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Abbreviations: BGS, British Geological Survey; BRGM, Bureau de Recherches Géologiques et Minières; CRM, Critical Raw Materials; EC, European Commission; Empa, Swiss Federal Laboratories for Materials Science and Technology; EIT, European Institute of Innovation & Technology; EU, European Union; GE, General Electric; HDI, Human Development Index; HHI, Herfindahl-Hirschman-Index; iCIRCE, Instituto Universitario Investigación CIRCE Universidad Zaragoza; INSEAD, Institut Européen d'Administration des Affaires; IRTC, International Round Table on Materials Criticality; ISO, International Organization for Standardization; KIRAM/KITECH, Korea Institute for Rare Metals/Korea Institute of Industrial Technology; LCA, Life Cycle Assessment; NEDO, New Energy and Industrial Technology Development; NIES, National Institute for Environmental Studies; NRC, National Research Council; NSTC, National Science and Technology Council; OECD, Organisation for Economic Co-operation and Development; OH, Oakdene Hollins; PGM(s), Platinum Group Metal(s); PPI, Policy Perception Index; REE(s), Rare Earth Element(s); SDU, University of Southern Denmark; SI, Supplementary Information; UBA, Umweltbundesamt; UNDP, United Nations Development Programme; UNEP IRP, United Nations Environment Programme International Resource Panel; US DOE, United States Department of Energy; USGS, United States Geological Survey; VDI, Verein Deutscher Ingenieure; WGI, Worldwide Governance Indicators

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ABSTRACT

The assessment of the criticality of raw materials allows the identification of the likelihood of a supply disruption of a material and the vulnerability of a system (e.g. a national economy, technology, or company) to this disruption. Inconclusive outcomes of various studies suggest that criticality assessments would benefit from the identification of best practices. To prepare the field for such guidance, this paper aims to clarify the mechanisms that affect methodological choices which influence the results of a study. This is achieved via literature review and round table discussions among international experts. The paper demonstrates that criticality studies are divergent in the system under study, the anticipated risk, the purpose of the study, and material selection. These differences in goal and scope naturally result in different choices regarding indicator selection, the required level of aggregation as well as the subsequent choice of aggregation method, and the need for a threshold value. However, this link is often weak, which suggests a lack of understanding of cause-and-effect mechanisms of indicators and outcomes. Data availability is a key factor that limits the evaluation of criticality. Furthermore, data quality, including both data uncertainty and data representativeness, is rarely addressed in the interpretation and communication of results. Clear guidance in the formulation of goals and scopes of criticality studies, the selection of adequate indicators and aggregation methods, and the interpretation of the outcomes, are important initial steps in improving the quality of criticality assessments.

1. Introduction

Raw material criticality is the field of study that evaluates the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame. Criticality assessments play an indispensable role for industry and policymakers alike, e.g. in material selection, product and process design, investment decisions, trade agreements, collaboration strategies, as well as in the prioritization of research projects, policy agendas, and undertakings towards increasing transparency in value chains (Buijs et al., 2012; Graedel and Reck, 2015).

Criticality assessments are conducted at different levels: for a specific product (Bach et al., 2016; Cimprich et al., 2017a; Clifton, 2013; Gemechu et al., 2017; Graedel and Nuss, 2014), technology (Bauer et al., 2010; Gauß et al., 2017; Habib and Wenzel, 2016; Helbig et al., 2018; Moss et al., 2011, 2013b), company (Duclos et al., 2010), country or region (European Commission, 2017a; Graedel et al., 2015; Hatayama and Tahara, 2015; Lee, 2014; NRC, 2008), or even at a global level (Graedel et al., 2015; Morley and Eatherley, 2008). The criticality of a raw material then can be considered in the short term (e.g. a few years) or in the long term (a few decades) (Bauer et al., 2010; Buijs et al., 2012; Erdmann and Graedel, 2011; Ku and Hung, 2014; Riddle et al., 2015). Criticality methods use a broad selection of indicators to describe various factors including geological, technological, geopolitical, social, and environmental factors (Achzet and Helbig, 2013; Dewulf et al., 2016; Erdmann and Graedel, 2011; Habib and Wenzel, 2016; Kolotzek et al., 2018). Due to the diverse perspectives and motivations to carry out such studies, there are considerable variations in the identification processes of critical raw materials (CRM) and their outcomes, as assessed by e.g. Erdmann and Graedel (2011); Graedel and Reck (2015); Dewulf et al. (2016) and illustrated in Fig. 1. One can say that *"Criticality is in the eye of the beholder"* (Eggert, 2011); that is, there is no generic standard approach to conduct a criticality assessment.

The diversity of raw material criticality assessments, the use of different indicators, and the complexity of the underlying data usually makes a comparison of the results generated by different studies difficult, if not impossible. Authors in the field have pointed out that there is a need to identify criticality assessment factors and indicators that provide an improved estimation of the degree of criticality, as well as suitable data sources for this purpose (Graedel and Reck, 2015; Speirs et al., 2013). Despite these gaps, an international forum dedicated to the harmonization of the development of criticality methods was missing (Dewulf et al., 2016). To begin to address these challenges, the EIT (European Institute of Innovation & Technology) Raw Materials project IRTC ("International Round Table on Materials Criticality") was established, bringing together international experts in round table dialogues to tackle the questions surrounding methodology, application, and future development of raw material criticality assessments. In the resulting publications, of which this paper is the first of an ongoing series, the IRTC Consortium integrates the views from a variety of stakeholders worldwide.

While previous review papers have mostly focused on highlighting the differences between criticality studies (Achzet and Helbig, 2013; Erdmann and Graedel, 2011; Helbig et al., 2016c), this paper aims to clarify the underlying reasons of *why* criticality method developers have made different choices that have resulted in the different methodologies. It focuses especially on how different assessments are framed (goal, scope) and then on the assessment methods themselves (indicators, aggregation, presentation). This analysis will form the basis to structure the current discussions around the methodological aspects of criticality assessments via an international collaborative effort. Understanding the status quo, and the directions in which criticality assessment and the debate surrounding it is moving, is vital for identifying the future needs of different stakeholders and for defining the next steps on a global level.

2. Methods

The following approach has been applied to identify the underlying relationships between stakeholder perspectives, methodological choices, and the outcomes of criticality assessments: firstly, a comprehensive overview of the available literature on criticality has been conducted in the form of a "Criticality Library" (see Supplementary Information A (SI-A)). Thereafter, methods have been selected for review based on the aim of providing a broad overview of early and more recent method developments, broad geographical coverage, and the

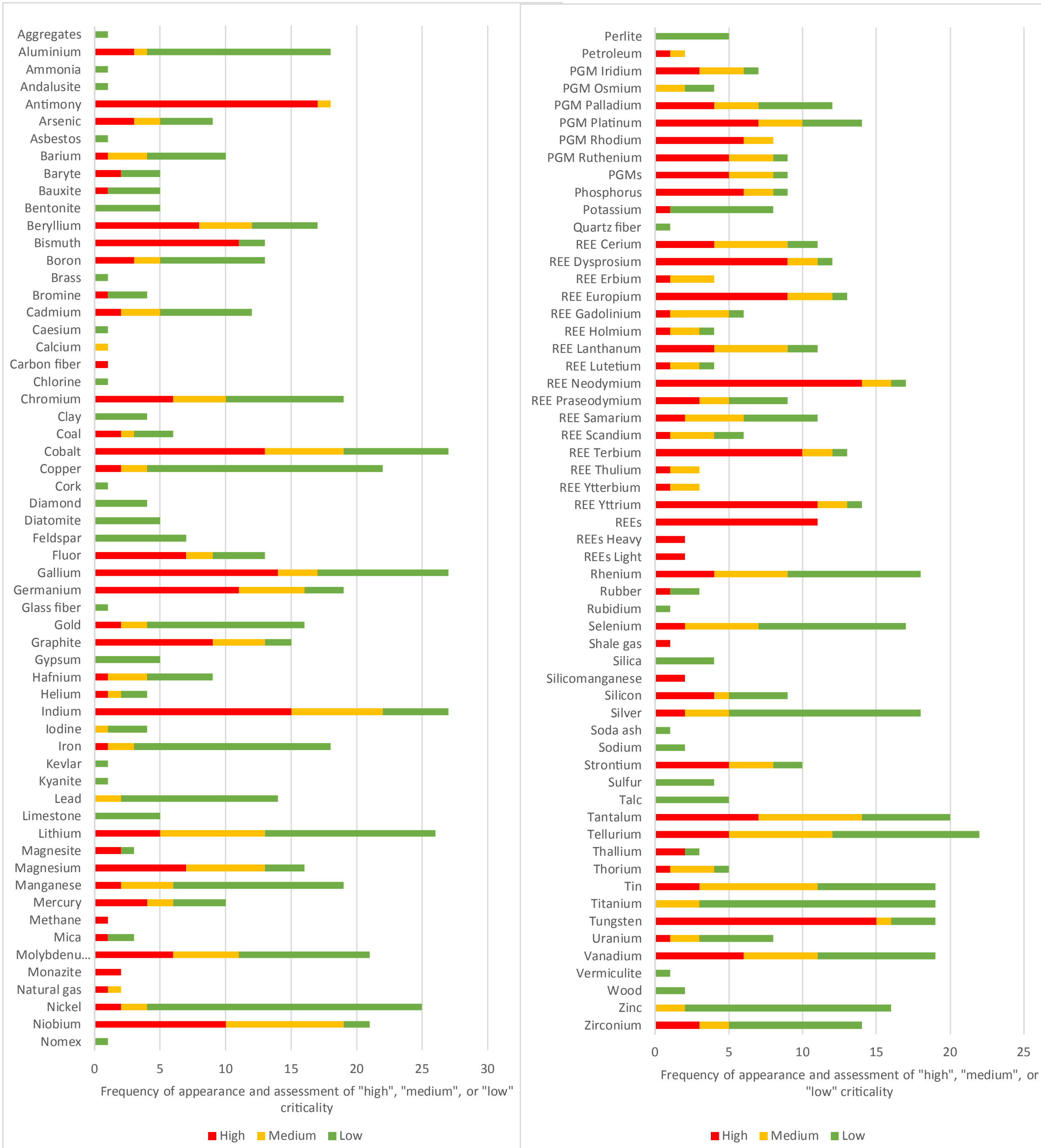

Fig. 1. Frequency of appearance in criticality assessments and criticality determination (high, medium, or low) of materials. Included methods (see Table 1.): NRC, Yale (global and country risk, only the supply risk axis), NSTC (2016 and 2018), EU (2011, 2014a,b, and 2017a,b,c,d), Helbig et al. (2016a,b,c and 2018), Augsburg, KIRAM/KITECH, NEDO, BRGM, Werner, General Electric, iCIRCE, NIES, GeoPolRisk, SCARCE, Oakdene Hollins, Thomason, Rosenau-Tornow, Öko-Institut, Roelich, SDU, China, BGS (2011, 2012, and 2015), OECD, US DOE (both short term and medium term for 2010 and 2011), Moss et al. (2011 and 2013). Excluded methods are BIRD, VDI and UBA (no results), Granta Design, ESSENZ and EBP/Empa (unaggregated results and/or company-specific), Angerer (no materials identified as critical). Multi-stage analyses and multiple forms of the same material are merged (only bottleneck is included), to avoid double counting of appearances. See SI-B for details on material inclusion and evaluation of methods.

inclusion of diverse scopes and stakeholders. Following the approach of previous review studies (Achzet and Helbig, 2013; Erdmann and Graedel, 2011; Graedel and Reck, 2015; Habib and Wenzel, 2016), aspects of the goal and scope and methodological choices were collected and summarized in a "Goal and Scope table" (SI-B). This table has, as far as possible, been filled in and/or reviewed by the method developers themselves. This is one of the unique features of the IRTC project: instead of one group discussing other's work, the method developers themselves came to the table. IRTC contacted as many method developers as possible in order to also integrate approaches that have not been discussed and reviewed in the literature before.[1] Method developers were contacted based on references in the scientific literature, and on the consortium representatives' identification of relevant studies and authors in their country or field of work. The project consortium itself was formed by the authors of relevant criticality studies as identified by the scientific literature (in particular Graedel and Reck, 2015); further members were included by recommendations of the members of this initial core group. Advisory Board members representing relevant stakeholders such as industry representatives and policy-makers were added based on recommendations from the consortium and under consideration of country and stakeholder balance.

From the "Goal and Scope table", key differences were identified between the assessment methods: this was done first by assessing the system under study (e.g. national economy, company, product, etc.), and the related spatial boundaries and the time horizon. Furthermore, IRTC narrowed into the details of the study on the level of criticality dimensions (e.g. the probability of a supply disruption and the vulnerability to such a disruption), factors (e.g. economic, geological, political, or environmental), indicators (e.g. the country concentration of supply, depletion time, etc.), and data sources used. The team assessed how the applied approaches assured the use of reliable input data for the assessment and which role experts played in this. Other methodological choices, such as aggregation methods and threshold values were also discussed. Furthermore, the boundary conditions of the studies were noted, such as the intended audience and the foreseen applications of the results, which may justify certain methodological choices.

In line with the observations of Erdmann and Graedel (2011), several aspects of the goal and scope are often not explicitly mentioned in the evaluated studies, such as the time horizon, material selection criteria, and the intended use of the results. Furthermore, as Achzet and Helbig (2013); Erdmann and Graedel (2011), and Lloyd et al. (2012) point out, several studies lack an explicit justification of choices. Through discussions with IRTC experts during the first IRTC Round Table in Vancouver (a summary is provided in SI-C), the underlying motivation of choices in these studies have been clarified in more detail, in order to be able to understand both explicit and implicit factors that affect the outcome of a criticality study. As this paper has been developed by many co-authors, a more detailed explanation on the establishment of the paper is provided in Section S1 of SI-D.

3. Results and discussion

The main mechanisms that were identified via the literature review which influence the outcomes of criticality assessments are schematically represented by Fig. 2. These mechanisms are presented in line with the methodological framework for Life Cycle Assessment (LCA), as standardized in ISO 14040 (ISO, 2006), which enables the use of the scheme as a methodology development and evaluation tool. Fig. 2 shows that the goal and scope of a study both directly and indirectly influence the results of the assessment. The goal and scope influences indicator selection. Indicator selection is affected by data availability, which can influence the material coverage of the assessment, and thus again the goal and scope. The availability and the quality of data finally influences indicator scoring. In most studies, indicator scores are aggregated to enable the identification of a material as critical or not. The aggregation method that is used is not determined by the indicator scoring, but instead by a choice or logic reasoning of the practitioner – represented by the goal and scope. Finally, the way in which the practitioner aims to communicate his or her results is solely determined by the objectives of the assessment itself.

[1] The goal and scope table is an ongoing work in progress and will contain methods that are not included in this review. If the reader knows about a method that should be integrated, please contact the corresponding author.

Therefore, the combined factors of goal and scope definition, indicator evaluation, and the chosen aggregation method lead to the classification of a material as "critical" or "non-critical". These mechanisms are further explained below.

3.1. Goal and scope

In this section, we discuss several key elements of the goal and scope of criticality methods: the system at risk, the anticipated risk, the objective of the assessment, and the materials that are evaluated. An overview of the goals and scopes of methods that are reviewed is provided in Table 1.

3.1.1. What is at risk?

Throughout the 20th century and mainly driven by governmental reports from the United States and Great Britain, the concept of critical – or "strategic", a more frequently used term - raw materials (CRM) mostly referred to materials used in the field of national security and defense (Ashby, 2016; Paley, 1952; Tilton, 2003, 2001). Typically governments determined their military material stockpiles as a response to anticipated demand surges and potential supply restrictions, either in preparation for, or during a war situation, with import dependence being a key consideration (Thomason et al., 2010).

From the mid-20th into the early 21st century, the industrialized world experienced a rapid increase in economic growth, driven by technological developments, against a backdrop of an increasing global population. The lack of locally sourced material resources for industrial needs in Europe, as well as the Chinese export restrictions of rare earth elements (REEs), starting in 2007 and reaching a peak in 2011, caught the attention of global users of raw materials (Frenzel et al., 2017). This development had a great impact worldwide, as China has dominated the global REE market with a 95% market share. Countries with a high level of industrialization and a high level of dependency on imports of

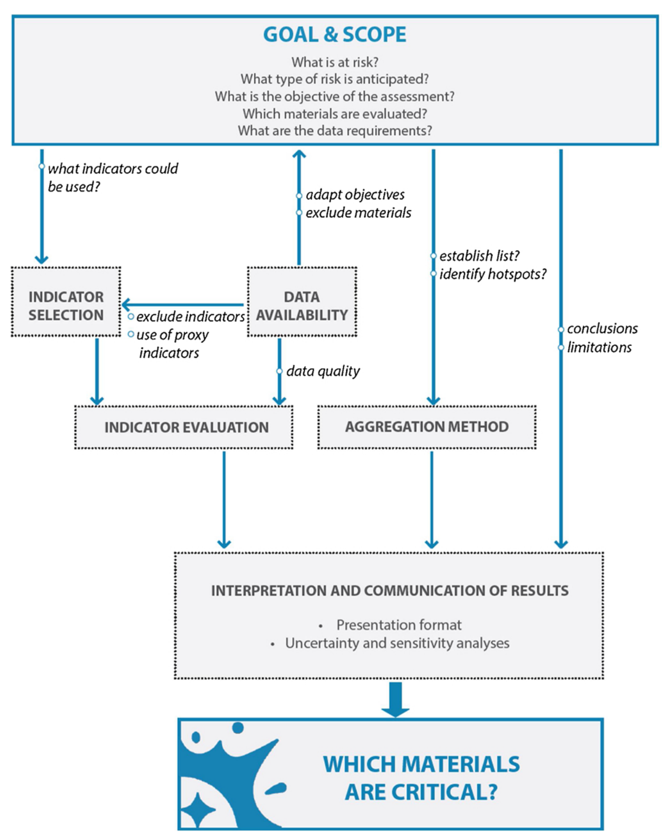

Fig. 2. How the goal and scope influences which materials are critical.

Table 1
Goals and scopes of reviewed criticality assessment methods (detailed information available in SI-B).

Method	Year	What is at risk?	Geographical scope of the system at risk	Time horizon	Anticipated risk	Objective
Oakdene Hollins (OH) (Morley and Eatherley, 2008)	2008	Economy	UK	Few decades	Insecure material supply, due to high price increases, shortages of supply, resource nationalism, a high concentration of supplying companies, or high environmental impacts can negatively impact economic sectors.	Inform policy makers, innovation support bodies and business on the need for resource efficiency strategies.
NRC (NRC, 2008)	2008	Domestic economy	USA	< 10 years	Physical unavailability of materials, high and/or volatile material prices, disruptions to economic activity	Establish a general conceptual framework for evaluating material criticality, which specific users can customize to their own situations
General Electric (GE) (Duclos et al., 2010)	2008	Company operations	Global	Not explicit	Increased economic growth, increased reliance on raw materials and sustainability challenges affects the company's supply chain.	Identify exposure to supply risks and guide selection of appropriate mitigation actions
Rosenau-Tornow (Rosenau-Tornow et al., 2009)	2009	Not specified	Not specified	5–15 years	Potential supply shortages due to demand growth and supply from politically instable countries.	Improve decision-making in companies in their selection of new technologies, anticipate critical market situations, implement mitigation measures
NEDO (Hatayama and Tahara, 2015; NEDO, 2009)	2009	Economy	Japan	Short term	Supply, price and demand risk, recycling restrictions on 39 minor metals, and their potential risks related to environmental aspects	Identify need for the development of substitutes
Öko-Institut (Buchert et al., 2009)	2009	Sustainable energy technologies	Global	NA	Combined demand growth, supply risks, and recycling restrictions result in a limited availability of materials that are needed in sustainable technologies	Analyse the availability and recycling potential of critical metals and identify framework conditions that enhance their recycling
Angerer (Angerer et al., 2009)	2009	Emerging technologies	Germany	2030	High volatility of prices of raw materials, of which costs contribute largely to manufacturing costs, and high environmental impacts of extraction contribute to unsustainable material use	Inform market actors about potential peaks in demand
USDOE (Bauer et al., 2010)	2010	Deployment of renewable/efficient energy technologies	Global	0–5 years and 5–15 years	Disruptions of supply in the short term of materials that are important for clean energy technologies	Assess risks and opportunities, inform the public dialogue, and identify possible program and policy directions
Thomason (Thomason et al., 2010)	2010	Defense	USA	3 years	Potential supply shortfalls in case of war	Identify needs for stockpiling of materials for the defense sector
USDOE (U.S. Department of Energy, 2011)	2011	Deployment of renewable/efficient energy technologies	Global	0–5 years and 5–15 years	Disruptions of supply in the short term of materials that are important for clean energy technologies	Assess risks and opportunities, inform the public dialogue, and identify possible program and policy directions
Moss (Moss et al., 2011)	2011	Low-carbon energy technologies for 2020-2030	European Union	Short-medium term	Shortages of materials due to a rapid growth in demand and political risks associated with the geographical concentration of the supply in the short to medium term (5–10 years) hinder the large-scale deployment of low-carbon technologies.	Collect data and monitor material supply and demand, identify potential bottlenecks, and mitigate risks.
EU2011 (European Commission, 2010)	2011	Economy (focus on manufacturing sector)	European Union	10 years	Disruption of supply due to high supply concentration and poor country governance, mitigated by recycling and substitutability	Monitor criticality, prioritize needs and actions, incentivize the European production of CRM, facilitate the launching of new mining and recycling activities, negotiating trade agreements, drafting legislation, challenging trade distortion measures, promoting research and innovation and inform on options of supply diversification, with the purpose to increase competitiveness of the EU economy
BGS (BGS, 2011)	2011	Economy and lifestyle	N/A	Now and in the future	Disruption of supply due to resource competition (demand by emerging economies), geopolitics ("haves" seeking to influence "have nots"), resource nationalism (state control of production), strikes, and accidents)	Inform policy-makers, industry, and consumers about the need to diversify supply, increase recycling, and decrease resource use
Yale (Graedel et al., 2015, 2012)	2012	Future generations	Global	Few decades	Use of elements at a rate that does not permit the next generation to acquire them to the extent that might be needed	Policy development of corporations and governments

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Table 1 (*continued*)

Method	Year	What is at risk?	Geographical scope of the system at risk	Time horizon	Anticipated risk	Objective
Yale (Graedel et al., 2015, 2012)	2012	Domestic economy	N/A, applied to USA	5–10 years	Unreliable supply of materials that are important for the economy due to geological, technological, economic, social, regulatory, and geopolitical restrictions.	Policy development of corporations and governments
Yale (Graedel et al., 2015, 2012)	2012	Company operations	N/A	1–5 years	Unreliable supply of materials that are important for the company due to geological, technological, economic, social, regulatory, and geopolitical restrictions.	Policy development of corporations and governments
BGS (BGS, 2012)	2012	Economy and lifestyle	N/A	Now and in the future	Disruption of supply due to resource competition (demand by emerging economies), geopolitics ("haves" seeking to influence "have nots"), resource nationalism (state control of production), strikes, and accidents)	Inform policy-makers, industry, and consumers about the need to diversify supply, increase recycling, and decrease resource use
Moss (Moss et al., 2013b)	2013	Low-carbon energy technologies for 2050	European Union	Short-medium term	Shortages of materials due to a rapid growth in demand and political risks associated with the geographical concentration of the supply in the short to medium term (5–10 years) hinder the large-scale deployment of low-carbon technologies.	Collect data and monitor material supply and demand, identify potential bottlenecks, and mitigate risks.
Granta Design[a] (Ashby, 2016; Goddin, 2019)	2013	Product	Global	1 year - few decades	Supply disruption from geopolitical activities, environmental or substances legislation, conflict mineral regulations – manifesting as increases in price volatility or possible supply shortages or changes in lead times. Social impacts from unethical regional practices manifesting as damage to consumer perception. Inability to substitute impacted materials with performant or suitably certified alternative.	Identify sources of risk and possible impact on business, identify suitable mitigation measures (e.g. substitution, product design, supply agreements, stockpiling, circular economy approaches)
Roelich (Roelich et al., 2014)	2014	Wind turbines	UK	2014–2048	Constraint on the deployment rate and scale of low-carbon technologies due to disrupted supply of materials.	Enable the identification of potential policy responses to reduce criticality.
OECD (Coulomb et al., 2015)	2014	Economy	OECD countries	2012 and 2030	Disruption of supply of minerals that are important for the economy and that are difficult to substitute and to recycle, due to reliance on supply from political instable countries or due to increasing demand from emerging markets and new technologies	Inform policymakers on recycling efforts and development of substitutes, stimulate R&D in the OECD. Formulate policy targets on "required" recycling and substitution rates. Stimulate data availability on indicators for supply risk and material use
KIRAM/KITECH (Lee, 2014)	2014	Economy	Korea	< 10 years	Instability of metal supply to the Korean economy due to high prices and low stocks.	Secure supply of raw materials to SMEs by identifying needs for stockpiling, new supply routes, substitution, and recycling
iCIRCE (Calvo et al., 2017; Valero, 2015; Valero et al., 2011)	2014	Availability of resources	Global	Few decades	Resources become too dispersed for efficient extraction or recovery	Identify needs for substitution and recycling
EU2014 (European Commission, 2014a)	2014	Economy (focus on manufacturing sector)	European Union	10 years	Disruption of supply due to high supply concentration and poor country governance, mitigated by recycling and substitutability	Monitor criticality, prioritize needs and actions, incentivize the European production of CRM, facilitate the launching of new mining and recycling activities, negotiating trade agreements, drafting legislation, challenging trade distortion measures, promoting research and innovation and inform on options of supply diversification, with the purpose to increase competitiveness of the EU economy
NIES Footprint Method (Nansai et al., 2017, 2015)	2015	Economy	Japan	2005	Disruptions of supply in the short term of materials that are important for clean energy technologies	Identify trade-offs against climate mitigation and supply risks by introduction of new energy technologies
BRGM (BRGM, 2018, 2015, 2014)	2015	Economy	France	Not explicit	Supply of metals with strategic importance to the French economy is affected by geological availability, recycling, and environmental, social and political factors.	Support public and private decision-making
BGS (BGS, 2015)	2015	Economy and lifestyle	N/A	Now and in the future	Disruption of supply due to resource competition (demand by emerging economies), geopolitics ("haves" seeking to influence "have nots"), resource nationalism (state control of production), strikes, and accidents)	Inform policy-makers, industry, and consumers about the need to diversify supply, increase recycling, and decrease resource use

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Table 1 (*continued*)

Method	Year	What is at risk?	Geographical scope of the system at risk	Time horizon	Anticipated risk	Objective
SDU (Habib and Wenzel, 2016)	2016	Wind turbines	Global	2020–2050	Constrained supply of metals for the deployment of wind turbines due to limiting geological or geopolitical factors	Support protection against supply constraints by improved understanding and interpretation of criticality results
NSTC (Fortier et al., 2018; McCullough and Nassar, 2017; NSTC, 2018, 2016)	2016	System using a material (any scale)	Global	5–10 years	Decreased availability of a material due to growing demand, dependency on political instable mining countries, by-product dependency, or regulatory constraints	Anticipate potential supply constraints, inform need for in-depth criticality assessment
Augsburg2016 (Helbig et al., 2016a)	2016	Photovoltaic modules	Global	Now and in the future	Disruptions of supply of materials that are important for Thin-Film Photovolatic modules	Identification of supply risks and guidance of product selection
GeoPolRisk (Cimprich et al., 2019, 2017a, 2017b; Gemechu et al., 2017, 2016; Helbig et al., 2016b)	2016	Product	Country	< 10 years	Supply disruptions of materials that are used in a product due to political instability of raw material producing countries	Identify hotspots to inform product design, material selection, and supply chain management
ESSENZ (Bach et al., 2016)	2016	Product	Global	< 10 years	Restricted availability of resources due to physical as well as socio-economic factors and societal acceptance, which compromises the productivity of companies	Identify hotspots to inform product design, material selection, and supply chain management
China (Ministry of Land and Resources of the People's Republic of China, 2016)	2016	National sustainable development	China	< 10 years	Limited access to resources per capita and decreasing investment in exploration hinders the country's sustainable development	Secure the supply of strategic resources by investing in upgrading and structural adjustment of the mining industry
Werner (Werner et al., 2017)	2017	Availability of resources	Global	Few decades	Depletion of geological availability of resources	Inform decision-making by public and private authorities on resource use and extraction
UBA (Manhart et al., 2018, 2017)	2017	Any system using materials	Global	N/A	Environmental impacts from mining and mineral processing make raw material supply unsustainable and in this sense decrease raw material availability.	Inform policy-making and industry in the potential environmental impacts of raw material from mining
SCARCE (Bach et al., 2017b)	2017	Economy	Germany	Not explicit	Restricted availability of resources to a country due to physical as well as socio-economic factors and social acceptance	Identify relative criticality for a country compared to global average and identify hotspots
EU2017 (Gian Andrea Blengini et al., 2017a; European Commission, 2017b)	2017	Economy (focus on manufacturing sector)	European Union	10 years	Disruption of supply due to high supply concentration, poor country governance, trade distortions, and import dependency, mitigated by recycling and existing substitutes	Monitor criticality, prioritize needs and actions, incentivize the European production of CRM, facilitate the launching of new mining and recycling activities, negotiating trade agreements, drafting legislation, challenging trade distortion measures, promoting research and innovation, with the purpose to increase competitiveness of the EU economy
EBP/Empa (Spörri et al., 2017; Swissmem, 2015)	2017	Company operations	Global	Not explicit	Supply risks related to metals relevant for the company's products, company vulnerability to metal supply restrictions, environmental and social impacts related to the supply of metals relevant for the company's products ("reputational risks")	Identify risks related to metals relevant for the company's products and provide measures to counter these risks
BIRD (Bach et al., 2017a)	2017	Company operations	Global	Not explicit	The availability of biotic materials to product systems could become restricted, which could affect the productivity or continuity of companies, which in turn affects society	Provide information about the global criticality of raw materials in product systems over the supply chain
VDI (Kosmol et al., 2017; VDI, 2018)	2018	N/A	N/A	< 10 years	Difficult raw material situations that can impair the system of interest caused by geological, technical, geopolitical, or economic factors	Provide guidance on resource efficiency to industry stakeholders, consultancies, researchers, governments, and public administration
Augsburg2018 (Helbig et al., 2018)	2018	Lithium-Ion batteries	Global	Now and in the future	Disruptions of supply of materials that are crucial for advanced battery technologies	Identification of supply risks and guidance of technology selection
Augsburg (Kolotzek et al., 2018)	2018	Company operations	Global	Now and in the future	Decreased competitiveness due to unsustainable use of raw materials	Inform sustainable decision-making by the corporate management

[a] The products of Granta Design are only commercially available.

raw materials, such as Japan, Korea, the USA, and the European countries, started to systematically assess the security of their raw material supply chains (Frenzel et al., 2017). Over this period, the USA and the European Union developed and published criticality methods, which were mainly influenced by economic and geopolitical factors. Such methods are designed to identify potential supply risks of materials that are important to sustain contemporary lifestyles, and for the development and growth of national or regional economies (BGS, 2011). National defense considerations have also remained a factor. The methods that are reviewed in this paper (Table 1) have been published from this time onwards, starting in 2008.

Methods continued to be developed in order to assess the criticality of raw materials for specific industrial sectors, such as low-carbon energy technologies (Bauer et al., 2010; Buchert et al., 2009; Helbig et al., 2018; Moss et al., 2011) and other emerging technologies. Criticality assessments also found increased application in companies who began to approach the topic from their own specific perspectives (Duclos et al., 2010; Goddin et al., 2013; Kolotzek et al., 2018; Marsden et al., 2013). As a subset of these approaches, methods have been designed that assess whether potential supply risks could affect the raw or intermediate materials supply for a specific product (Bach et al., 2016; Cimprich et al., 2017b; Gemechu et al., 2017; Helbig et al., 2016a). Finally, some methods assess the potential supply shortage of raw materials for future generations (Calvo et al., 2017; Graedel et al., 2012).

Table 1 shows that studies do not always specify a geographical scope, except for most criticality assessments for national or regional economies. Regarding the time horizon, most studies evaluate criticality for the status quo. A few studies make future projections, e.g. KIRAM/KITECH for the Korean economy in the year 2020, US DOE (2010 and 2011) for clean energy materials in 2011–2016 and 2016–2026, OECD (Organisation for Economic Co-operation and Development) for the OECD economies in the year 2030 (Coulomb et al., 2015), Habib and Wenzel for the deployment of wind energy up to the year 2050 (Habib and Wenzel, 2016), Moss et al. for low-carbon energy technologies up to 2050 (Moss et al., 2013a,b) and Oakdene Hollins for global use up to the year 2050 (Morley and Eatherley, 2008). Studies classified as "dynamic criticality studies" investigate the development of criticality indicators in the past, with the purpose of identifying trends of increasing or decreasing criticality (Goddin, 2019; Habib et al., 2016; Habib and Wenzel, 2016; McCullough and Nassar, 2017; Roelich et al., 2014)).

3.1.2. What type of risk is anticipated?

Changes in the demand and supply of materials have led, at least locally, to periods of material scarcity and shortage (Ashby, 2016, 2013; Johnson et al., 2007; Tilton, 2003). Relevant changes in supply can have the form of supply disruptions (short-term) or declines (long-term – for a distinction see Sprecher et al., 2015). Changes in demand can be relevant both in positive and negative terms. A positive change in demand refers to a (frequently sudden) increase in demand in a possibly relatively short period of time, e.g. by the rapid dissemination of a new technology. A negative change in demand describes a demand drop, for example when a technology becomes superfluous (Langkau and Tercero Espinoza, 2018), which can be a risk for the company or (regional) economy relying on the adoption of this technology. Most criticality assessments evaluate either the probability of a decrease in supply, the probability of an increase in demand, or a combination of both, which can be generalized by the risk of price increase (Frenzel et al., 2017), or price fluctuations (Lee et al., 2019). Table 1 shows an overview of the anticipated risk of the reviewed methods, which illustrates that supply and demand changes can be intertwined, such as in the case of decreased availability of a material due to a growing demand (e.g. NSTC). Several studies only consider supply and demand changes as a risk when the system at risk is vulnerable to these (e.g. USDOE and OECD). Vulnerability is frequently marked by a lack of available substitutes or a lack of options to adapt supply or demand to the anticipated change, leading to, for example, decreased competitiveness when supply is disrupted. Even if vulnerability is not always mentioned in the anticipated risk, as summarized in Table 1 it is often implicitly considered in criticality assessments via the selection of vulnerability indicators (see Section 3.2.1.2).

3.1.3. What is the objective of the assessment?

Three main objectives could be distinguished that were addressed in the reviewed criticality methods of Table 1. Firstly, criticality studies are generally performed to raise the attention of decision makers in government and industry towards issues related to raw materials supply and demand. There is no apparent or reasonable interest on the side of the funders or performers of such studies to either create panic or instigate tension among countries or companies. On the contrary: for example, Sprecher et al. (2015) show that the stockpiling activity of Japan amid the REE crisis raised prices even further. Also, a 10-fold increase in the price of iridium (one of the Platinum Group Metals (PGMs)) over the last 15 years has motivated industrial users, such as the magnetic storage sector, to develop their own stockpiles, which further stimulated speculation by investors (European Commission, 2016). Calm, stable raw materials markets are at the core of effectively facing the challenges related to the secure supply of raw materials for industries worldwide.

Secondly, studies often aim to provide information to policymakers, industry, and/or consumers on mitigating criticality. Mitigation measures could be focused on decreasing criticality in the short term, such as pointing out the need for stockpiling of raw materials or challenging trade-distortive measures. Also, mitigation measures on the medium to long term could be proposed, such as by diversifying supply, for example by increasing recycling, launching new mining activities, finding substitution alternatives, developing new technologies, or negotiating trade agreements. For most economies, different mitigation strategies may be considered in parallel, such as the exploration of new mining sites, increased recycling, finding substitutes, and increased investments in material processing (see also Lee et al., 2019).

Thirdly, generic criticality assessments could be used as "prescreenings" for in-depth studies with a more specific focus (e.g. NSTC). Screening studies help to prioritize the type of information that needs to be gathered for more detailed criticality studies. Dynamic criticality studies could be considered as a subset of screening studies in which materials are followed over multiple years considering a limited number of indicators.

3.1.4. Which materials are evaluated?

Fig. 1 provides an overview of the frequency with which materials are included in a selection of the reviewed criticality assessments. Most recent criticality assessments only included non-energy minerals, as the supply of fossil fuels has been widely covered in earlier analyses (Angerer et al., 2009; European Commission, 2010). Some studies only included metals (e.g. Graedel et al., 2015), or only biotic materials (Bach et al., 2017a), while others were very comprehensive and included all elements of the periodic table and/or other types of materials, such as industrial minerals or biotic materials (European Commission, 2017b). A few studies focus only on one specific material or element (e.g. Rosenau-Tornow et al., 2009). Materials that are most frequently included are indium, gallium, cobalt, lithium, nickel, tellurium, copper, the PGMs and the REEs (see Fig. 1). Materials that are only included in a single study are, among others, aggregates, ammonia, cork, carbon fiber, and a few branded products (e.g. Nomex® and Kevlar®).

While most studies look at material supply at the mining stage (e.g. BGS (2012)), several studies evaluate criticality at different points in the supply chain of a material (e.g. European Commission (2017c); Granta Design (2019); NSTC (2016)). For example, the EU study identifies the bottleneck in the supply chain and quantifies supply risks at that point. Cimprich et al. (2019) apply a life cycle perspective and

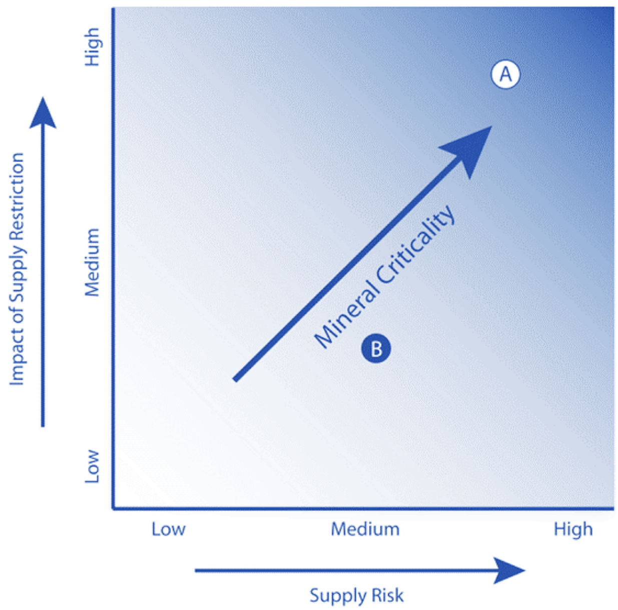

Fig. 3. Classical criticality assessment, combining a supply risk dimension and an importance/vulnerability dimension (NRC, 2008).

aim to include all the resources extracted from nature, as well as all the intermediate products (including ancilliary products) that are required to produce the product under study. Achzet and Helbig (2013) stress the differences in the supply chains of materials in different forms, which are used in different applications, such as high-grade lithium for batteries and low-grade lithium for lubricants. Thomason et al. (2010) differentiate five types of carbon fiber for use in national defense technologies, of which only one is identified as being critical. Also, among five different forms of manganese (battery-grade manganese dioxide (natural and synthetic), ferromanganese, metallurgical-grade manganese ore, and electrolytic manganese metal), only electrolytic manganese metal was evaluated as being critical (Thomason et al., 2010). Such precision is not provided in most other studies.

Erdmann and Graedel (2011) already noticed that the reasons to include or exclude materials in criticality assessments are not always explained. Material selection can be based on a first identification of materials that are vulnerable to a supply disruption (compare, e.g., Kolotzek et al. (2018)). BGS excludes elements with little or no commercial use, synthetic elements, and elements naturally occurring in a gaseous state (BGS, 2011). Initial material selection is very relevant, as materials that are not included in the assessment cannot be identified as being critical. If data on specific materials are not available, these materials are sometimes excluded from the assessment as well, which reinforces the influence that data availability exerts on the goal and scope. This strategy is, for example, applied in the BGS studies: due to a lack of available data, the studies exclude boron, bromine, calcium, carbon (coal), chlorine, helium, phosphorous, potassium, sodium,

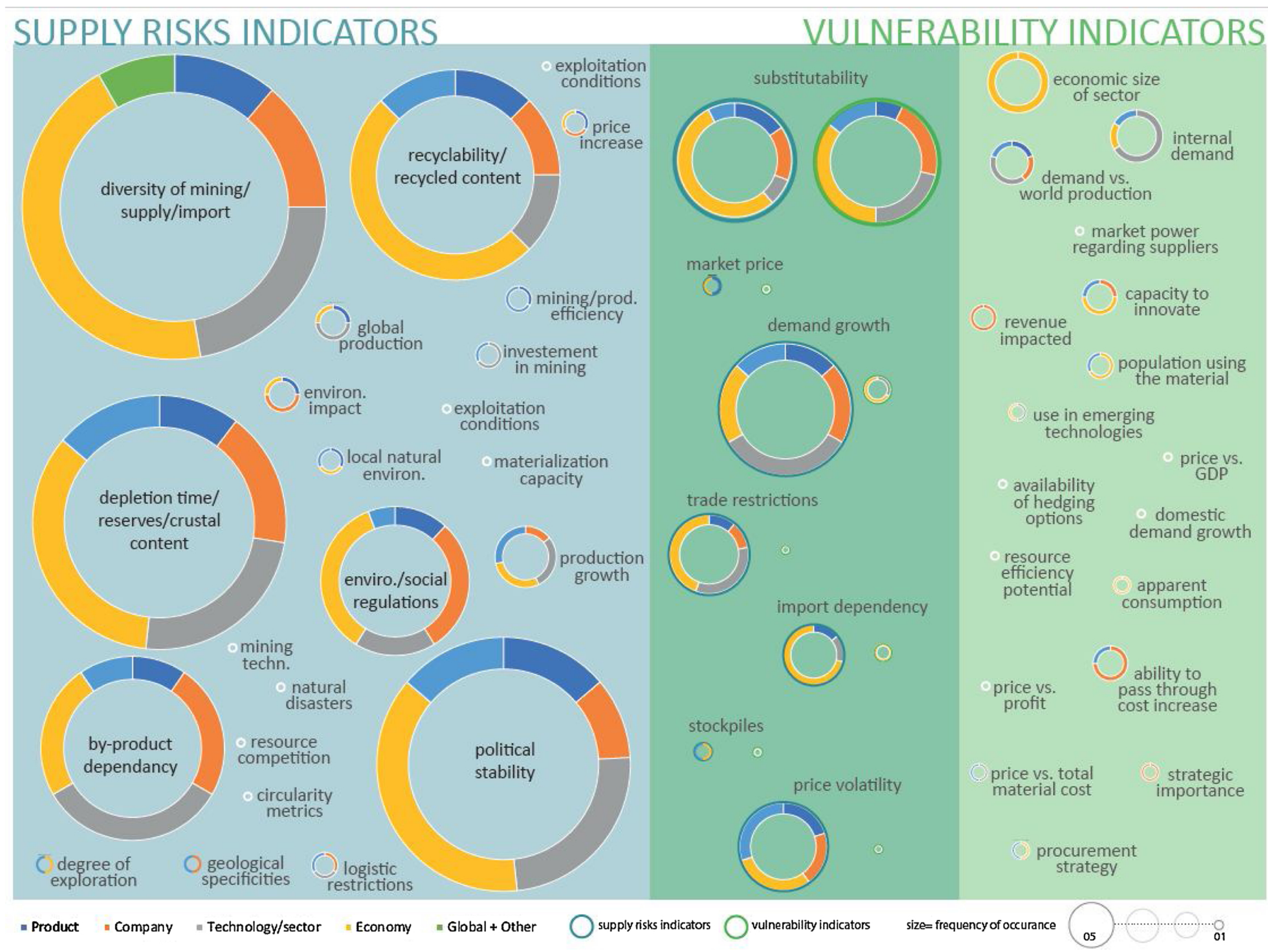

Fig. 4. Indicators for the probability of a supply disruption and/or the vulnerability to a supply disruption, their frequency of use, and the scope in which they are used. Detailed tables with background information are provided in Section S2 and S3 of SI-D.

sulphur, and iodine (BGS, 2015, 2012). NSTC exclude hafnium and osmium due to unavailable data (NSTC, 2016). For some materials, available data are very scarce for a large range of indicators – such as calcium, helium, barium, boron, magnesia, wood, graphite, and clay – or data are limited on specific material grades or material forms, such as coking coal (European Commission, 2017d). The REEs and PGMs suffer from a lack of differentiation between the individual elements belonging to these groups, although they can have very different uses and supply situations (e.g. the REE cerium is mostly used in catalysts and produced in surplus, while the REE neodymium is mostly used in magnets and the market is comparatively tight (European Commission, 2014b)). Besides lacking data on specific materials, there are large data gaps concerning the intermediate products of critical materials and their indirect trade in intermediate and final products, which hinders a full understanding of the criticality challenges for different countries or regions and at different life cycle stages (like in a trade-linked global value chain (Liu and Müller, 2013a)). This can explain the fact that most studies focus on materials at an element level.

3.1.5. Data requirements

Several aspects of the goal and scope of a criticality assessment determine the type of data that can be used, i.e. data requirements. Studies should be defendable, especially if the results are used to decide on public expenditure. This is relevant for government assessments (e.g., EC, NSTC, BGS) and studies conducted by academics. Public studies have a general preference for quantitative data, as they are perceived as being more objective (Coulomb et al., 2015). Furthermore, these data should be, ideally, publicly available, which contributes to the transparency and reproducibility of the study. Relying on such data is defendable against potential criticism that qualitative assessments reflect the biases of the researchers – a criticism that is especially important to avoid for government assessments. The EU method has been slightly revised for the 2017 assessment (European Commission, 2017a) to decrease the influence of expert judgement, e.g. by a more precise calculation of substitution or economic importance and establishing the priority of data to be used. Companies also must be able to defend their results, although mostly internally. Therefore, for these, it will be easier to use confidential data. On the other hand, Kolotzek et al. (2018) eliminate expert judgment in order to keep indicators more quantitative, which they consider to better serve decision-making. Also, Granta aims with their proprietary software at quantifying multi-faceted parameters such as substitutability (Granta Design, 2014).

As stated in Section 3.1.4, data availability has a direct influence on the materials and life cycle stages included in a criticality assessment. Constraints in the availability of resources (time, money, and personnel) can put a limit on the type of assessment that can be done. Especially public entities do not have the time or the staff to invest in data collection before conducting a criticality assessment, and they usually are missing the deep market insights which are necessary to understand especially the markets for specialty metals, limiting therefore the assessment factors to data that are readily available (Coulomb et al., 2015). Readily available data is also a requirement for assessments that have to be repeated regularly or that assess the evolvement of criticality over time. The use of quantitative or readily available data might compromise the quality of the data regarding the representativeness of the available data for the specific material, technology, geographical area, and time frame under study. The requirements for the quality of the data should therefore be anticipated by the study commissioners.

3.2. Indicator evaluation

Fig. 2 shows that the evaluation of indicators is a key parameter which affects the outcome of a criticality study. Indicator evaluation is based on two components: indicator selection and indicator scoring. As there is no adequate database specifically created for criticality studies, criticality evaluators have to resort to idealized constructs more or less fitting their situation, and relate these to available indicators and data sources (Buijs et al., 2012; Graedel et al., 2012).

3.2.1. Indicator selection

Many of today's criticality methods have emerged from the approach developed by the US National Research Council in 2008 (NRC, 2008), which was the very first systematic take on measuring criticality. As part of the NRC methodology, the criticality matrix was introduced containing axes for supply risk (later often referred to as "probability/likelihood of a supply disruption") and impact of supply restriction (Fig. 3) – also referred to as "vulnerability to a supply disruption". Starting from there, new approaches have developed, taking parts of established methods as well as adding new aspects. Thus, there are certain similarities as well as significant differences between the approaches. This section discusses indicator selection for these two criticality axes, illustrated by the examples of substitutability and environmental and social factors.

3.2.1.1. Supply disruption. An overview of indicators for the probability of a supply disruption that are used in different criticality methods with different scopes is provided in

Fig. 4 and Section S2 of SI-D.

Fig. 4 shows that the most widely used indicator is the diversity of producing or supplying countries, measured by the Herfindahl-Hirschman-Index (HHI), often in combination with the political stability of this country, measured by one or more sub-indicators of the Worldwide Governance Indicators (WGI) (Achzet and Helbig, 2013; Frenzel et al., 2017). These indicators aim to capture the probability of a supply disruption within current or future supply structures, either from the perspective of global supply or the country-specific import mix. Other frequently used indicators are depletion time, recycling rates, environmental and social regulations, and by-product dependency.

Some indicators reflect potential supply disruptions only for certain time horizons. For example, it is unlikely that physical scarcity will limit the accessibility to any material in the foreseeable future, which is why depletion is not considered a relevant factor in several criticality studies (e.g. Coulomb et al. (2015)). In others, the indicators depletion time is calculated using different sub-indicators that represent different time horizons. For example, the Yale approach considers depletion time based on reserves for the short/medium term and based on the reserve base for the long term. Also the indicator "Diversity of supply" can on one hand be based on current production or import structures, and on the other on the geological distribution of the material, reflecting the flexibility to change supply routes either on the short/medium term or on the long term, respectively (Roelich et al., 2014). Furthermore, it is not always clear in what time horizon supply or demand changes are anticipated, which is sometimes illustrated by the parallel inclusion of indicators that are relevant in the short term (e.g. import shares, current production rates) as well as indicators that provide information about resource availability in the long term (e.g. reserve base, crustal content). Evaluation on an indicator level – i.e. without aggregation – would provide valuable information on, for example, in what time horizon a supply might be disrupted (e.g. as applied by Öko-Institut (Buchert et al., 2009)), or which risk mitigation options might be of interest for the specific material.

It is noteworthy that, despite the different scopes of the different studies, frequently the same or similar indicators are selected for the evaluation of the probability of a supply disruption.

Fig. 4 shows that the indicators most frequently used in studies focusing on a national economy are also often chosen in studies with a technology, company, or product focus. A few indicators are indirectly reflected by other, more frequently used indicators (such as market price, price increase, or elasticity of supply that could be represented by price volatility or by-product dependency). Some indicators are mainly used by methods which aim to provide a holistic sustainability approach, or which consider technical limitations, including environmental impacts, geological properties, or natural disasters. Only a few studies include indicators that reflect potential bottlenecks in the supply chain downstream from the mining activity, such as restrictions regarding storage and transport and material processing capacity. Finally, a few indicators refer to mitigation measures (e.g. stockpiling, exploration, or resource efficiency). A key difference between methods seems to be the consideration of demand growth. Not all the studies focusing on a national economy consider demand growth, which is however more often included in technology-oriented methods. This implies that the criticality of material use for an economy is often considered only in the context of the current economic situation, disregarding the future development of the economy. Indicator selection is sometimes dependent on only a few aspects of the goal and scope. For example, Kolotzek et al. (2018) select indicators based on their perceived relevance by company actors, established via a survey. Hence, indicator selection implicitly depends on the experience and anticipated risks of the individual stakeholders that filled in the survey.

It also happens that studies with a similar scope use different indicators (Frenzel et al., 2017), for example illustrated by the evolvement of the methods applied by the EC and BGS over the years, which is further specified in Section S2.2 in SI-D. This demonstrates that, over time, the relevance of indicators can be perceived differently, which can be influenced by discussions in the scientific arena on indicator selection, as well as by indicator choices of newly published studies with similar scopes.

Neither dissipation nor rebound effects have been considered as potential risk indicators. This could be due to the difficulty of quantifying such effects, or, regarding rebound effects, due to the delay of occurrence: they are often an unforeseen, unintended, but relevant side effect after the implementation of an innovative functional material or process. Frenzel et al. (2017) state that, in many studies, the choice of indicators is rather dependent on subjective opinions (or a "gut feeling" of the method authors) than on empirical evidence. Also Erdmann and Graedel (2011) mention the lack of description of the foreseen dynamics of supply disruptions, adaptation measures, and impacts. This could partly explain the weak link between the anticipated risk and the selected indicators. For example, the risk factors that were suggested by BGS are not fully reflected in the final set of indicators. Furthermore, while political stability is considered as an indicator of supply risk in many studies, the possibility of active trade policy is less often included – although China's industrial policy on rare earth production in the late 2000's and early 2010's is considered to be an important factor in the rare earth supply crisis during that period (Wübbeke, 2013). A potential solution to establish this link is by the description of cause-and-effect mechanisms – such as commonly used in environmental Life Cycle Impact Assessment (Frischknecht and Jolliet, 2016) and demonstrated for criticality methods by Cimprich et al. (2019) for the methods GeoPolRisk, Economic Scarcity Potential (ESP), and ESSENZ. Such a description of cause-and-effect mechanisms aids in identifying methodological differences and deciding whether an approach is compatible with the goal and scope of the study.

3.2.1.2. Vulnerability. Besides the indicators for risk of supply disruption, Fig. 4 also presents the indicators that are used to evaluate the vulnerability to a supply disruption for different study scopes. The indicator that is included in most criticality studies is substitutability. Regarding the other indicators, there is little overlap between the indicators that are used to evaluate the vulnerability for a company and for technologies – showing the scope-dependency of vulnerability indicators. A few indicators (demand growth, internal demand, and use in emerging technologies) are used both for methods focusing on technologies and economies.

Indicators could be divided into three groups:

1. Indicators that reflect that the material is used by the system under study (e.g. internal demand, sectors using the material, population using the material, and apparent consumption) – indicating that the more a material is used, the more vulnerable the system is to a supply disruption.
2. Indicators that reflect the relative use of the material compared to other users (e.g. globally), or the relative importance of the material compared to other materials that are used by the same system (e.g. via the price of the material or the revenue or GDP that is impacted by a supply disruption).
3. "Other indicators", which are also used (by other methods) to evaluate supply risks: substitutability (further discussed in the next section), demand growth, import dependency, trade restrictions, price volatility, stockpiles, and resource efficiency.

The first and second group of indicators are useful to rank materials considering their relative importance for a system. For the indicators of the third group, the establishment of cause-and-effect mechanisms as discussed in the previous section would be helpful to evaluate whether they better reflect the anticipated risk as an indicator for the probability of a supply disruption or as an indicator for the vulnerability to such a disruption, and whether they provide useful information to fulfil the objective of the study.

3.2.1.3. Substitutability. As mentioned before, substitutability is included in most criticality assessments, either as an indicator for supply disruptions or as an indicator for vulnerability. In the EU method (European Commission, 2017a) the substitution parameter affects both the economic importance in terms of technical and cost performance of the available substitutes for individual applications, and the supply risk in terms of physical availability of a substitute, its criticality and the way it is produced, e.g. as a main product or a by- or co-product. The GE method (Duclos et al., 2010) integrates a measure of substitutability both in the evaluation of supply risk and of importance: high substitutability in the market decreases the probability for a supply disruption, while a low substitutability of a material in the technology that is important for the system under study makes the system highly vulnerable for a supply disruption. There does not seem to be agreement on whether the inclusion of substitutability in two criticality factors leads to double counting of this attribute – a risk that could be minimized if scoring would be communicated at an indicator level and results were not further aggregated.

Not all studies include substitutability in the initial assessment. Some (e.g. NEDO) aim to identify elements for which substitutes need to be found, which make substitution a potential mitigation strategy based on the outcome of the study. The EU explicitly distinguishes between currently available substitutes and potential substitution, and only includes the former in the study – recommending the latter for future research needs. This differentiation clearly marks the short-to-medium-term time frame in which supply risks are assessed in the EU method.

3.2.1.4. Environmental and social factors. Many of the criticality methods shown in Table 1 include environmental and/or social factors in their analysis. While there is overlap in the type of indicators that are used (such as human health, ecosystem quality, and biodiversity as assessed by the Life Cycle Impact Assessment method ReCiPe (Bach et al., 2017b; Graedel et al., 2012; Kolotzek et al., 2018)), the indicators seem to reflect different perspectives regarding the anticipated risks that may or may not be correlated to one another. The following perspectives have been identified in the reviewed methodologies:

- *Perspective 1: Environmental/social impacts as a source of supply risk* (e.g. European Commission, 2010): Environmental impacts cause a high or low probability of a supply disruption of a material due to potential regulations

- *Perspective 2: Vulnerability of the environment/social values to material use* (e.g. Graedel et al., 2012): The use of a material has a high or low impact on the environment
- *Perspective 3: Environmental/social risk* (e.g. proposed by Frenzel et al. (2017)): The disrupted availability of a material has a high or low impact on the environment or on social values
- *Perspective 4: Reputational risk* (e.g. ESSENZ): The use of a material with a high environmental or social impact affects the reputation of the company.

A discussion is provided in Section S4 of SI-D as to how these different perspectives are considered within the reviewed criticality assessments. Several method developers (e.g. EU and KIRAM/KITECH) highlight environmental and social issues as future research needs. An evaluation of the appropriate perspective(s) can be helpful for a potential integration of environmental and social factors into existing methods. As long as clear cause-and-effect mechanisms are not yet formulated on the influence of environmental and social implications on criticality, it is recommended to present environmental and social implications as a separate dimension for the identification and resolution of possible trade-offs.

3.2.1.5. The resilience concept. The previous sections demonstrate that a clear-cut separation of supply risk indicators, vulnerability indicators, or suggested mitigation options is not always applied nor straightforward in criticality evaluations. Dewulf et al. (2016) point out that most criticality assessments are backward-looking and that a more forward-looking approach could be a promising new perspective in criticality research, investigating how economies could respond to potential supply disruptions by responsive actions to improve supply chain resilience (see e.g. Mancheeri et al. (2018) and Sprecher et al. (2017)) – or, in other words, to decrease the supply chain vulnerability to supply disruptions. Recent studies have discussed barriers and enablers for mitigation strategies to enhance supply chain resilience on the company level (Gardner and Colwill, 2018; Griffin et al., 2019; Bustamante et al., 2017); some of them with an emphasis of circular economy strategies (Gaustad et al., 2018; Lapko et al., 2018). Further exploration of the resilience concept could provide more understanding in the cause-and-effect mechanisms between supply risks, vulnerability, and potential mitigation options and whether it is indeed useful to distinguish these three types of indicators.

3.2.2. Data availability

Fig. 2 illustrates that data availability influences the outcomes of materials criticality assessments in at least three different ways: by affecting the goal and scope of the assessment, the selection of the indicators, and the evaluation of the selected indicators. Whereas the first relationship was covered in Section 3.1.4, the latter relationships are further discussed in sections 3.2.2.2 and 3.2.2.3, following a review on data sources and their limitations.

3.2.2.1. Data sources and their limitations. Criticality methods use a wide range of data sources to identify and quantify the level of specific risks associated with their production or consumption, such as mining and smelting/refining statistics, indicators related to country-level sociopolitical factors, life-cycle inventory data to assess the environmental impacts of materials provisioning, recycling rates, industry reports, and expert judgment. Fig. 5 visualizes the data sources used in the criticality methods of Table 1.

According to Fig. 5, the major data providers are geological surveys (USGS, BGS, BRGM, BGR, etc.), the World Bank providing the Worldwide Governance Indicators (WGI), the Fraser Institute Annual Survey of Mining Companies reporting the Policy Perception Index (PPI) (Fraser Institute, 2019), scientific literature (i.e., peer-reviewed publications and technical reports), UNEP IRP data on recycling rates (UNEP, 2011), UNDP's Human Development Index (HDI), ecoinvent for environmental data, as well as a wide range of industry reports (e.g., Roskill) and expert opinions. Furthermore, each method uses unique data sources not widely shared among methods. For example, the Yale criticality method developed for corporations uses INSEAD's Global Innovation Index, while the Augsburg method uses the Social Hotspot Database and Granta's method uses material property data from Material Universe as well as company-specific information. Further examples can be deducted directly from Fig. 5.

Ideally, the criticality assessor has complete awareness of material

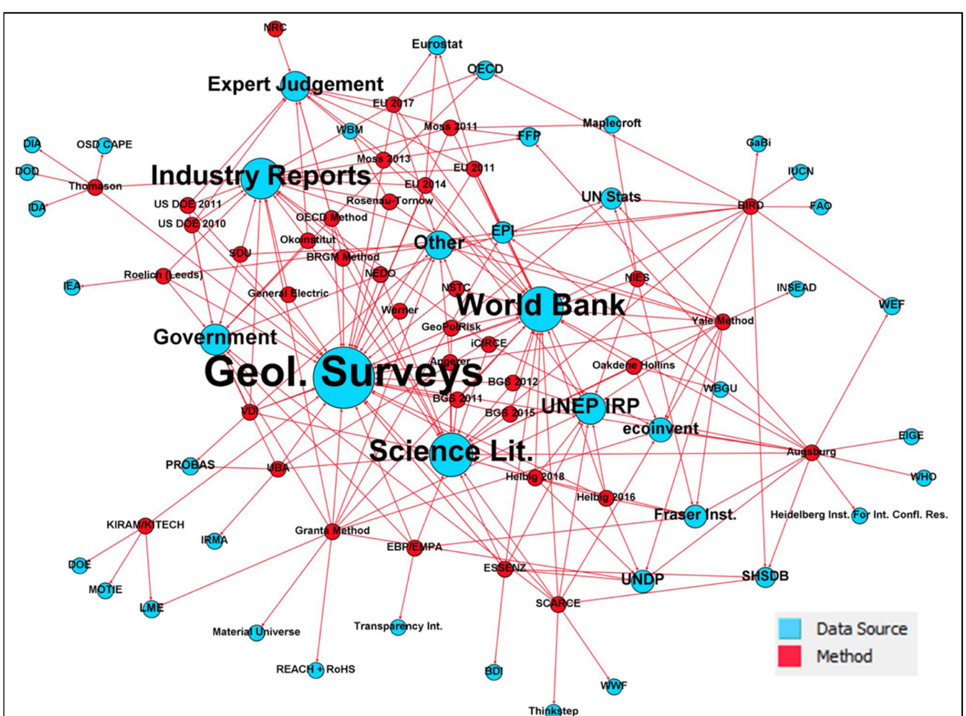

Fig. 5. Network visualization of data sources used by the 39 criticality methods examined in this study (China is excluded as data sources are unspecified). Blue nodes represent data sources, their size is shown proportional to the number of times a data source is being used. Red nodes represent the criticality methods assessed. More details are available in SI-B.

flows and added economic value at each link in the supply chain of all materials that are used within the system under study. However, data availability and data quality can vary significantly by raw material. Production and consumption data for major metals such as iron and aluminum tend to be widely researched and complete (Cullen et al., 2012; Liu et al., 2013; Liu and Müller, 2013b; Pauliuk et al., 2013), whereas data for many minor metals (e.g., germanium, indium, tellurium, europium, and scandium) are more difficult to obtain and more prone to variation and error. These data may exist but kept proprietary by industry. Examples include actual pricing and materials usage data – particularly for materials that are not traded on large open exchanges, but rather through direct contracts between the producer and the user – and materials embedded in products, such as rare earth magnets that might be incorporated into motor components that downstream users may not even recognize. Moreover, the proprietary data may also be dispersed among many different entities, so that no single entity has access to all the data. Hence, public data can be unavailable for specific indicators, specific materials or material grades, and specific points in a materials' supply chain.

3.2.2.2. Influence of data availability on indicator selection. Criticality is mostly considered to be a relative concept: one material is more or less critical than another. Therefore, ideally only materials and indicators are included in the assessment for which the same type and quality of data are available. This becomes a limiting factor in criticality assessments with very large scopes, such as the OECD study that includes 51 materials and assesses their economic importance for all countries within the OECD (Coulomb et al., 2015). In studies evaluating criticality over time, only materials and indicators are included of which data is available in time series. Data availability was explicitly considered for the operationalization of indicators in the studies of OECD, BGS, and the most recent assessment of the European Union. Examples of indicators for which data are lacking are provided in Section S5 in SI-D.

If data on a certain indicator are missing, a proxy indicator might be used, such as import data instead of production data (BGS, 2011). The probability of supply disruption and economic importance are based on very complex mechanisms that are difficult to measure. Instead of identifying and measuring all contributing factors, often an indicator is chosen that is directly related to economic impact (Frenzel et al., 2017). Examples of proxy indicators for substitutability and availability of reserves and by-product dependency are expected demand growth and price elasticities of supply, respectively (Moss et al., 2011). Several indicators could also be combined to more accurately represent the aspect of interest. For example, due to lacking available data for a large range of materials to accurately represent the supply of raw materials to the EU, the revised EU method uses a new indicator that combines global supply and actual supply to the EU (i.e. the mix of domestic production plus import) (Blengini et al., 2017a,b; European Commission, 2017c).

Proxies can also be useful to estimate future indicator values. The OECD study conducts the same assessment on two different points in time. For their assessment of 2015, the country concentration of production in 2030 is assessed by the estimation of global reserves using data from 2014. Hence, "global reserves" are used as a proxy for "global production in 2030". Habib and Wenzel (2016) use a similar approach to assess the country concentration of raw materials production in 2050. Ioannidou et al. (2019) recommend using more concrete indicators, such as estimations of population and material intensity, instead of a generic estimation of future demand, for dynamic assessments with respect to future trends and scenarios.

3.2.2.3. Influence of data availability on indicator scoring. The data that are available should be interpreted with care. Data collection and reporting of the physical stocks and flows of critical materials are often not done with the criticality context in mind. Data quality is affected by an inherent uncertainty, and routinely updated data contain frequently inherent errors resulting from the primary data reporting. Global production data e.g. differ between the USGS and BGS; thus the selection of the source or combining these sources will result in different risk evaluations. Many studies convert data ranges into a mean value, resulting in a loss of information on uncertainty on the way. Using data ranges for the criticality calculations also provides a range of criticality determinations. Such ranges can be calculated if the original data sources present uncertainty ranges as well. These are provided by, among others, the World Bank for the WGI. However, for most indicators, such uncertainty ranges are not provided, implying that the data point is an absolute, true value. This is overcome by Graedel et al. by calculating their own uncertainty ranges (Graedel et al., 2012).

Besides the inherent uncertainty of data, data should be evaluated regarding their representativeness for the technology, the specific material, the geographical area, and the time frame formulated in the goal and scope of the study. Data often represent current or historic situations, and should be updated regularly. Data from different sources, such as production and trade nomenclature, are usually not harmonized. This leads to inconsistencies that weaken the robustness of the monitoring of the physical material flows and the evaluation of raw material criticality. Extremely difficult to assess are trade statistics. Fig. 4 shows that such statistics (e.g. UN Stats and Eurostat) are used as input data for several assessments. The accuracy and reliability of these data directly impact the outcome of these studies. For example, most reports group minor producers into an 'Other' category. Treating this as one source, or a collection of many sources, will materially impact the degree of monopoly of supply that is indicated in the assessment. Furthermore, criticality of raw materials can vary for materials with different purity grades (e.g. pure metals, ingots, etc.), making it important that data sources differentiate between different material forms. For the trade of metal concentrates, it is challenging to find numbers about metal content and associated elements. The trade of complex products is even more difficult, and results of "objective, statistics-based" CRM assessments should be cross-checked by (industry) experts. However, even for experts, trade data are a complex puzzle that require much additional information and market knowledge. If the experts articulate serious doubts on how to interpret the data, the "objective" assessment should be carefully revised.

More examples on the evaluation of data uncertainty and representativeness are provided in section S5.2 of SI-D. Section S5.2 also presents how studies have dealt with lacking data, for example by attributing arbitrary scoring, using proxy data, or by additional data collection. In most reviewed criticality studies, data quality is not addressed in an explicit or quantitative manner. This could be further improved by adopting practices that have been implemented in other domains, such as LCA, where data quality indicators have been developed which can be used to calculate uncertainty ranges (Weidema et al., 2013; Weidema and Wesnæs, 1996).

3.3. Aggregation

In order to reach a final criticality outcome, different aggregation tasks can be performed: a) the aggregation of sub-indicators to composite single score indicators (e.g. the WGI, which contains 6 sub-indicators), b) the aggregation of various indicators (e.g. HHI and WGI) to a single score for a specific dimension (e.g. the probability of a supply disruption), c) the aggregation of different dimensions (e.g. probability of a supply disruption and vulnerability) to a raw-material-specific single-score criticality index, and d) the assessment of a single-score criticality index for a whole technology, consisting of multiple raw materials, which is performed by a few studies (Goddin, 2019; Helbig et al., 2018, 2016a). In Section S6 of SI-D it is discussed how criticality assessments apply different scaling and aggregation methods on each of these levels. Aggregation is necessarily related to loss of information and includes normative decisions. Therefore, it is recommended to display the disaggregated data and perform a sensitivity analysis.

3.4. Interpretation and communication of the results

Once the indicator scores are calculated and the required aggregation steps are done, the results must be interpreted and communicated. Firstly, the results should always be interpreted with the context of the study in mind. The results will only reflect the criticality of the evaluated materials for the specified system under study, and only the indicators that are included in the assessments will determine the criticality of the materials, which explains the dependency of the interpretation of the results – besides on the indicator scoring and aggregation – on the goal and scope in Fig. 2. Secondly, not only the method is tailored to capture and combine the elements of major interest, but also the way in which the results are communicated can be very stakeholder-specific, which influences further interpretation of the results by the intended audience. Further elaboration is made here on two main aspects of the communication of the results that is divergent in the reviewed studies: the level of aggregation and the use of a threshold value. Furthermore, it is discussed how the interpretation and communication of the results could merit from uncertainty and sensitivity analyses.

3.4.1. Level of aggregation

A main difference in the presentation of the results of different studies is the number of aggregation steps that are applied. Communication of criticality scoring per indicator provides the most detailed information and enables understanding of the sources of criticality (Hatayama and Tahara, 2015). Hotspot analyses on a material level might provide more information than the ranking of materials due to a low data availability and high data uncertainty (Speirs et al., 2013). Furthermore, understanding of the sources of risk enables to identify suitable mitigation strategies. Scoring of materials per indicator is provided by, among others, the EC in their background reports, by BRGM, Granta, Moss, and Yale. Furthermore, dynamic criticality studies can provide more detail on an indicator level by providing scores for different points in time (McCullough and Nassar, 2017). The presentation of indicator scores might be cumbersome if a lot of indicators are included in the assessment, or if a lot of materials are evaluated. However, it provides flexibility to the user to conduct tailored studies with the inclusion or exclusion of certain indicators, or with alternative weighting factors of the indicators.

Many studies present their results on the level of scoring per criticality dimension. Materials are often plotted in a 2D or 3D matrix in which the axes represent the probability of supply disruption, the vulnerability to this disruption (or importance of the material), and potentially a third axis, such as environmental importance in the Yale method.

Several methods end up with a single criticality parameter. This is the case for, among others, NEDO with the aggregated score (Hatayama and Tahara, 2015) and NSTC with a criticality potential score. Although the EC also presents a list of critical materials, no final numerical aggregation of the criticality dimensions is done in their study. The CRM are presented in rigorous alphabetical order to eliminate any references to relative criticality levels, which is a specific policy need (Blengini et al., 2017a,b). Frenzel et al. (2017) argue that, following classical risk theory, a single score could be obtained by multiplying an axis of "probability for supply disruption" with an axis of "vulnerability". In practice, however, most methods are not designed with this perspective in mind, making such a multiplication potentially erroneous.

Different forms of communication can be used by different audiences, i.e. reflecting different assessment objectives. Lists are practical for policymakers that oversee targeting public funding to mitigation programs. Lists can also be useful in early-warning screenings. For example, NSTC produced a list of potentially critical minerals for the US, to be followed by a second stage in-depth analysis. Hence, the initial list aids in prioritizing the materials that require further study. Studies that aim to inform different types of audiences can chose to communicate the results in different forms. For example, the EC provide single raw materials factsheets, with structured and detailed information and data, as a complement of the 2011, 2014 and 2017 lists of CRM for the EU. Raw materials factsheets show the data used in the assessment and bring further information and data that third parties might want to use in their ad hoc criticality studies. Detailed information is relevant for both suppliers and users of individual raw materials, as such information can be used to better assess individual risks.

3.4.2. Use of a threshold value

An important element in the presentation of criticality results is the concept of a "critical" vs a "non-critical" raw material, based on which a list of CRM can be drawn (European Commission, 2017a, 2014b, 2010; US Department of Interior, 2018). The scientific community is generally less favorable to the adoption of a sharp criticality threshold value and more inclined to qualitative or quantitative levels of criticality (ideally with the recognition of uncertainty ranges) (Graedel et al., 2012; Hatayama and Tahara, 2015; Kolotzek et al., 2018; NRC, 2008), as this highlights that criticality is not an absolute status, but rather a relative condition. In contrast, policymakers have historically shown a preference for sharp and simpler communication solutions (European Commission, 2017a, 2014b, 2010; Lee, 2014), which are easier to understand for non-experts and more practical to translate into effective policy actions at large scale. The determination of the threshold value is not a scientific exercise but can be motivated politically, such as comparability with previous studies or the designation of a specific number or share of the evaluated materials as "critical".

3.4.3. Uncertainty and sensitivity analyses

As shown in the previous sections, criticality assessments are unavoidably affected by many uncertainties and methodological choices, e.g. regarding the acceptable quality of the data, the selection of materials, the choice of data sources, and the choice of aggregation methods. The robustness of the criticality results is strongly dependent on the transparent communication of (the effect of) uncertainties and assumptions. For example, Helbig et al. (2016a) evaluate the influence of aggregation methods on the final outcomes via a sensitivity analysis and conduct uncertainty analyses. Graedel et al. (2015) present the relative criticality of each material in the form of a "criticality cloud" that accounts for uncertainty ranges. As very few methods report uncertainty ranges of the criticality results, it is not known whether the assignment of materials as "critical" is generally robust, especially in studies that apply criticality threshold values.

4. Conclusions and perspectives

After more than a decade of 21st century raw material criticality assessments, conducted by scientists and governmental institutes, the question *"Which materials are critical?"* has not provided an unambiguous response, even if one has a specific nation or industry in mind. Materials such as chromium, cobalt, gallium, lithium, molybdenum, tantalum, tellurium, and vanadium have very diverging criticality determinations: in some studies they appear to be highly critical, while in other studies they are considered to be not critical at all. This paper seeks to clarify which contextual factors and choices affect the outcomes of criticality assessments. The IRTC team demonstrated that there are diverging views on what criticality is about. Some studies are concerned with the criticality of raw materials for national defense or a national economy, while others focus on specific technologies, companies, or products. Most studies anticipate a disruption in the supply of raw materials, either due to unstable supply routes, or due to sudden increases in demand, for example caused by the relevance of a material for emerging technologies. The assessments often aim to provide recommendations regarding criticality mitigation or the need for a better understanding of the supply chains of prioritized materials. Studies mostly cover a large range of materials in their assessment: including most metals or as many elements from the periodic table as possible – however focusing often solely at the mining stage.

These differences in goal and scope of criticality studies can partly explain the different outcomes – but not entirely. Some indicators appear very frequently to assess the probability of supply disruption or the vulnerability to supply disruption, such as the country concentration of production, political stability of supplying countries, by-product dependency, and the use of a material in a technology that contributes to a company's revenue or a country's economy. Studies with seemingly similar goals and scopes do not, however, always select the same indicators. This is largely dependent on the anticipated events that could affect raw material supply. A clear mechanism between the selected indicators and a resulting supply risk, for example in the form of a cause-and-effect diagram, is often missing, resulting in diverging selections of (proxy) indicators.

Data availability is also a key factor that influences the design of criticality methods. Study composers do not necessarily have access to the same data sources, as this is influenced by, among others, the required transparency, the perception of objectivity, and ease of access, which are often limiting factors in governmental assessments. Data availability influences the selection of indicators and the inclusion of materials in the assessment, as well as the accuracy of the results. There are important data gaps on specialty elements and materials that are frequently produced as by-products. Data sources often do not differentiate between different material grades or forms, although these can have important differences in supply. Also, data on intermediate products is lacking, which explains why most studies evaluate material supply primarily at the level of mines. Remaining differences in criticality determinations could be ascribed to different aggregation procedures and the formulation of a criticality threshold value, which is especially useful in the communication of the results to policymakers.

During the course of the IRTC expert discussion, the potential value of criticality concepts taking a more holistic approach on sustainable development throughout the whole material value chain came up repeatedly. These reflections go beyond the scope of this review paper but will be investigated in more detail in upcoming publications of the project.

From this paper we can extract several lessons that could contribute to the future development and implementation of criticality assessments. A clear description of the goal and scope, including a description of the anticipated risks that are considered within the study will help the readers of a study to evaluate whether a study fits their perception on criticality and to identify which studies are comparable. Researchers should develop an increased understanding of the cause-and-effect mechanisms that link anticipated risk factors to concrete indicators, possibly with the application of the resilience concept. This could also aid in developing aggregation methods that contribute to a meaningful determination of risk. Furthermore, it would be interesting to evaluate whether risk scenarios exist that are currently underrepresented by criticality assessments, such as the risks of negative demand changes (i.e. demand drops). Communication on critical raw materials should be more transparent regarding the used methodology, data sources, and uncertainty ranges, especially when criticality determinations have consequences on public decision-making.

Increased understanding on the relevance of indicators for different goals and scopes can stimulate more efficient data collection. With judicious assumptions, it might for some cases be possible to establish order-of-magnitude estimates. While this is not as rigorous as a validated model with full data access, these types of analyses can be used in an initial round of screening to create the basis for further investigation. The results of our study also highlight the value of expert judgment both as a source of data as well as in interpreting publicly available data sources. Further efforts should be put in the identification of best practices regarding data sources, (proxy) indicator selection, aggregation methods, and presentation and communication formats. In this regard, the rise of machine learning and big data offers an interesting opportunity, as this information might allow criticality assessments to become more dynamic and comprehensive. Recent advances in data science may also offer new ways to collect data, e.g. the concept of differential privacy is gaining traction among business users to share information while maintaining a degree of privacy. This area merits further exploration for the enhancement of criticality assessments.

Stakeholders interested in the evaluation of raw material criticality would further benefit from the availability of clear guidance in the formulation of their goals and scopes, the selection of potentially useful indicators and aggregation methods, and the interpretation of the outcomes. Such guidance could be a first step in improving the quality of criticality assessments, and fostering more standardized approaches.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2019.104617.

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