Selecting and prioritizing material resources by criticality assessments

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SUMMARY

Material resources each face different levels of risks in terms of supply disruption, vulnerability, and environmental and social impacts. Countries and companies apply criticality assessments to select or prioritize material resources requiring attention and measures to mitigate their associated supply risks. This Primer gives an overview of typical use cases and frequently used indicators in the criticality dimensions supply risk, vulnerability, and social and environmental aspects. We illustrate the basics of criticality assessments by the examples of copper and indium. We also provide practical guidance in conducting a criticality assessment. It is good practice to follow four steps to enable a coherent evaluation: defining the goal and scope, selecting and evaluating indicators, selecting an aggregation approach, and interpreting and communicating the results.

INTRODUCTION

Critical material resources are more than just Rare Earths or Conflict Minerals. The concept of criticality is also not limited to those resources on official "criticality lists," such as, for example, the Critical Raw Materials (CRMs) list by the European Commission or the Critical Minerals list by the United States Geological Survey. The COVID-19 pandemic has painfully reminded us that supply chains are vulnerable and that even physical supply shortages are very well possible. For every material resource, some criticality criterion is fulfilled, and therefore one can say that there is some degree of criticality for every material resource.

Carrying out a criticality assessment is a prerequisite for determining the degree of criticality of any specific material resource. There are various possible goals and scopes, system boundaries, and detail levels that can be applied for this purpose. One could undertake a company-level assessment of potential price risks, looking at all the company's raw materials and starting this process with a screening study to identify those raw materials that need more detailed analysis. Another study could focus on all material resources used by, for example, clean energy technologies, specifying all possible factors that could lead to physical shortages due to a forecasted increase in demand. Understanding this variety and recognizing the non-exclusiveness of the criticality concept helps to comprehend why different actors, from the national level to the company level, come up with different conclusions on which material resources are critical. This diversity is also displayed in terminological differences. Very often, the differences in labeling the assessment itself, the assessed resources, or the identified critical resources are nuances rather than conceptual discrepancies. For example, the label critical raw materials may highlight that the assessment also considers biomass or petrochemicals next to metals and mineral resources that are most commonly evaluated.

Within this Primer, we will call these assessments criticality assessments, which assess any material resource to identify CRMs. We first show typical applications of criticality assessments, starting with the goal and scope definition. The extensive list of criticality indicators is discussed in the section on criticality dimensions, including the main aspects "supply risks" and "vulnerability," and less frequently used dimensions, such as social and environmental aspects. Selected typical results of such criticality aspects are briefly discussed using the two metals, copper and indium. We further illustrate good practices in criticality assessments via step-by-step guidance, represented by the hypothetical question "Are copper and indium critical for a specific small European manufacturing company?"

APPLICATIONS OF CRITICALITY ASSESSMENTS

Is indium a CRM? What about copper? There is no unified list of CRMs. Each study on CRMs has been conducted with a specific "Goal and Scope" in mind. The National Research Council, which formulated a criticality assessment method in 2008 that inspired the design of other methods since, evaluated the criticality of material resources for the United States economy. In 2010, the European Commission developed a methodology leading to a list of raw materials critical to the European economy, which is updated regularly. Many other national assessments have been conducted, for example, for the Dutch, French, Japanese, Korean, Indian, or Brazilian economies. However, a criticality assessment does not necessarily have to focus on a national economy. A material resource can be identified as critical for a specific sector or technology, such as renewable energy, electric mobility, or defense, a particular company, as performed by Apple or General Electric, or even for a single product's value chain. Material resources could even be identified as critical for a larger societal goal, such as global sustainable development. Therefore, when talking about CRMs, it must always be clear for which actor, or for what system, a material is considered critical.

Many criticality studies are conducted with the initial purpose of raising awareness of potential issues in material supply chains. Materials identified as critical can accordingly be prioritized for continuous monitoring. Other studies can be classified as screening studies. Such studies evaluate a material with regard to a small number of indicators, e.g., the concentration of production, price volatility, and production growth, potentially considering the evaluation of the indicator performance over time. Materials with indicator scores that raise concern could be subject to a more in-depth follow-up criticality assessment that evaluates many additional supply chain aspects, such as the material's substitutability, recyclability, use in emerging technologies, or recent investments in exploration. Regardless of the approach, the ultimate purpose of assessing which materials are critical is to mitigate supply risks and create stable, resilient supply chains.

Supply risk mitigation can take several forms. Results of criticality assessment studies conducted by governments have led to investment in public research and development programs aiming for resource efficiency, substitute development, or circularity strategies. For example, numerous research programs have been funded in the past decade to manage, recycle, and substitute Rare Earth Elements in products, such as magnets and lighting. Governments furthermore contribute to a secure supply of raw materials via the establishment of stable trade relationships and national policy frameworks that favor exploration, development of national mining activities, and investments in recycling technologies and infrastructure. Companies can take a pro-active role in mitigating criticality by considering supply risk indicators already during the product design phase. Investments in private R&D can enhance the recyclability or substitutability of raw materials. Other strategies, such as stockpiling, vertical integration, hedging, supplier diversification, or involvement in sustainable certification programs, can secure a specific company's stable supply of materials and products. Often, multiple mitigation strategies need to be applied in parallel, as these strategies can be effective against different types of risks, to different kinds of economic actors, or on different time scales.

CRITICALITY DIMENSIONS

Most criticality assessments consider aspects in the two dimensions describing the supply risk of a material resource and the system's vulnerability to a supply disruption of this resource. The basic idea behind these two dimensions is to separate indicators on the likelihood of a supply disruption from indicators on the severity of such a supply disruption. There are, however, also methods that consider aspects of social implications or environmental impacts as essential factors for criticality assessments. Each of the dimensions has its own set of criticality aspects considered in quantifiable indicators. Figure 1 provides an overview of frequently used indicators for supply risk and vulnerability assessments identified by an author group of the International Round Table on Materials Criticality.

Supply risk

Within the assessment of supply risks, all aspects are collected that give rise to concern for a mismatch between supply and demand for a specific material resource. Such a disruption may occur for various reasons and, therefore, this dimension may include many different indicators.

For example, supply may be limited due to physical scarcity or a lack of exploration, often expressed by indicators, such as the ratio between primary production rate and reserve volume. Although often called "depletion time," this ratio does not precisely measure physical depletion but instead provides information on the urgency of further exploration of resources.

Supply may also be limited due to sudden disruptions in the market caused by single countries, companies, or production facilities. For example, a government may decide to restrict exports and thereby cut the global market off from its country's production volume. A company may file for bankruptcy, and a mine may be affected by an accident, natural disaster, or strikes. In any such cases, the higher the market concentration, the more prone the global market is to supply disruptions. This concentration is, therefore, a crucial indicator in most criticality assessments. Many assessments additionally rate the market participants, in particular countries, concerning their reliability. Supply is potentially at risk if mining or processing happens in conflict regions or regions that are likely to impose strict regulation concerning trade or mining operations. Countries that do not have domestic material resources and mostly depend on their import are especially concerned about relying on only a few unstable suppliers.

Supply reliability is essential for material resources that are difficult to substitute or for which a rapidly growing demand is expected. A limiting factor for many resources' primary production is the predominant occurrence as a by-product of mining activities mainly targeted at another mineral. Compared with this "host mineral," such by-products generate a low economic value. Therefore, even if the by-product price increases, its supply may not increase, contradicting common market mechanisms. If the primary production of a raw material is disrupted, some materials still have anthropogenic resources available. For others, however, the recycling rates are insignificant, and supply entirely depends on primary production.

Vulnerability

The purpose of vulnerability assessments is to estimate the possible impact of a supply disruption. In principle, the higher the vulnerability from a material resource, the more damage would be caused by a supply disruption. Vulnerability assessments depend much more on the goal and scope definition of each criticality assessment than supply risk assessments because the definition of damage caused depends on the system boundary.

One central question often asked in vulnerability assessments concerns the availability and performance of substitute materials. If there is a next-best solution for the material's specific

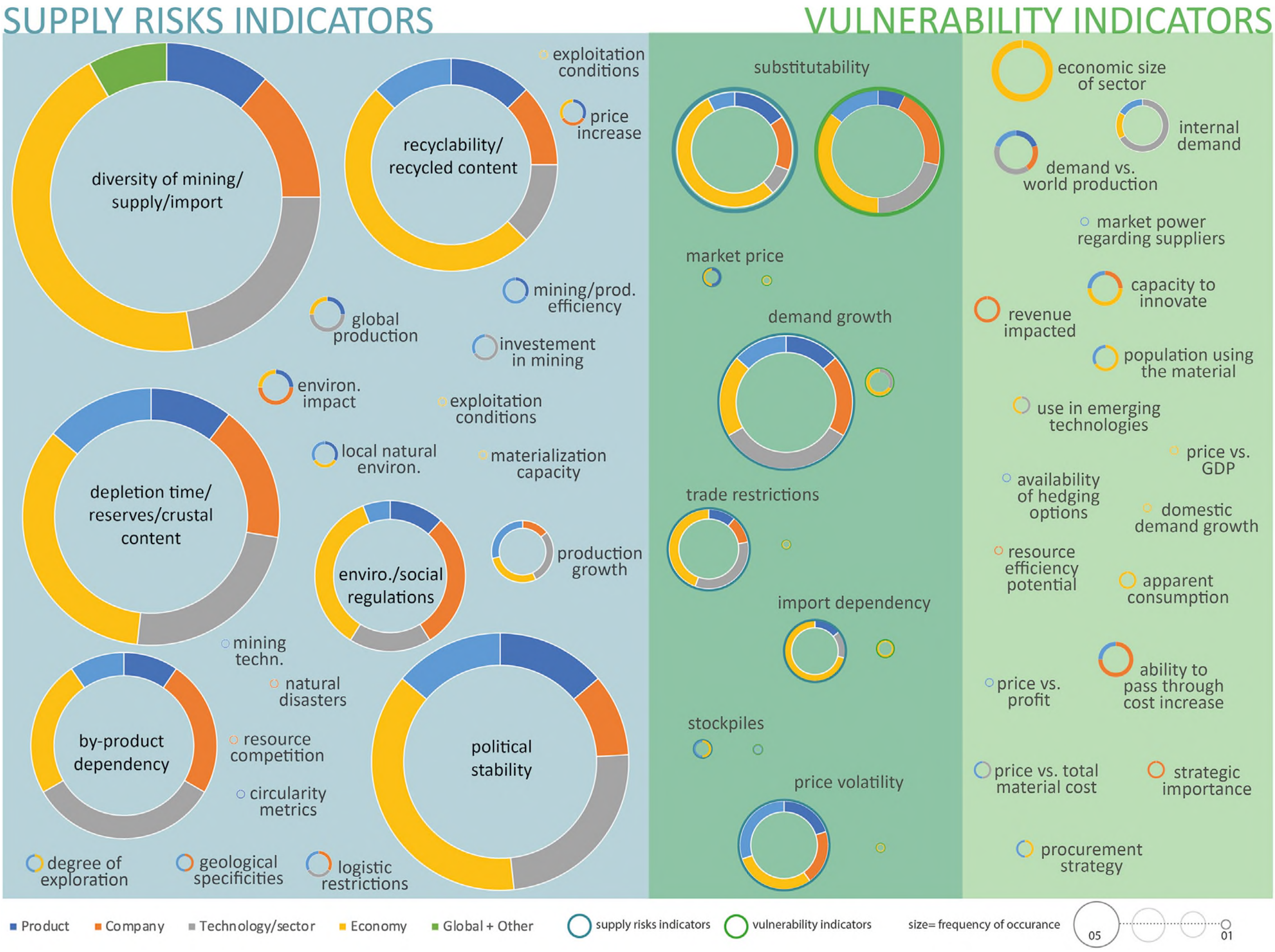

Figure 1. Supply risk and vulnerability indicators
Indicators for the probability of supply disruption and the vulnerability to a supply disruption, their frequency of use, and the scope in which they are used. Reproduced with permission from Schrijvers et al. (2020b).

application, this limits the possible damage caused by any supply disruption. Being able to innovate quickly in new market environments will also limit the damage caused by unforeseen events.

Very often, vulnerability assessments also estimate the potential damage caused by the disrupted supply of a material resource, for example, by quantifying the revenue of products or the value added by economic sectors dependent on the material. This perspective considers physical shortages, in which case the products using these materials could no longer be provided.

In contrast, vulnerability assessments can also estimate the damage caused by market factors: through higher prices, through the inability to pass on cost increases to the customer, which makes the production activity less profitable, or by merely evaluating how important a business is to the total market in terms of demand share.

Social and environmental aspects

Besides economic damage, other sustainability aspects are also used as criticality factors and dimensions. These mainly concern the social implications and environmental impacts caused in the raw material value chain. Many of these are linked to reputational or regulatory risks and are sometimes integrated into the supply risk dimension. Some criticality studies, however, incorporate social and environmental impacts as a separate dimension.

Regarding possible social implications, local communities may be harmed by mining or refining operations. In addition, mining, processing, and production of raw materials might be associated with inhumane labor conditions, such as child labor or forced labor. In extreme cases, such as the "conflict minerals," raw material mining can fuel violence and even civil wars. Also, societal aspects, such as corruption, may need to be considered.

When it comes to environmental impacts, not only general implications of mining and processing operations toward ecosystem quality or greenhouse gas emissions occur, but also environmental impacts directly affecting workers and local communities, such as pollution of soil and air affecting human health, or water scarcity and contamination. Such environmental information could be provided by Life Cycle Assessment

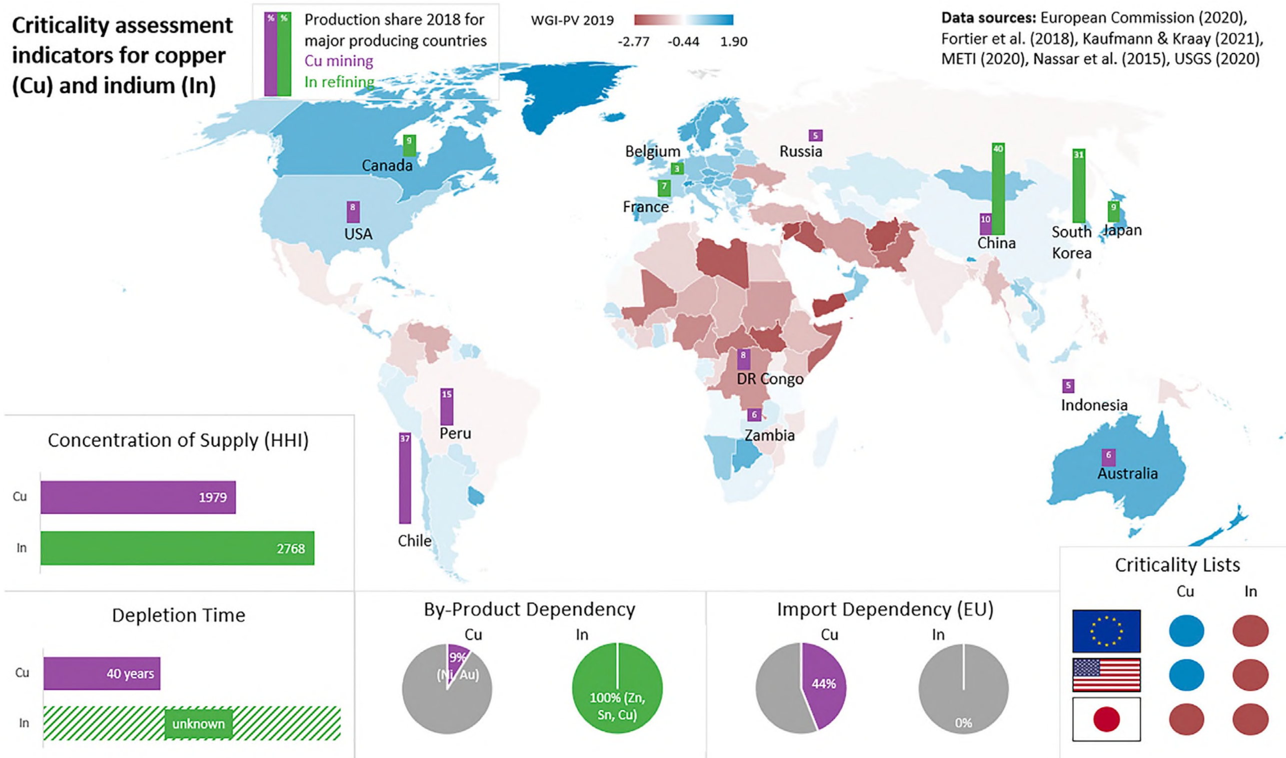

Figure 2. Selected criticality aspects of copper and indium
Global production shares for copper (Cu) mining and indium (In) refining in 2018. Only country production shares of at least 2% are displayed. Countries are colored based on their score in the Worldwide Governance Indicators in the category Political Stability and Absence of Violence (WGI-PV), where lower values are considered critical. The Herfindahl-Hirschman Index gives the production concentration. Reserves-to-Production Ratio calculated from reserves volume and annual production rate in years. By-Product Dependence shows the production share from other metal mining. Import Reliance for the European Union. Results for criticality lists are for 2020 for European Union and Japan and for 2018 for the USA. Data from European Commission (2020), Fortier et al. (2018), Kaufmann and Kraay (2021), METI (2020), Nassar et al. (2015), and United States Geological Survey (2020).

(LCA)—as LCA is a standardized methodology to evaluate products' environmental impacts throughout their value chains, including extraction, manufacturing, use, and disposal or recycling, and covers a broad range of environmental problems.

CRITICALITY ASPECTS OF COPPER AND INDIUM

Copper and indium are two examples of potentially critical metals. Copper is contained, for example, in electric and electronic equipment as well as brass. The most important indium use is the transparent, conducting indium tin oxide, used in flat screens and touch screens, and some solar panels. Both the European Commission and the United States Geological Survey have identified indium as a CRM and copper as a non-CRM for the economies of Europe and the United States, respectively. Does that mean that indium is also critical for a hypothetical European manufacturing company and copper not? Whether the company is vulnerable to supply disruptions of copper and indium depends strongly on the specific manufactured products. If electric and electronic equipment, brass, or photovoltaics are essential for the company, copper and indium are potential CRMs. In contrast, a company active in the steel or aluminum industry might not consider these elements potentially critical. Hence, the definition and assessment of material criticality can vary significantly in different contexts, highlighting the "case-dependency" feature of criticality assessment.

Figure 2 illustrates the evaluation of a few selected criticality indicators for both copper and indium: diversity of supply, political stability of supplying countries, depletion time, by-product dependency, and import dependency. The majority of copper is mined in Chile and Peru, while China and South Korea refine the majority of indium. Overall, the indium market shows a higher country concentration—measured using the Herfindahl-Hirschman Index—than copper. Parts of the copper production happen in countries with very low (Democratic Republic of Congo) or low (Peru, Russia) estimates for political stability and absence of violence. In contrast, all of the major producing countries for indium are politically stable. The estimated reserve volume of copper is 40 times the annual production. Such a ratio cannot be calculated for indium because indium reserves are not reliably quantified, highlighting that criticality sometimes needs to be assessed under consideration of significant data gaps or uncertainties. Copper is mainly mined as the main product, with only small quantities coming as by-products from nickel or gold mines. Indium, however, is primarily a by-product of zinc, as well as of tin and copper. Therefore, the extractable amount of indium is limited by the global mining of those host metals.

If we consider a manufacturing company in Europe, the dependency on supply from outside of the European Union may be interesting. Because important secondary copper smelters and indium refiners operate within the EU, more than half of the European copper demand and the indium demand can be met with EU production. Whether copper and indium are finally considered critical or not depends not only on the specific geographical area in which the company under study is active but also on the selection of indicators—of course, this selection of considered indicators can be extended significantly—and the combination of these indicators into a final criticality evaluation, which might include different weighing factors.

PRACTICAL GUIDANCE AND GOOD PRACTICES

Criticality assessments do not follow a standardized approach. However, applying the following steps in an assessment enables a coherent evaluation in line with the objectives of the study commissioner: (1) the definition of the goal and scope of the study, (2) the selection and evaluation of indicators, (3) the aggregation of indicators, and (4) interpretation and communication of the results. These steps, along with examples of typical methodological choices, are depicted in Figure 3. Understanding these steps helps in interpreting the results of other criticality assessments, judging the comparability of results of different studies, and evaluating the suitability of results for a specific application.

Define the goal and scope

Imagine a small manufacturing company operating in Europe that wishes to evaluate its exposure to material risks. The European company might not be exposed to the same risks as a company in the USA or another European company operating in another sector or another step within the value chain. Therefore, the study results will be specific to this company. The use of materials can entail different types of risk. There is the risk that the company suddenly does not have access to the material or product in question anymore—which became a reality with various products during the COVID-19 pandemic. Other types of risks are a strong fluctuation of prices or potential reputation damage due to the use of certain materials, such as conflict minerals or materials associated with high environmental impacts. Distinguishing these risk types is essential to select criticality indicators for the assessment and target-relevant mitigation strategies.

Presumably, the company is interested in evaluating supply risks across its whole product portfolio. In that case, all products, components, and materials used, and potentially also those produced by this company, should be included in the assessment. A company's access to materials and products could be affected by disruption at any point in their value chain, from the refining stage down to a disruption experienced by their first-tier supplier. A comprehensive assessment of all possible risks hence requires full transparency of the value chain. Due to the complexity of most value chains, such detail is often missing. The level of detail can be improved by focusing on the disrupted access of a selection of metals that are used by the company, including, for example, indium and copper, at the extraction stage. Let us consider that the company that we have in mind does not yet have a full overview of its value chain and is unaware of potential supply bottlenecks. It can be worthwhile for this company to conduct a quick screening study that enables to select materials that merit a more in-depth evaluation at a later stage.

Select and evaluate indicators

The next step in the criticality assessment of our fictional European manufacturer is selecting and evaluating indicators. Among the broad number of indicators that have been used in past criticality assessments, only the indicators that effectively reflect the type of risk that the company gave priority in the goal and scope of their assessment (e.g., physical accessibility problems) should be included in the study. As demonstrated by Figure 1, the diversity of supply—often used in combination with the political stability of supplying countries—is a commonly used predictor of potential accessibility problems. The availability of public and up-to-date data for many metals at the extraction stage makes this indicator suitable for a screening assessment by a small company with limited resources to invest in data collection.

Define an aggregation approach

Once the indicators are evaluated for each material, an aggregation procedure must be applied in most criticality studies to combine multiple indicators into a final criticality score. Both the level of aggregation required in the assessment and the need for a threshold value indicating which materials are critical and not depend on the result the assessor aims to obtain. For example, in the small European manufacturer's screening study, it is useful to state that "indium merits a more in-depth analysis, but this is not required for copper." Such a list of CRMs is generally the outcome of studies that aim to undertake action based on the results: for which materials do we need to find substitutes? Of which materials should we increase our stockpiles? However, an improved understanding of criticality hotspots in material value chains is obtained by a communication of the unaggregated results—as this reveals why certain materials might be subject to a supply disruption and others not. Studies apply different aggregation strategies, such as the multiplication of indicator values, calculating the weighted average, or merely selecting the indicator value with the highest score (the "bottleneck approach"). The relationship between the indicators should be considered while choosing the aggregation method, as some indicators might correlate, or reinforce or mitigate one another.

Interpret and communicate the results

Once the list of CRMs is created, it is essential to interpret the study's outcome—especially if the results are used to inform on further action, such as investment decisions. One could be made aware of the sensitivity of the results (e.g., the conclusion "indium is critical, and copper is not") to methodological choices, such as the inclusion or exclusion of indicators, the application of the aggregation procedure, or the definition of the threshold value. Furthermore, data uncertainty should be acknowledged. If the data used in evaluating the indicators are not perfectly representative of the material under study, or if different sources provide different data points, the final

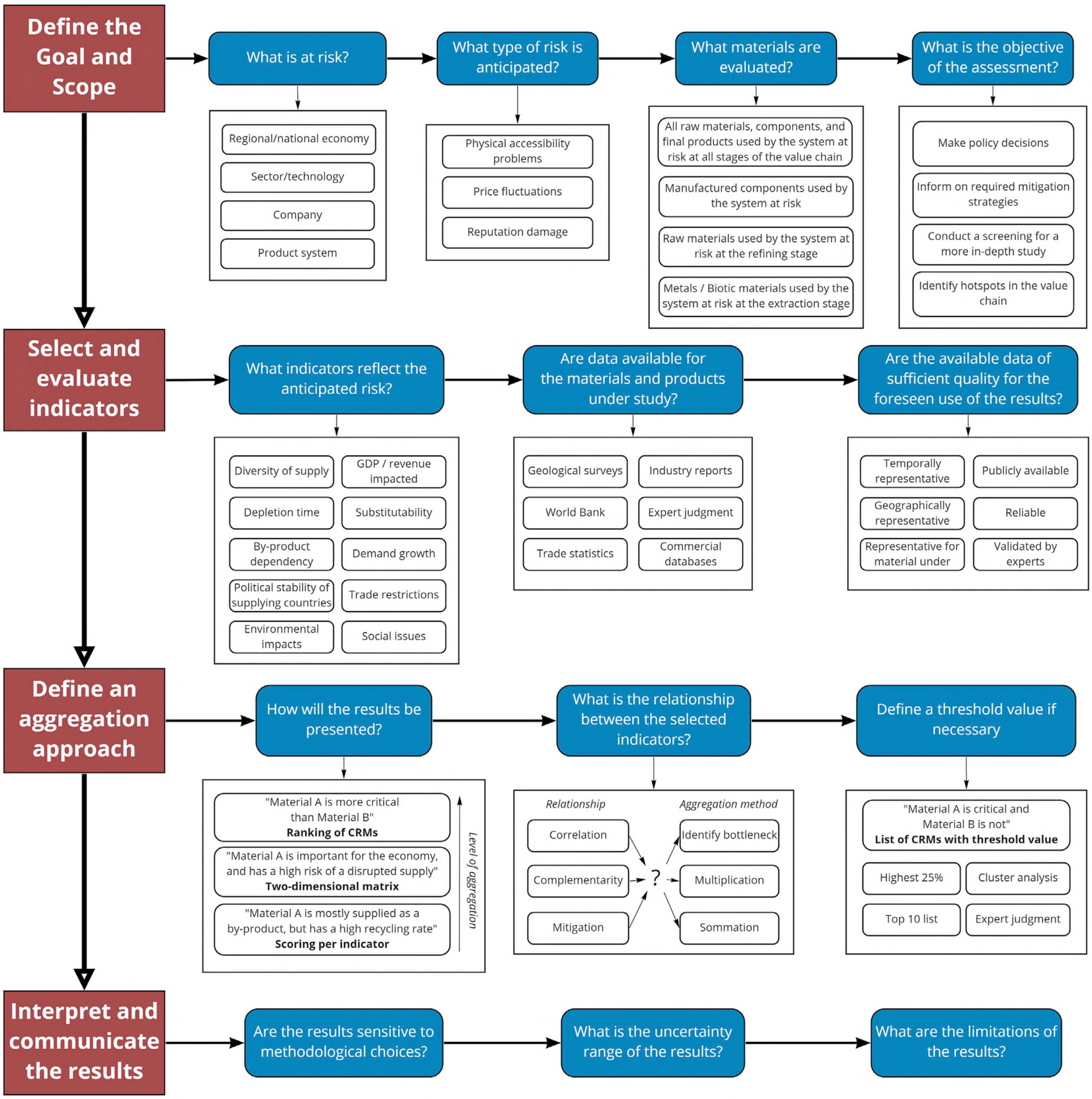

Figure 3. Step-by-step guidance for the design and communication of a criticality assessment

The different steps in the development of a criticality assessment from (1) goal and scope, (2) indicator selection and evaluation, and (3) aggregation to (4) interpretation and communication are illustrated by examples of methodological choices.

criticality scoring could be accompanied by uncertainty ranges. Such an uncertainty range might show that there is a possibility that, in the criticality study of the European company, the uncertainty range of copper reaches the criticality threshold value established by the company and becomes critical after all. Finally, clear communication of the limitations of the results, for example, regarding the exclusion of materials or important indicators due to a lack of available data, or the temporal validity of the results considering rapid developments of technologies and the material's markets, enables to put the results into perspective and inform the need for continuous monitoring or additional analyses.

GOING FORWARD WITH CRITICALITY ASSESSMENTS

Next to a consistent goal, scope, and method, criticality assessments rely on a large amount of secondary data and their quality. The assessment quality also depends on the availability, comprehensiveness, and update frequency of these datasets. For example, the latest comprehensive review on global metal recycling rates was published about a decade ago and, so far, no update is expected. But even if the data are regularly updated, there needs to be more information and transparency on the cause-effect chains for each of the criticality indicators alongside more research on empirical evidence for their impact.

Addressing criticality does not stop with the assessment itself. The assessment is only the essential step toward identifying, communicating, and eventually managing the various risks associated with CRMs. Companies and countries alike can mitigate the damage of supply disruptions and increase their sustainability by extending the scope of criticality assessments and increasing the resilience of their corporate supply chains and national economies.

Today, another essential topic is integrating social and environmental impacts into the notion of "criticality," as touched upon in this Primer. Assessing how the local population is affected by water from saline lakes for lithium production or ensuring safe, healthy, and ethical working conditions for cobalt mining without child labor are just two examples of prominently discussed issues. Governments and companies are becoming more and more aware of citizens' and consumers' expectations toward a responsible winning and sustainable use of resources. Striving toward attaining the Sustainable Development Goals is a goal in itself by industries and nations. How to best include these less-used dimensions in an approach that is still mostly an economic risk evaluation (cf. Figure 1) will undoubtedly be a matter of ongoing research and debate.

Finally, as more and more regions of the world are coming forward with their methodologies for assessing their exposure to criticality—including countries that traditionally represent the supply side, with an accordingly different focus on where possible risks could emerge—the need for international exchange becomes more important. As discussed in this Primer, the aim should not be to establish uniform methodologies since the goals, scopes, and focal points of different stakeholders differ in many ways. However, to avoid possible resource bottlenecks that could impede global sustainable development, international exchange and collaboration are indispensable.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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