disruptions) are discussed where there are clearly different practices in elaboration and quantification. In the subsequent section, some particular attributes (e.g. scope of materials covered, the role of substitution and recycling, the modeling of the supply chain, and indicators and data) are discussed. Finally, some considerations on future directions in the international context are presented. The positioning of criticality assessment in the sustainability assessment toolbox is also discussed. Equally the paper addresses the distinction between criticality calculations of raw materials for a certain entity and the way the entity is able to respond to this criticality, i.e., its resilience.

2. The criticality concept and the predominant two-axis approach

2.1. More convergence than divergence: a concept with two axes

A review of recent international approaches reveals a general consensus that criticality is comprised of two main dimensions (Fig. 1): supply risk, graphically represented on a horizontal axis, and the impact of or vulnerability/exposure to that supply risk, graphically represented on the vertical axis. While there is general consensus on the intentions of the supply risk dimension, there are notable differences in its underlying components and computation among the various approaches. In contrast, there is little consensus regarding the vertical axis aside from the overall theme of attempting to quantify the impact or vulnerability that may arise from the supply risk. Indeed, the variations in the vertical axis highlight the general differences in intentions and the targeted beneficiaries or scope of the various approaches. Some studies, like those of the European Commission (EC, 2010, 2014), examine the potential economic impact on a region (i.e., the European Union) or the vulnerability of a specific country (NRC, 2008; Graedel et al., 2015; BGS, 2012). Others examine the impact of specific sectors (Moss et al., 2013; USDOE, 2010, 2011) or a specific company (Duclos et al., 2010). In general, however, the different interpretations typically tend to quantify the potential impact that supply disruption may have on the system under study. Glöser et al. (2015) bring the two approaches mathematically together based on the reasoning that raw material criticality equals the product of supply risk and vulnerability, but at the same time also that it is the result of the multiplication of likelihood of supply disruptions and economic consequences. Roelich et al. (2014) take a similar, albeit more dynamic approach, by suggesting that material criticality is the product of supply disruption potential and exposure to disruption.

2.2. Convergence and divergence: the two axes approach as a basis for quantifying criticality

The two dimensions are typically kept separate, a reflection of the idea that the two dimensions are independent. A raw material is thus only considered critical if it is found to have both a high supply risk (x-axis) and a high importance/vulnerability (y-axis). The aggregation of the criticality axes into one single criticality indicator is seldom done. A notable exception is Graedel et al. (2012) who use a criticality vector magnitude (i.e., the distance from the origin to a metal's location in criticality space) as the basis for aggregation. Based on classical risk assessment, Glöser et al. (2015) also explored some potential paths for providing a single criticality indicator by multiplying the two factors resulting in convex contour lines in the two dimensional plot and by defining the vector length resulting in concave contour lines. However, there are multiple ways to combine the two axes; in case the criticality is defined as an abstraction of classical risk assessment, i.e., a simple multiplication of the two axes, one ends up with convex contour lines – see Paley et al. (1952) for a further discussion.

A remarkable divergence in approach on levels of criticality is to be mentioned. The quantification of criticality often leads to a relative ranking of raw materials along the scale and, eventually, a categorization of the raw materials as being either critical or not. In the 2014 The EC study (EC, 2010, 2014), for example, twenty raw materials are considered to be critical: Antimony, Beryllium, Borates, Chromium, Cobalt, Coking coal, Fluorspar, Gallium, Germanium, Indium, Magnesite, Magnesium, Natural Graphite, Niobium, Platinum Group Metals (PGMs), heavy Rare Earth Elements (REEs), light REEs, Silicon metal, and Tungsten. From an overview of criticality studies, Erdmann and Graedel (2011) distinguish three levels of criticality for all materials where sufficient studies are available. In the highest level of criticality, Scandium, Yttrium, Niobium, Tungsten, PGMs (Ru, Rh, Pt) and REEs (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) are listed. The methods used to perform this categorization are often somewhat arbitrary, which draws criticism and concern regarding the raw materials close to the thresholds. One exception is the recent criticality methodology presented by the U.S. President's National Science and Technology Council, which uses a hierarchical cluster analysis as the basis for the categorization of the raw materials as critical or not. Graedel and Reck (2016) emphasize that criticality is rather a matter of degree, not a state of being. Presenting criticality as a state of being has clearly the advantage of easier communication to a broader audience. Apart from the (absolute) degree, important is that criticality calculations lead to a relative ranking: certain raw materials are "less secure" and/or "more important" than others.

2.3. Mostly divergence: the role of environmental issues

Some studies include environmental issues into the assessment of criticality, but there is very little consensus regarding the purpose and method used for its inclusion (Achzet and Helbig, 2013). In certain assessments (EC, 2010) environmental issues are considered to be an extension of issues related to ensuring supply and is thus included as a component in the supply risk dimensions (e.g., using the environmental performance index at country-level; www.epi.yale.edu). Despite the relevance of environmental impacts as an issue in the sustainable supply of materials, it is questionable if it is inherent to criticality either as an immediate supply risk factor or in terms of immediate (economic) importance.

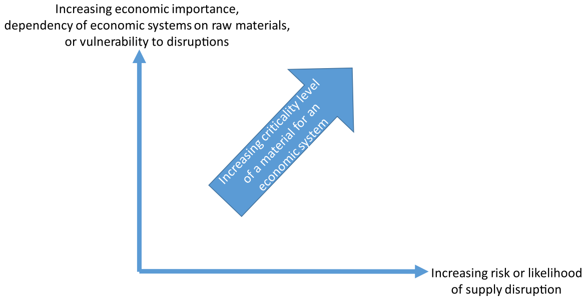

Fig. 1. Illustration of the two main dimensions in the assessment of the criticality of materials.

Therefore, in other assessments (Graedel et al., 2012) environmental issues are viewed as a separate issue that should be considered during the material selection process that is separate from supply risk and is thus given an independent third axis, thereby moving from a two-dimensions criticality matrix into a three-dimensional plot (Graedel et al., 2015, 2012). Such assessment typically rely on data and information from life cycle assessment literature (Nuss and Eckelman, 2014). Given that life cycle impact assessment often includes an abiotic resource depletion metric, such indicators are removed to avoid double-counting (Nassar et al., 2015).

3. Holistic vision on risk or likelihood for supply disruption factors: essential for the international debate

As noted by Erdmann and Graedel (2011), supply disruptions may stem from governmental interventions, market imbalances or physical disruptions of the supply chain, all in addition to absolute abundance. The supplier country concentration is generally included in most if not all criticality calculations, typically measured using the Herfindahl-Hirschmann Index (HHI). HHI is usually further complemented with country-level indicators that reflect the political stability and governance of the respective producing countries (e.g. the World Governance Index (WGI)), attractiveness toward mining investments (Policy Perception Index (PPI), previously known as the Policy Potential Index), levels of human development (Human Development Index), and others. Undoubtedly, many more phenomena could be mentioned that complement the abovementioned supply risk factors and indicators: the practiced methods are very diverse in bringing in social, physical, technological, geological, economic, or market components. Some methodologies report so-called additional supply risk influences, i.e., influences that are considered to play a role in supply disruption but which are not incorporated in the calculation. As an example, the EC identified eight influences in this context, e.g., by-product dynamics and land competition (EC, 2014).

The many supply disruption factors and indicators may stem from different viewpoints on supply disruption or from a lack of a holistic vision on it. A careful holistic analysis of all kinds of supply risk factors may facilitate the international debate and may help in underpinning a common view that advances the operationalization of the risk or likelihood of supply disruption axis.

Even though not all supply risk factors might be equally influential in determining criticality, as this strongly depends on different stakeholders' perspectives and the scope of the overall study, it can help to structure such risk factors in terms of their nature: we thus propose the TERP concept. Very different natures of factors that potentially determine the risk or likelihood of supply disruption can indeed be identified along the supply chains. They are structured into four types following Fig. 2, according to a TERP structure (see also the Appendix for a more detailed discussion):

- Technical, physical and geological factors;
- Economic, market and strategic factors;
- Regulatory and social factors;
- Political stability and governance factors.

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We acknowledge that several risk factors are interlinked and, therefore, might fit into more than one category. We also emphasize that this TERP structure does focus on risk factors as such and does not comprise factors that mitigate risk: (1) Substitution by other primary materials: substitution by other raw materials can mitigate the criticality of some raw materials thereby reducing the economic importance and/or supply risk for the industrial sectors; (2) Substitution by secondary raw materials through recycling: certain levels of recycling rates can be seen as a factor that reduces the economic importance and/or supply risk of certain primary raw materials. Several of the elements shown in Fig. 2 are already (partly) integrated into existing criticality frameworks, while others would need to be examined/developed in context of available data and policy needs. While a systematic examination of each element against existing studies and data is outside the scope of the current paper, we recommend such an examination for the future.

4. A better understanding and characterization of the economic importance or vulnerability to disruptions

Raw materials are a fundamental input in economic systems, thus strategically important. This is generally acknowledged, though sometimes given low priority in national / regional policy, as for decades few doubted the availability of secure and inexpensive supply from international markets. This perception is generally changing, and governments, as well as end-users in industry, are now generally more interested in gaining a better understanding of the role of raw materials in supply chains and their flow across economic systems. For example, material flow accounting and analysis constitutes a description of the economy in physical units (Brunner and Rechberger, 2004; EUROSTAT, 2013; OECD, 2008a, 2008b) and can be applied to express material supply chains (BIO by Deloitte, 2015). Furthermore, physical input-output tables (Weisz and Duchin, 2006) can help to better understand the detailed flow of metals and materials across economic sectors (Chen et al., 2016; Ohno et al., 2016).

The role and economic importance of raw materials is quite challenging to measure, and the approaches and methods are very diverse. There is very low international consensus in this area, but some common ground can be extracted and formulated as follows: high economic importance means that the raw material is fundamental in industry sectors to create added value and jobs, which are lost in case the raw material is not available and adequate substitutes cannot be used instead. Essentially, the importance of a material is intertwined with lack of substitutes. An additional element in the determination of high economic importance may be the in-use stocks. However, the objectives and scope can dramatically change the perspective and therefore the characterization. For instance, in the recent research at the United States Critical Materials Institute, the scope is a selection of metals used in low carbon energy technologies and the objective is to secure adequate supply in order to reach given levels of CO_2 abatement. For this reason, the capacity of a technology and related metals to reach

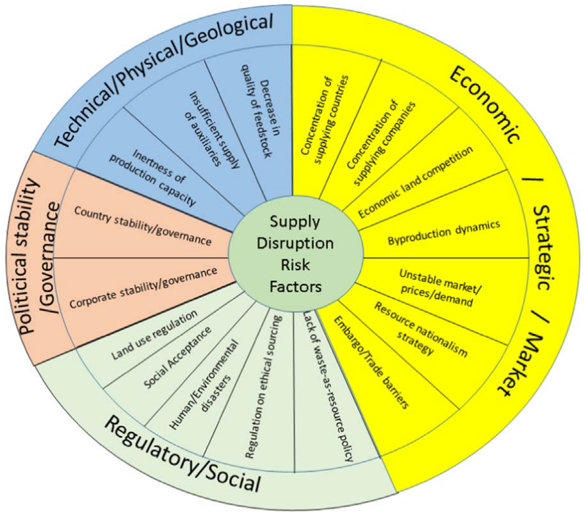

Fig. 2. The TERP framework to structure supply risk factors. Supply risk factors are organized into four different groups of risk factors according to their nature: risk factors of physical/technical/geological nature (3 factors); of economic/strategic/market nature (7 factors); regulatory/social nature (5 factors); and of political stability/governance nature (2 factors).

the abatement targeted is one of the key elements in the assessment of economic importance. In that case, the wording “importance to clean energy” is used instead of “economic importance”. In other cases “Impact of supply restrictions” or “Vulnerability to supply restrictions” is used for the same criticality axis.

Quantitative characterization of economic importance remains a challenge. As an illustration, some studies (e.g. EC, 2010 and 2014) completely disregard the size, in terms of tonnage, and the market value of the raw materials supply, measuring the economic importance downstream only, via allocating the share of end-uses to mega-sectors. The consequence is that even specialty metals with very tiny supply, but which serve strategically important high added value industry sectors, can have extremely high economic importance. This calls for better mapping of physical flows of a wide range of materials in national economies. A recent Japanese study (Daisuke, 2015) combines the value of the raw materials supply and the added value downstream, using the added value downstream to position the raw material in the two axes criticality diagram and the value of the commodity supply to visually represent the market scale.

An interesting study (Bastein and Rietveld, 2015) used a combination of trade data and economic Input/Output (IO) modeling to obtain a detailed picture of raw materials use in the Dutch economy. Recent work has also started discussing the importance of a better understanding of supply chain structure in the determination of crucial supply chain actors (e.g., economic sectors) and bottlenecks using tools of complex network analysis (Nuss et al., 2016). This approach may become more relevant as better data on the supply chains of materials becomes available in the future.

Two main groups of criticality studies can be categorized as those that are economy-wide and those that are sector-specific. In addition, corporate and global criticality studies exist. Economy-wide criticality studies embrace whole national or regional economic systems (EC, 2010, 2014; NRC, 2008; Graedel et al., 2015; BGS, 2012; Achzet et al., 2011; Coulomb et al., 2015; NSTC, 2016), thus the raw materials in scope rapidly expand in number and diversity of supply chains, which increase the difficulty of the analysis. In case of economy-wide criticality assessments, the use of added value of industry sectors is a possible measure of the economic importance of raw materials. In this approach, the economic importance of raw materials is not related to the quantity or the economic value of commodities, but rather to the added value downstream, which would be lost in case supply is not adequate and no adequate substitutes are available. In any case, when an economy-wide criticality study is performed, it is extremely complex to find reliable and representative data about where the raw materials are used, because some are used nearly everywhere (e.g. some industrial minerals), and thus, not surprisingly, the results are sometimes controversial.

Sector-specific criticality studies target selected technologies and/or selected end-uses (Moss et al., 2013; USDOE, 2010, 2011), which are considered of strategic importance. In this way, the number of raw materials in scope is drastically reduced and the role of the raw material in providing its envisaged function (e.g., reducing carbon emissions from energy generation) is easier to determine. Measuring the economic importance, or the vulnerability to supply disruptions, is still carried out in different ways, and not without uncertainties, but with a clearer objective in mind.

It seems unlikely that some common methodology can be found for both economy-wide and sector-specific criticality assessments (although the methodology proposed by Graedel et al. (2015) provides a corporate, national, and global methodology using the same overall structure and assessment framework). In sector-specific criticality assessment, the specificity itself of the study could be an obstacle for convergence in methodology. As economy-wide criticality assessment is concerned, a crucial point is the definition of the sub-sectors where raw materials are used, the related added value and linkage criteria. Physical Input/output models can help to indicate the economic sectors where raw materials are being used and support the visualization of inter-linkages in economic systems (Chen et al., 2016; Ohno et al., 2016; Nuss et al., 2016). Examples include aluminum use in the US economy (Chen et al., 2016; Nuss et al., 2016) and the flows of several alloying elements (manganese, chromium, nickel, molybdenum, niobium, vanadium, tungsten, and cobalt) in the US economy (Ohno et al., 2016). However, the calculation of physical I/O tables may only be feasible for a subset of materials (for which separate economic sectors exist in I/O tables, or can be introduced via further sector disaggregation) and only if the resolution of the corresponding monetary I/O table is sufficiently high. Therefore we note that, while physical I/O approximations can offer some complementary insights to today's criticality assessments, they also have several limitations and might lead to misinterpretation if not carefully framed.

5. A number of elements essential for advancing criticality on the international scene

The analysis of the current interpretation and operationalization of criticality reveals different levels of divergence. The two-axis backbone and the respective axes in the above sections have to be addressed in the international debate, but there are many more elements to be involved in the discussion. In this context, we focus on the scope of the materials, the role of substitution, a coherent modeling of the supply chain, and data and indicator selection.

5.1. Scoping the materials

Criticality studies evaluate a range of materials for certain economic entities but different resource assets are studied: sometimes ‘minerals’ (Buijs et al., 2012), sometimes ‘non-fuel minerals’ (Erdmann and Graedel, 2011), sometimes ‘metals’ (Graedel et al., 2015); sometimes ‘raw materials’ (Glöser et al., 2015), but also ‘resources’ (Sonnemann et al., 2015). This significant divergence stems from different viewpoints and interests and differences of the value chain among different materials, but also from a lack of commonly applied definitions in the value chains, and in particular on a lack of common vision as to what stage in the value chain should be the anchor for criticality analysis. Recently, Dewulf et al. (2015a) proposed a common stage to anchor the point of the ‘raw materials’ stage in all kind of supply chains, ending up with a set of 85 raw materials, next to a set of 30 primary energy carriers. It offers a frame to scope the range of materials under study: only those derived from stocks and deposits, or also those from biobased production. In conclusion, the scoping of the materials will remain heterogeneous as criticality is an assessment tool that serves different bodies with their particular range of materials and their specific scale of analysis.

5.2. The role of substitution and recycling

Most criticality approaches have the intention to account for substitution and recycling but the implementation into the calculations diverge. With respect to substitution, the 2014 EC methodology (EC, 2014) considers it as a factor that mitigates supply risk, totally different from the approach adopted by Graedel et al. (2015) where substitutability is factored into the vulnerability axis (Graedel et al., 2012). There may be arguments to justify the role of (lack of) substitutability in the two axes. Equally, the 2014 EC methodology (EC, 2014) considers sourcing from secondary resources also as a supply risk mitigation factor for supply risk disruption, mathematically in a same way as substitution. This is different from Graedel et al. (2012) where both primary and secondary (recycled) sources are considered in the calculation of supply risk and metal recycling rates incorporated into the depletion time model (to determine the amount of time it would take to deplete currently known geological stocks at the current rate of demand).

5.3. Modeling of the supply chain

For economy-wide criticality assessments, the modeling of the supply chain may be based on generic production data, i.e., starting from the worldwide production data to picture a generic country concentration pattern. Alternatively, the modeling may start from the economic system under study and model its specific supply, which may be different in terms of geographical spread from the aforementioned approach. Both modeling approaches may have pros and cons: the first one may be more robust and feasible from data point of view; the second may be more representative for the specific country or region under study. Eventually, a mixed approach could be developed. The two modeling approaches are illustrated in Fig. 3, showing the difference in the NRC-US (2008) (NRC, 2008) (US-specific) and the European Union (worldwide) approach (EC, 2014).

5.4. Data and indicator selection

From interactions with many specialists, it is obvious that data are a constraint in criticality calculations. Some indicators are well accepted; although sometimes controversial, and very far from being representative of the minerals industries; and generally used as they are provided by well-established bodies (e.g., the World Governance Index (WGI) or the Policy Perception Index (PPI)). On the contrary, other information is less specific, e.g., on sourcing from waste-as-resource (e.g., with generic data from Graedel et al. (2011)). In case criticality intends to integrate further supply disruption phenomena identified in the TERP framework, then data availability and specificity might be one of the main challenges.

The modeling of the supply chain is for sure also key in data selection as the supply chain comprises many stages beyond the mining, e.g., beneficiation, concentrating, smelter, refining. Attention has to be paid to differences in the supply concentration in these different steps. This is illustrated in the EC 2014 study for some raw materials, e.g., manganese where contributions at the mining stage from Australia and China are almost equal, but where China overwhelms all countries at the refining stage (EC, 2014). Criticality studies typically focus on the mining stage at least as far the studies are transparent. Using data from the U.S. Geological Survey, Graedel et al. (2015) do, however, use production at multiple stage, where data are available. It is questionable if they capture the key step in terms of likelihood of disruption. In any case, criticality calculations should be transparent on what stages they rely on in the 'primary production'. A step further would be to calculate a country concentration based on all involved stages in the supply chain of the raw material under study, or at least pointing to the weakest step in the chain (bottleneck).

For some supply disruption or economic importance elements, characterization and quantification is poorly generally accepted and available. A typical example is the characterization of the decrease in quantity and quality of feedstock. The quantification of the decrease typically done in function of the 'Area of Protection Natural Resources' (change in cost or energy, extraction rates to reserves ratios, decline in ore quality) (Dewulf et al., 2015b) is heavily debated. Additionally, involving new specific factors in critical analysis should be well thought if they may be brought along with rather overarching and aggregating indicators that capture several factors at the same time. An example is the combination of WGI with HHI in the EC methodology that covers factors from political stability/governance, regulatory/social, economic/strategic/market nature at the same time. If these aggregated factors need to be combined with more specific factors like on decrease in quality of feedstock, the role and weight of the different indicators needs careful attention.

6. Elements for the future international debate

6.1. The criticality assessment method itself

With the current development of criticality assessment, it may be timely to bring together the international criticality assessment community on a more systematic base. Initiatives at the international level may stimulate a better common understanding and interpretation of criticality, e.g. by setting globally accepted definitions (e.g. common understanding and definition of the two main dimensions of criticality) or common approach and mapping of supply risk factors). First initiatives may be mentioned: criticality has been discussed on international events (e.g. World Resources Forum in Davos, 2015) or at governmental level (e.g. trilateral workshops US-EU-Japan). However, these are just first initiatives and an international body that facilitates or manages the debate is not (yet) in place.

Definitely, the debate should concentrate on the abovementioned elements of criticality assessment methodology. It may investigate where there should be convergence and consensus and where there may be room left for flexibility. At least it should help in better addressing a better common understanding by setting definitions, by specification of goals and scope (economic entity, materials …), by listing particular attributes (transparency on data sources, review process …) ….

6.2. The criticality assessment in the sustainability assessment toolbox

Apart from the elaboration of criticality assessment itself, the international community should reflect on the positioning and the delineation of criticality. Resource criticality assessments help in understanding the sustainability of a certain economy and hence the welfare and wellbeing of the involved population. It is evident that it is a key instrument in sustainable management of resources for mankind. But sustainability is multifaceted exemplified by the 3 P approach: people, profit and planet. Resource criticality does not deal with economics solely; the TERP concept shows factors beyond economics

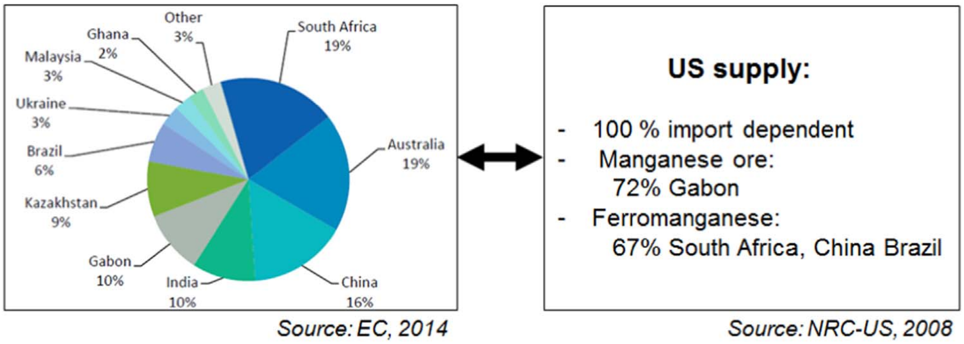

Fig. 3. Differences in modeling the supply chain of manganese with its country concentration, either starting from worldwide production of the raw material, or starting from a supply to a specific economic system.

as such. On the other hand, it must be acknowledged that other sustainability assessment tools for resources are in place and that the positioning and range of scope of criticality and the other tools need to be critically analyzed in terms of overlaps and gaps. One approach could be an integration of criticality factors in Life Cycle Assessment that has historically an environmental emphasis, hence allowing coverage of environmental and economic aspects of resource and material supply and use. A recent example is provided by Sonnemann et al. (2015).

Alternatively, a more profound and conceptual approach for a proper role of resource criticality evaluation may be at stake, as exemplified by Dewulf et al. (2015a). In their analysis for an integrated sustainability management for raw materials, they rely on different quantitative frameworks, mainly ecosystem services, classical life cycle assessment (LCA), social LCA, and resource criticality assessment. From the analysis, they identify a consistent set of ten specific sustainability concerns for raw materials, where three stem from the criticality framework. The paper leaves the open question if this integrated framework should lead to one single assessment tool, or if rather the existing toolbox should stay a diverse set of tools. Even in the latter case, it is worth to reflect on the role of resource criticality in terms of its role and functionality in the toolbox.

6.3. From criticality analysis to resilience

Criticality calculations point to supply disruptions that economic systems may undergo with severe consequences. What the methods so far do not offer systematically is insight on how an economic system responds to disruptions and how it is able to mitigate or absorb them. In Fig. 4, we introduce the concept of resilience using outcomes from a recent paper by Sprecher et al. (2015). Within this broader view, resilience could be seen as a third factor in criticality screening, or additional step in terms of further analysis and response. This proposal could overcome the fuzziness of having recent/current versus future-oriented elements in the criticality calculation. Indeed, criticality calculations can be either based on recent past/current characteristics (e.g. recycling rates, substitution) or characteristics reflecting future-potential or resilience (e.g. potential to increase the recycling rate, substitutability). The former approach intrinsically does not reflect resilience in the future, the latter may do. By proposing a clear split in between criticality calculations based on recent past/current characteristics and resilience that can be based on future potential characteristics, we may come not only to a better common interpretation of criticality but also reduce the level of uncertainty in the calculation.

According to Sprecher et al. (2015), resilience can be defined as the capacity of a system to tolerate disruptions while retaining its structure and function. In case of criticality of raw materials, it reflects how well the system is able to deal with supply disruptions. Resistance, rapidity and flexibility are considered as the cornerstones of resilience. In the work of Roelich et al. (2014), this is somehow captured by the 'susceptibility' component which includes, among other things, the Global Innovation Index that aims to quantify how well a country can adopt to a supply disruption by innovation. Relying on the study of the rare earth crisis (Sprecher et al., 2015), Sprecher et al. identify the following ways to mitigate supply disruptions:

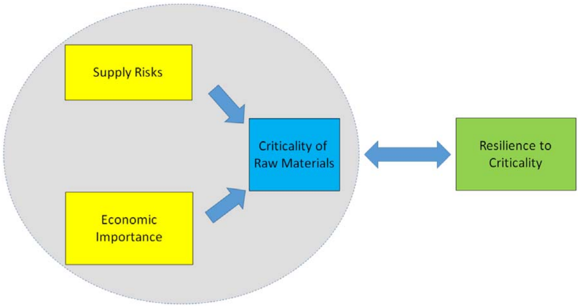

Fig. 4. Resilience as a way to respond to criticality?.

- Increasing the diversity of supply: new primary production and recycling, among others;
- Feedback loops through price mechanism;
- Material substitution and improved material properties;
- Stockpiling.

It is noteworthy that the authors see substitution and recycling rather as factors in the mitigation of supply disruptions; but nor as supply risk factors nor having a role in the vulnerability/economic importance.

Rosenau-Tornow et al. (2009) combined past and future trends for supply risk, hence combining criticality and response – resilience. For the latter, they relied on factors like exploration budgets, planned investments and demand trends.

In conclusion, criticality assessment could take advantage of an international forum to identify common ground for approaches, calculation methods and required data, and indicators for criticality assessment. Simultaneously, such an international forum could define what aspects of the assessment may be left flexible, as criticality assessments cover different purposes with a varied coverage of raw materials, and different audiences. Equally, it would be welcome to reflect on positioning criticality in the broader sustainability debate of raw materials supply.

Appendix A

Discussion of the 17 supply risk factors of the TERP concept

Technical, physical, and geological factors

As a first type of supply risk factors, technical, physical and geological supply risk factors are identified. They reflect potential limitations in the physical supply of raw materials in any form, e.g., geological issues related to natural resources that are essential to produce primary resources, or technical problems in the production of secondary raw materials from end-of-life products. The latter element is valid in case secondary sourcing is in scope, at least for raw materials that can be sourced from waste.

Detailing the physical/technical/geological factors, three specific risk factors are recognized:

- Decrease in quality of feedstock. The decrease in quality, e.g., decreasing ore grade, or mineral deposit depth, or mineralogical complexity, for primary production, or decreasing content of precious metals in electronic waste for secondary production, are geological/technical issues that may lead to increased product and recovery costs thus making the material potentially less economically available.
- Insufficient supply of auxiliaries. Apart from a high-quality feedstock, the availability of auxiliaries, e.g., water, energy, labor, capital and logistical infrastructure (rail, trucks, highways, ports, etc.) is technically essential to ensure the supply.
- Lack of elasticity of the production capacity. Installations to produce primary or secondary raw materials are usually large installations with often high level of inertness, beyond the flexibility for which they have been designed, i.e., the adaptiveness or readiness to meet (changing) demand can be considered as a technical supply risk factor.

The abovementioned issues are not generally included in criticality assessments.

Economic, strategic and market supply risk factors

Secondly, risk factors of economic, strategic, and market nature are identified. Under this type, seven specific supply risk factors are listed:

- Concentration of supplier countries. As current supply may come from a limited number of countries in the current economic market, this high level of concentration intrinsically increases the likelihood and risk for supply disruption.
- Concentration of supplying companies. Similarly to countries, a concentration of production within a limited number of companies may lead to an increased supply risk, though of a different type and potential consequences in respect to the concentration of supplier countries.
- Economic land use competition. As supply of especially primary raw materials requires access to natural deposits, access to these terrestrial deposits can be threatened by economic land use competition, e.g., for urbanization or agricultural developments.
- By-production dynamics. As the supply of some raw materials is largely dependent on the co-mined or co-produced byproducts and their economics, changing market conditions of one raw material can affect the economic profitability of another one.
- Unstable market/prices/demand. As the supply is fully dependent on a certain market demand, instabilities in the demand can be seen as a potential supply risk factor, resulting in high price volatility and hence rather low willingness to engage in a risky business. As an example, projected low future demand for REEs is a major source of concern when talking about investments in non-Chinese primary supply.
- Resource nationalism strategies of supplying countries. For strategic reasons, producing countries can stimulate domestic down-stream sectors disfavoring export to raw material dependent countries (example Indonesia).
- Embargo/trade barriers. For reasons of different nature, embargos or trade barriers can significantly impact the market situation and lead to supply risk for importing countries.

Analyzing the current practice, country concentration has already been widely incorporated into criticality studies. By-production dynamics is sometimes integrated as well, allocating additional level of risk for a by-product. The latter might be valid in many cases, but there may be also by-products that are today not fully recovered (e.g., gallium from bauxite with currently only 10% of alumina producers extracting gallium) and that may result in sufficient additional supply in case of shortages, but under the condition that processing facilities are adapted in the due time. Other factors here are not quantified in current methods, but are considered qualitatively, e.g., land use competition by the EU criticality study (Chapman et al., 2013). Trade barriers, and to the extreme export bans, may have become more relevant these days, as the number of export restrictions have drastically increased since 2005 (OECD, 2014).

Regulatory and social factors

Thirdly, supply risk factors of regulatory and social nature are identified:

- Land use regulation. National and international land use regulation for nature conservation are often perceived by the industry as an additional (domestic) supply risk.
- Social Acceptance. Supply disruption due to lack of social acceptance can be a substantial supply risk factor, e.g., interference with social values of the local communities.
- Human and environmental disasters. Immediate impacts onto the local community and environment, e.g., catastrophes during operations, can lead to supply disruptions. Essentially, the impacts are rather of an immediate and local nature, i.e., human and environmental disasters, not the longer-term impacts that are modeled for example through classical life cycle assessment.
- Regulation on ethical sourcing. Due to international agreements to limit sourcing of raw materials from specific areas with political instability, unrest, conflicts and/or civil war, supply of specific raw materials may undergo supply disruption risk.
- Lack of waste-as-resource policy. As waste can be an important source of secondary raw materials, the framework offered by authorities should facilitate their supply. In case policies are not sufficient, (secondary) raw materials may stay within the urban mine (e.g., storage of electronics in households), or in mining waste deposits, or may leak through illegal exports. Import estimates to the countries supposed to be the major recipients of e-waste exports from the OECD globally suggests that ~5000 kt may have been imported annually to these non-OECD countries alone, which represents ~23% of the amounts of e-waste generated domestically within the OECD (Breivik et al., 2014).

The abovementioned supply risks are often acknowledged, but seldom adequately addressed in the criticality calculation methods with specific quantitative indicators. Nevertheless, social acceptance is considered as an important item by the mining sector (Prno and Slocombe, 2012). In the mining sector, local communities have emerged as particularly important governance actors. Conventional approaches to mineral development no longer suffice for these communities, which have demanded a greater share of benefits and increased involvement in decision making. These trends have been spurred by the growth of the sustainable development paradigm and governance shifts that have increasingly transferred governing authority towards non-state actors. Accordingly, there is now widespread recognition that mineral developers need to gain a ‘social license to operate’ (SLO) from local communities in order to avoid potentially costly conflict and exposure to social risks.

Whereas the assessment has been largely developed with primary sourcing in mind, the sourcing from waste becomes more and more prominent in an industrial ecology and circular economy context. This secondary sourcing is dealt with in criticality differently; in the Yale methodology recycling is covered by a depletion time model; in the EC methodology, recycling is considered as a mitigation factor for supply risk of primary sources.

Political stability and governance factors

A last type of supply risk factors is to be highlighted, i.e., political stability and governance supply risk factors:

- Country stability and governance. Lack of sufficient political stability and governance in countries where a major part of the materials are sourced from can lead to risk of supply disruption.
- Corporate stability and governance. Similar to the country level, supply risk due to insufficient corporate stability and governance of major players in the supply chain can affect the supply of raw materials. SLO is also connected to this aspect.

While this fourth group of supply risk factors is generally acknowledged in criticality calculations, only country stability and governance are usually incorporated. This is often due to a lack of company-level data for the minor metals.

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