UNDERSTANDING THE METHODOLOGY BEHIND THE EU LIST OF CRITICAL RAW MATERIALS

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This working papers aims to unravel the methodology for the determination of Critical Raw Materials for the EU first at a very high level – allowing for a quick and general understanding of the approach – and then in more depth, examining the data and equations behind the well-known 2D criticality matrix. Special emphasis is placed on the chain "intention" (what should be measured) → "decision" (how to measure or approximate it) → "effect" (how this affects the scoring results).

Introduction

The term "critical" is both intuitive and misleading, as can be the definition of lists of Critical Raw Materials (CRM). Different methodological approaches have emerged to assess the criticality of selected raw materials in different contexts and with different focuses (Schrijvers et al. 2020). Among these, the methodology for defining Critical Raw Materials for the EU is without a doubt one of the most relevant worldwide, and has had visible influence on EU policy (European Commission 2011, 2014b, 2017a, 2020a), in particular on research and development funding including large initiatives such as the establishment of the EIT RawMaterials (https://eitrawmaterials.eu/). With the recent proposal and rapid progress on a CRM Act (European Commission 2023b), understanding the method and data behind the European definition of a "critical raw material" has become even more important.

This Working Paper aims to provide an introduction to the EU CRM methodology in order to allow newcomers to the criticality debate to quickly and effectively grasp the intention and mechanisms behind the EU list of Critical Raw Materials. The following is structured in two levels. The first level provides a concise overview of what the current methodology for defining Critical Raw Materials does. The second level dives deeper into the data and equations behind the current list of Critical Raw Materials, to examine the influence of individual factors on the results and the effort related to obtaining and maintaining such data.

The idea behind the methodology

The original version of the list was based on a transparent and quantitative methodology covering a long list of candidate raw materials, and profited from the broad participation and input from governments, research and industry (European Commission 2010). Some key features of that methodology, such as the use of the Herfindahl-Hirschman-Index to measure supply concentration and the World Governance Indicators (World Bank 2018) to account for political factors, have become a quasi-standard approach in criticality methodologies (cf. Schrijvers et al. 2020). Refinements to the methodology were proposed (e.g., Blengini et al. 2017a; European Commission 2014a) and implemented, leading to the current version of the methodology and list of Critical Raw Materials for the EU (European Commission 2017b, 2020b).

Methodologies for assessing Critical Raw Materials have, in principle, (at least) two axes: one related to the likelihood of supply shortages and one related to the impact of a supply shortage (Tercero Espinoza 2013). In the EU methodology, these two dimensions are called "supply risk" (likelihood) and "economic importance" (impact), as shown in Figure 1. Criticality methodologies are, therefore, related to classical risk assessment (Glöser et al. 2015), for which there is a clear mathematical basis.[1]

The key difficulty in implementing this concept for the case of Critical Raw Materials is the data. Data to analyse the likelihood of events such as car crashes and their monetary

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[1] Some methodologies only focus on the risk axis. In these cases, the second axis is implicit in the scope. For example, the German Raw Materials List (DERA 2021) implicitly takes all raw materials used by the German economy as "sufficiently important".

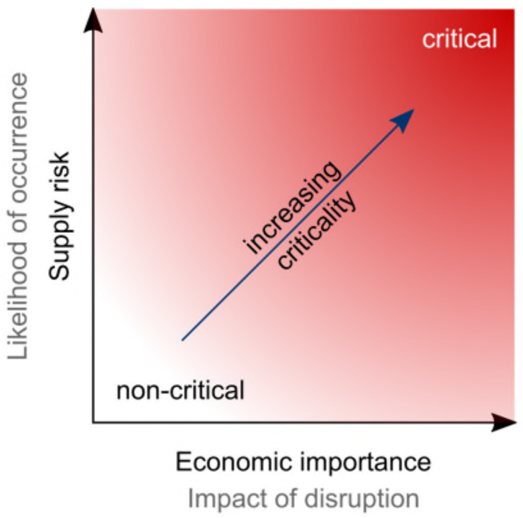

Figure 1: Dimensions of the EU criticality methodology.

costs, resulting in appropriate insurance premiums, is readily available. However, large disruptions to the supply of metals and minerals are fortunately rare events – so that data is also rare – and unfortunately very heterogeneous in their causes, encumbering their analysis (Hatayama & Tahara 2018). This is not sufficient when the goal is to compare many raw materials on a fair basis. Therefore, the implementation of a quantitative criticality methodology requires devising transparent, plausible mechanisms relating available data to the likelihood of occurrence of a supply shortage and to the expected impact of such a shortage.

The key idea behind the "supply risk" dimension of the EU methodology is that reliance on a dominant provider or small number of providers is inherently riskier than sourcing from a diversified supplier base. Factors such as governance in the producing countries, the degree of import reliance, trade restrictions, the availability of substitutes and the supply from recycling modify the scoring. Yet the central element remains the existence of monopolistic or oligopolistic supply structures.

The key idea behind the "economic importance" dimension is that the value of the raw materials to the European economy is tied to the products they enable rather than their tonnage or price. Therefore, the possibility of providing the same function with a different material or technology also plays a role.

Supply risk score

Figure 2 places all factors influencing the supply risk score in relation to each other. The key source of risk assessed by the EU methodology is the existence of monopolistic supply structures. The thinking behind this is that adverse events in a supplying country will only affect European industries to the extent that this country participates in the supply side of the market. The typical example here is China and its dominance of the rare earth market, but there are many more. The focus is on European supply (where does the EU source its raw materials?), but the global market becomes increasingly important with increasing import dependence. Therefore, the degree of import dependence serves as a weighting factor between these two concentrations (global vs. EU sourcing).

A difficult aspect to assess is the reliability of providers. There is no appropriate measure for this and so, the World Governance Indicators (World Bank 2023) are used as a proxy. The thinking behind this is that good governance provides a reliable environment to conduct business in and the likelihood of adverse events such as civil unrest is low (Blengini et al. 2017a; European Commission 2010).

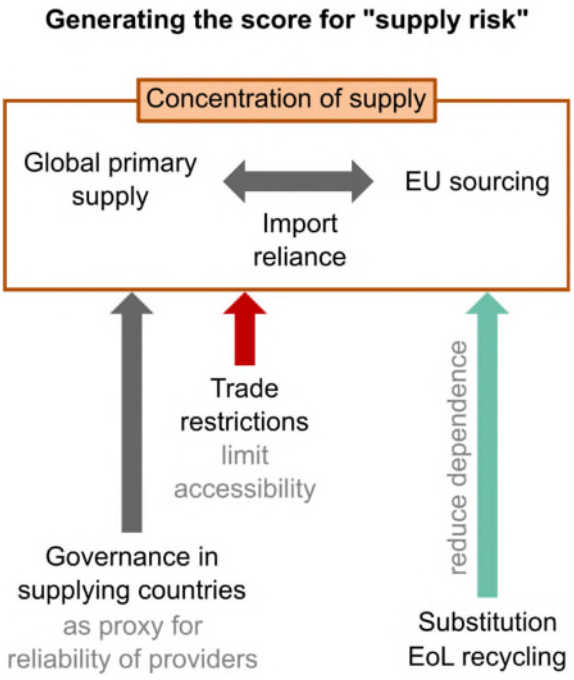

Figure 2: Elements of the equation for calculating the "supply risk" score in the EU criticality methodology.

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A further aspect of reliability of providers is their willingness to impose trade restrictions such as export bans, quotas or taxes. This is evaluated using a database provided by the OECD (2020a, 2020b).

Finally, two factors are seen to reduce supply risks. First, the availability of substitutes allows provision of the same function through different means (e.g. an alternative technology or a different raw material). Insofar as the raw material is valuable not in itself but because of the function it provides, being able to supply this function through a substitute decreases the supply risk for the function. Consequently, substitution is assessed per application of the raw material and an aggregated value is used in the scoring of "supply risk".

The second risk-reducing factor is post-consumer recycling. Especially seen from a European perspective with its well-developed infrastructures and large stock of products in use, post-consumer recycling is a potentially large source of (secondary) raw materials. The EU is less dependent on domestic mining and imports of raw materials to the extent that European raw material needs are satisfied by recycling European post-consumer scrap in the EU.

The economic importance score

While unequivocally defining the value of raw materials for the European economy has not been possible to-date, it is clear that this value does not equal the tonnages used, as this would essentially discard the value of so-called "technology metals", which are used in small quantities but are indispensable to modern technologies (cf. Figure 3, top). At the same time, focusing on price as a measure of value would highlight precious metals but essentially ignore the value of industrial metals (e.g., iron) or industrial minerals (e.g. fluorspar), which have low per tonne prices but are indispensable for myriad applications (cf. Figure 3, middle). Finally, multiplying these two values also does not yield a satisfactory solution because price and tonnage extremes still prevail in such a ranking scheme (cf. Figure 3, bottom).

The EU criticality methodology follows the thinking that the value of raw materials to the EU economy is related to the products they enable and the value added by industries in the EU. Therefore, the score for economic importance is independent of raw material price and tonnage used in the EU. Instead, the share of use of raw materials in different sectors becomes a weighting factor to the gross value added of those sectors, and this value is provisionally assigned as the "economic importance" score.

Since "economic importance" is the impact dimension in the criticality assessment and the availability of substitutes can reduce impact of a supply shortage, substitution options are accounted for on an application-by-application basis.

The elements of the economic importance calculation are shown in Figure 4. These factors are discussed in more detail below.

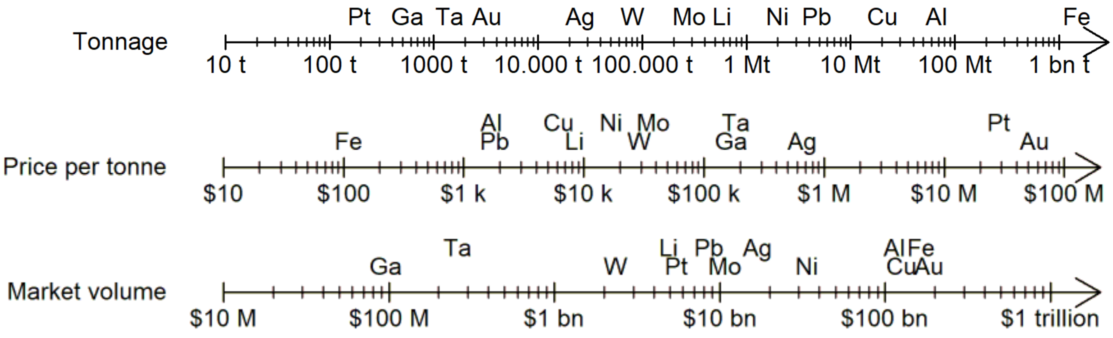

Figure 3: Ranking raw materials by tonnage (global primary production), price (average for 2020) and market volume (tonnage × price per tonne) (DERA 2020; Tercero Espinoza & Erdmann 2018). Pt = platinum, Ga = gallium, Ta = tantalum, Au = gold, Ag = silver, W = tungsten, Mo = molybdenum, Li = lithium, Ni = nickel, Pb = lead, Cu = copper, Al = aluminium, Fe = iron.

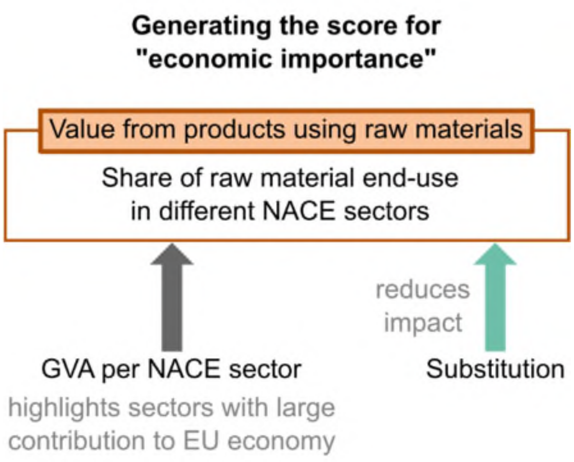

Figure 4: Elements of the scoring equation for economic importance. GVA = gross value added; NACE (*nomenclature statistique des activités économiques dans la Communauté européenne*) is the industry standard classification system used in the European Union.

Rapid assessment of the criticality methodology

The replication and adaptation of the approach centered on concentration of supply by many other reports and academic papers argue for the robustness and appeal of the reasoning at the heart of the supply risk indicator. Incidents such as the Rare Earth crisis of 2010, shortly after publication of the first study on Critical Raw Materials for the EU (European Commission 2010) and the recent shortage of magnesium attest to the supply risks associated with a dominant global provider. Efforts to increase security of supply for rare earths and other Critical Raw Materials include, next to diversification of primary supply, significant research and development efforts into substitution and recycling. These aspects are explicitly included in the methodology. Thus, in general, the quantitative assessment of "supply risk" in the EU methodology appears to be performing its function well.

There is no real consensus in the literature as to what key factors to include on the impact side of criticality analyses. The more common indicator is substitutability, introduced qualitatively by NRC (2008) and Commission of the European Communities (2008), and operationalized quantitatively in the original EU methodology (European Commission 2010; cf. Schrijvers et al. 2020). Many studies bypass the question of impact by using a suitable definition of scope (e.g., raw materials for green energy technologies; Blagoeva et al. 2016; Moss et al. 2011; Moss et al. 2013), focusing on supply aspects. The EU CRM approach centering on the needs and economic contributions of individual industrial sectors remains conceptually attractive and operationally manageable.

The description above is but a first glance at the logic and factors underlying the determination of Critical Raw Materials for the EU. It conveys the necessary understanding of the process to adequately interpret and use the results of the criticality exercise at a high level. However, it is not sufficient to challenge or improve on the methodology itself. This second part of this Working Paper is dedicated to this.

Strategic raw materials

The methodology for defining Critical Raw Materials examines current raw materials supply and use in the EU based on the latest available data. As such, it cannot reflect future developments (e.g., continued digitalization or the transformation of the energy sector) or emphasize strategic sectors (e.g., aerospace and defense). Therefore, the Critical Raw Materials Act introduced the notion of Strategic Raw Materials (SRM), in order to "ensure that the Regulation brings within its scope the materials that are the most needed to achieve the EU’s objectives for the green and digital transitions as well as for increased resilience and security" (European Commission 2023b). Strategic Raw Materials are to be considered alongside Critical Raw Materials. The determination of Strategic Raw Materials has its own methodology and data basis. The results overlap largely with those of the CRM methodology: 14 out of 16 SRM are also identified as CRM, the two exceptions being copper and nickel.

Strategic Raw Materials are characterized by (1) high expected demand growth, (2) a difficulty to significantly increase production, and (3) comparatively low level of identified economically extractable geological resources (reserves) compared to current production. The exercise to determine SRMs was conducted for the first time this year. Though some equations and reasoning are published, the data, assumptions and further details are not public (yet?). Therefore, the rest of this Working Paper focuses exclusively on the EU criticality methodology.

The supply risk score – in depth

The calculations behind the supply risk score have grown in complexity since its initial development in 2009-2010 (Blengini et al. 2017a; Blengini et al. 2017b). While the core idea – reliance on one or very few suppliers as the main source of risk – has remained the same, the methodology has become more sophisticated both on the assessment of supply concentration and substitutability (cf. Figure 5). In the following, we focus on the revised methodology, as this is the basis for the current List of Critical Raw Materials (European Commission 2023a).

Assessing concentration of supply

The concentration of primary production is assessed at the global level and for the actual EU sourcing. The reason for assessing both is that EU sourcing may differ strongly from global production patterns. Both – global production and EU sourcing – are quantified using the Herfindahl-Hirschmann-Index (HHI), which emphasizes the role of large suppliers by squaring the shares in production of each country. Figure 6 shows three different measures of concentration for three example raw materials, and exemplifies how using the HHI red flags markets with a dominant player (i.e., raw material #2) but has a more moderate view when several large players are present (i.e., raw material # 1). Raw material #3 has the lowest HHI score. This follows from the squaring of the production shares: The larger the share of the dominant producer, the higher the HHI score; the larger share of the market serviced by small contributors, the lower the score. The share of the largest producer for raw material #1 is similar to that of raw material #3. However, the HHI score for raw material #3 is lower because the share of the dominant producer is smaller and the remaining production is distributed over a larger number of smaller producers. Notice that by using the shares, all markets are treated equally regardless of their overall tonnage.

As mentioned above, the methodology attempts to qualify the producing countries in addition to quantifying their contribution to global and/or EU supply. This qualification is done through the Worldwide Governance Indicators (WGI), which are published regularly by the World Bank (World Bank 2023). The methodology uses the simple average of all sub-indicators, chosen to match the last five years of production data (in the case of the 2023 assessment: 2016-2020). The numerical range of the WGI is from -2.5 to +2.5, the higher, the better. A high ("good") governance score is taken to represent a low risk in the EU methodology, as shown in Figure 7.

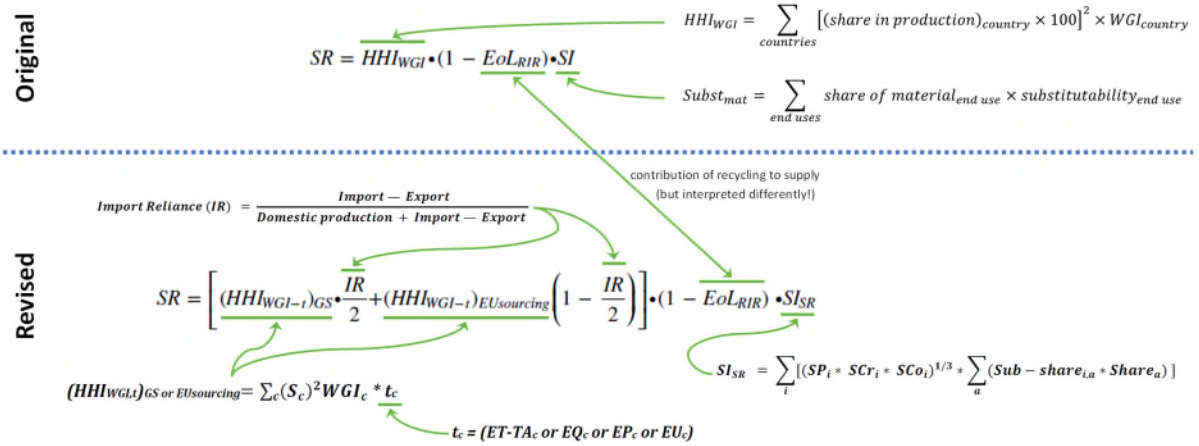

Figure 5: Calculation of the supply risk score in the original and revised EU methodologies (Blengini et al. 2017a; Blengini et al. 2017b; European Commission 2010, 2017b). *SR* = supply risk; HHI_{WGI} = Herfindahl-Hirschmann-Index weighted with the *WGI* = World Governance Indicators; EoL_{RIR} = end-of-life recycling input rate; *SI* = substitutability index; *GS* = global supply; IR = import reliance; HHI_{WGI-t} = HHI_{WGI} but also including trade restrictions (t_c) as a weighting factor; t_c acounts for export taxes and trade agreements ($ET\text{-}TA_c$), export quotas (EQ_c), export prohibitions (EP_c) in non-EU countries while EU countries receive the scoring of 0.8 (EU_c), ; SI_{SR} = substitutability index for the supply side considering substitute production (*SP*), substitute criticality (*SCr*), substitute co-production (*SCo*) as well as the share of the raw material in a given application and the sub-share that the substitute may achieve.

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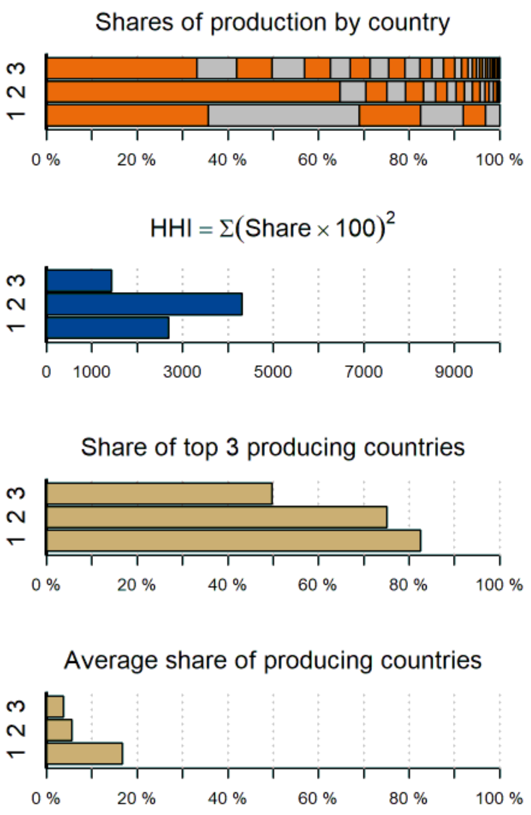

Figure 6: Production shares for three example raw materials (top), with corresponding concentration measures. The HHI (in blue) is the concentration measure used by the EU methodology. Primary production data for 2012 obtained from https://www.grondstoffenscanner.nl/.

Accounting for governance in producing countries

Combining the Herfindahl-Hirschmann-Index with the Worldwide Governance Indicators creates a compound indicator that red flags markets dominated by large producers with poor governance. In theory, a monopoly by a country with a perfect governance score would yield a zero risk score, which is counterintuitive. However, there are no perfect governance scores in reality (cf. Figure 8) such that this case may be neglected. Similarly, a very large number of small producers will yield a low risk score, regardless of how poor their governance scores may be. This follows from the decision that the prime source of risk for supply disruption is reliance on a single dominant producer.

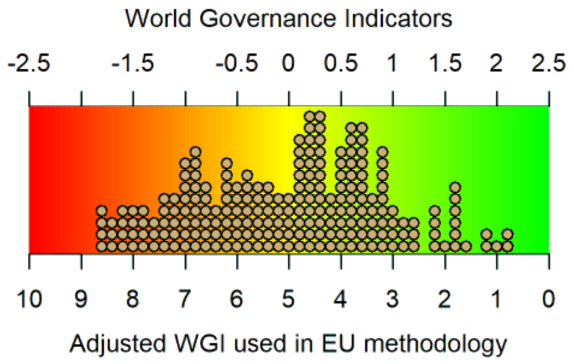

Figure 7: Original (top axis) and adjusted (bottom axis) scaling of World Governance Indicators used in the 2023 criticality exercise. The dots represent the producing countries relevant for the latest criticality exercise (notice that the extreme values are theoretically possible but not present in the data). Scores taken from European Commission (2023a).

Figure 8 compares the values of HHI vs. HHI_{WGI} for all raw materials considered in the 2023 criticality exercise. Notice that that modifying the HHI by the WGI of each producing

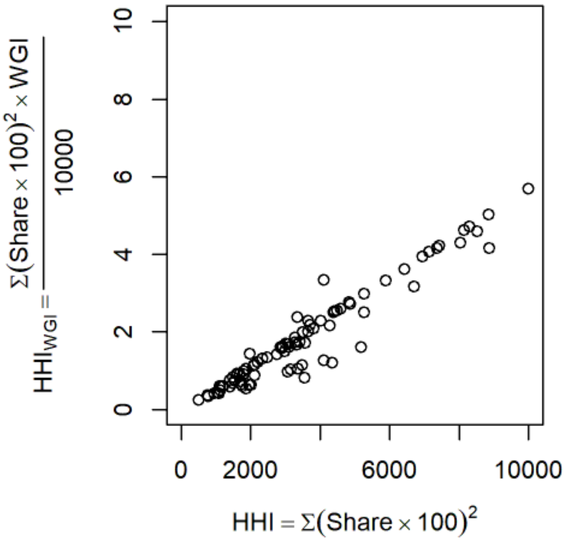

Figure 8: HHI vs. HHI_{WGI} for all raw materials (ungrouped), both mining and processing stages, considered in the latest criticality exercise (data from European Commission 2023a). The vertical axis is divided by 10^4 for readability. This is the same scaling applied to the final supply risk score to fit it in the range [0, 10].

country leads to a largely uniform scaling. This follows from the fact that most raw materials are sourced from different countries having different governance scores, such that the effects tend to average out. However, there are cases where the major producer(s) has/have unusually high/low governance scores, leading to larger deviations from the trend. Some examples:

- the methodology sees the supply risk as lower than using the pure HHI as an indicator for beryllium at the mining stage (HHI ≈ 5100), with the dominant producer being the USA (better than average WGI) and for lithium at the mining stage (HHI ≈ 3500) where the two largest producers are Australia and Chile (better than average WGI)
- conversely, the supply risk score is comparatively high vs. the pure HHI for cobalt at the mining stage (HHI ≈ 4100), with the D.R. Congo as the dominant producer (lower than average WGI).

Raw materials for which China is the dominant producer do not stand out in Figure 8 because China's WGI score (5.7) is close to the center of the distribution (cf. Figure 5).

Accounting for trade restrictions

A final adjustment to the WGI is for the willingness of producing countries to impose trade restrictions. Trade restrictions do not necessarily mean a physical restriction to exports (export quotas, export prohibitions) but also include taxes (Blengini et al. 2017a). The HHI_{WGI} scoring for for each raw material at the mining and processing stage is adjusted for trade restrictions (t_c in Figure 5) using a compound score centered around 1. EU countries are assigned the value of 0.8 by default (thus reducing the risk perceived by the methodology). Figure 9 shows all t_c scores used in the latest criticality exercise. Notice that the most common case is "no restrictions" (t_c = 1.0), followed by sourcing from the EU (t_c = 0.8). However, the small number of t_c > 1 are noteworthy and can potentially shift the risk scoring. In 2023, this was the case especially for natural teak wood (Myanmar), tin (China at the refining stage), phosphate rock (China), tungsten (China), phosphorous (China), and cobalt (D.R. Congo at the extraction stage) as highlighted in Figure 10.

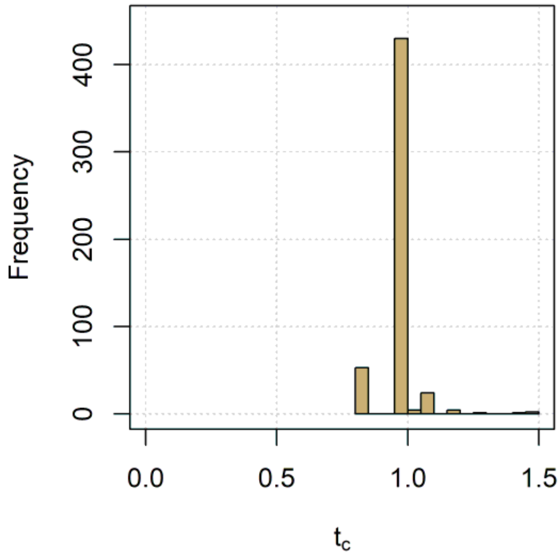

Figure 9: t_c scores for all countries and all raw materials at both the mining and processing stage included in the 2023 criticality exercise (data from European Commission 2023a).

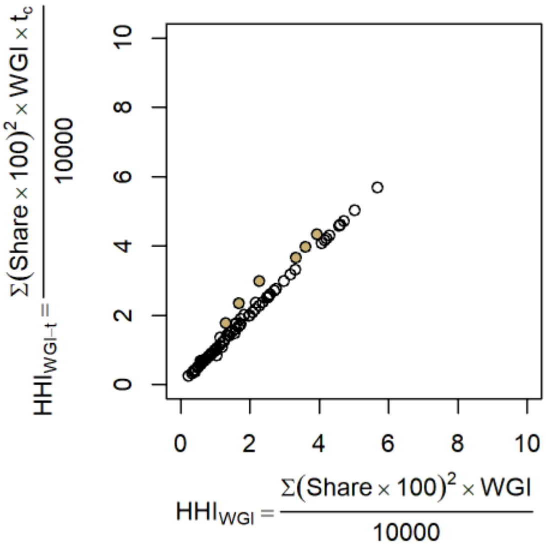

Figure 10: Comparison between the scoring before (horizontal) and after (vertical) consideration of trade restrictions. Data from European Commission (2023a).

EU sourcing, global sourcing and import reliance

The next step in the methodology is considering EU sourcing vs. global sourcing. The steps for EU sourcing are equivalent to those for global sourcing, described above.

EU sourcing not only includes material produced in the EU but also net imports. Net imports are estimated from trade data provided by eurostsat (ComExt database, https://ec.europa.eu/eurostat/comext/newxtweb/). This estimation is based on a selection of trade codes and assumptions about their content of the desired material, which introduces two key uncertainties: reporting and content. The uncertainty in reporting refers to the completeness/accuracy of the reported figures, but is considered comparative small in the EU (good data quality). The uncertainty in the content refers to the mean content for a trade code (e.g. content of x in master alloys of x), its changes over time (e.g., metal content in concentrate) and granularity of the codes (i.e., some codes cannot be exclusively assigned to one metal).

Despite the difficulties outlined above, the difference between the scores for EU sourcing and global sourcing is significant, as shown in Figure 11 using data for the 2023 criticality exercise (European Commission 2023a). At the mining stage (Figure 11, top) there is a large number of materials for which global and EU sourcing have very similar $\mathrm{HHI}_{\mathrm{WGI\text{-}t}}$ score, clustered around the diagonal line between 0 and 2. However, there is a significant number of materials that strongly deviate from the diagonal. The proportion of raw materials for which EU and global sourcing scores are very different is even higher at the processing stage (Figure 11, bottom).

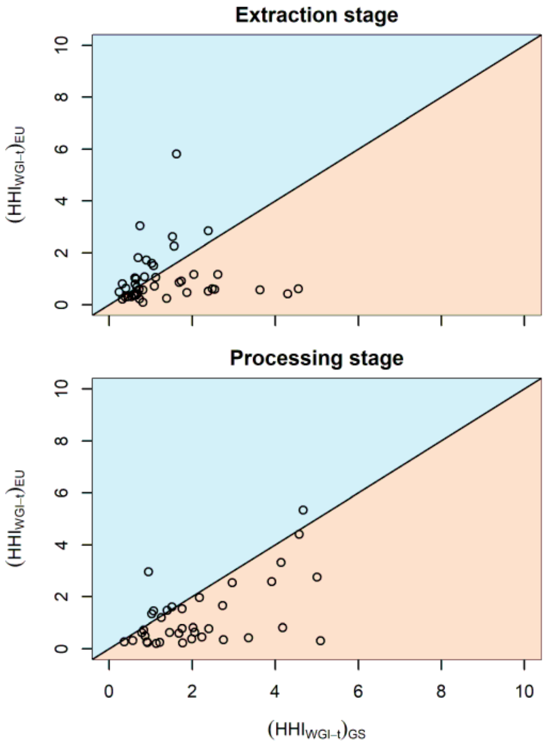

Figure 11: Global vs. EU sourcing at the mining (top) and processing stage (bottom). A dot in the orange half shows a higher risk of global sourcing vs. EU sourcing. A dot in the blue half shows higher EU sourcing risk compared to global. Data from European Commission (2023a).

The EU methodology takes this difference into account by building a weighted sum of EU sourcing risk and global sourcing risk (cf. Figure 5), using the import reliance (IR, share of imports in total EU sourcing) as a weighting factor. Even though the scaling of the weights varies linearly with import reliance, there is an implicit decision to give more weight to EU sourcing compared to global sourcing, as shown in Figure 12. Numerically, while the import reliance varies between 0% and 100% (cf. Figure 13, below), EU sourcing accounts for ≥ 50% weight in the calculations, namely, $weight_{IR} = 100\% - IR/2$.

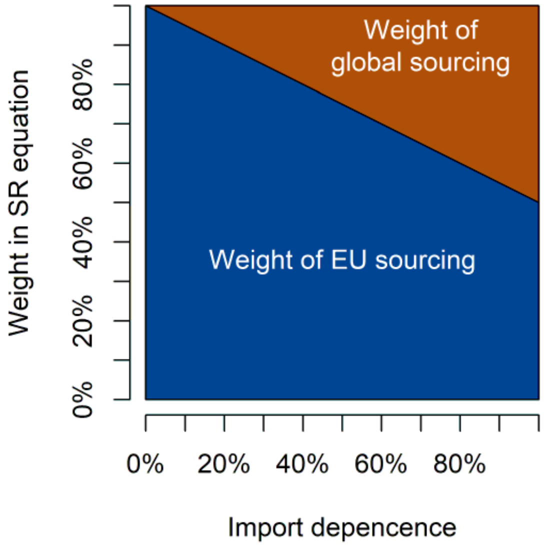

Figure 12: Relative weight EU and global sourcing in the supply risk equation as a function of import reliance (IR).

Values for the import reliance (IR) tend to cluster around the extremes of self-sufficiency and complete import reliance, with intermediate values covering the entire range for the extraction stage. At the processing stage,

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100% import reliance is the only noticeable cluster. Figure 13 shows the distribution of values for the import reliance at both stages.

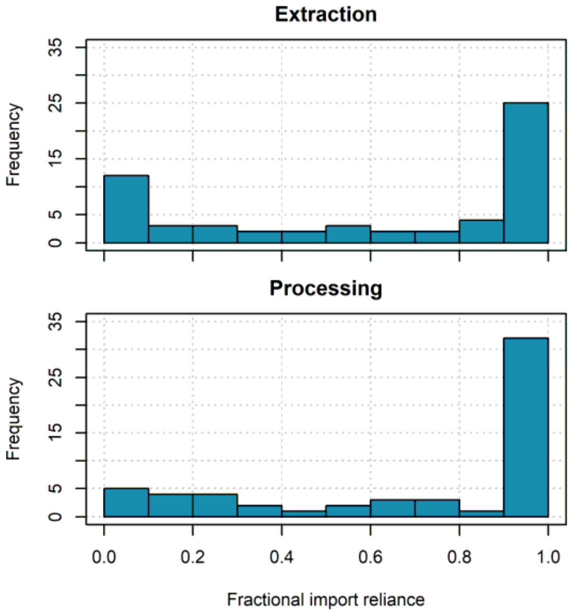

Figure 13: Import reliance for all materials considered in the 2020 criticality exercise (data from European Commission 2023a).

Simultaneously considering the values of import dependence (Figure 13) with their corresponding weights (Figure 12) and the differences seen in EU vs. global sourcing (Figure 11) leads to a nuanced assessment of supply concentration that differs, in many cases strongly, from the global assessment of supply at the global scale only using the Herfindahl-Hirschmann-Index as a measure of concentration. Figure 14 shows this comparison for all raw materials at both the extraction and processing stage. For convenience, in the following we define *C* to be the part of the supply risk equation that combines the assessment of EU and global sourcing together with trade restrictions and governance of the producing countries, weighted by the EU import reliance:

$$C = \left[(HHI_{WGI-t})_{GS} \times \frac{IR}{2}\right] + \left[(HHI_{WGI-t})_{EU} \times \left(1 - \frac{IR}{2}\right)\right]$$

where the definitions are exactly those used in Figure 5.

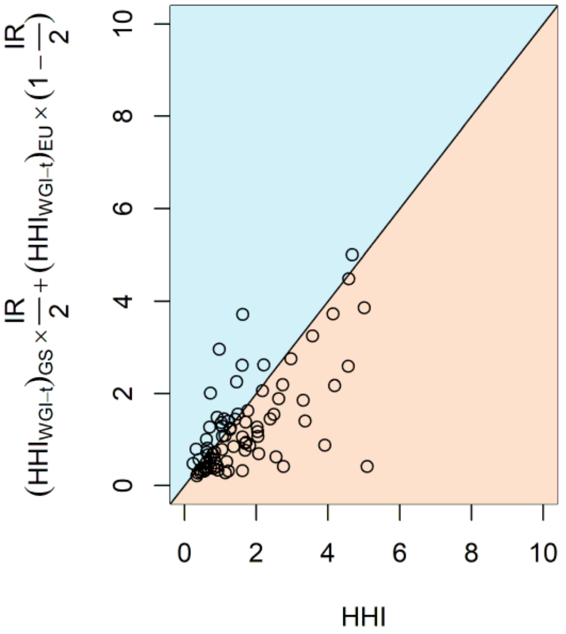

Figure 14: Comparing the concentration of supply term in the EU methodology (*C*, comprising global concentration of supply at the country level, the governance of the producing countries, trade restrictions, EU sourcing and import dependence) vs. a simple measure of concentration of supply (HHI) at the global level. Data from European Commission (2023a).

Accounting for recycling

The perceived risk attached to the primary supply of a raw material does not apply to its secondary supply. In other words, inasmuch as a raw material is supplied through recycling, it is independent of the risk associated with extraction and processing from primary sources. This is accounted for in the methodology by multiplying the measure of concentration by the share of raw material that is obtained from primary sources. This thinking was introduced in European Commission (2010) and remains basically unchanged and used in many criticality exercises (cf. Schrijvers et al. 2020) despite some weakness (Blengini et al. 2017a; European Commission 2023a).

The main critique is that it implicitly assumes recycling to be riskless (cf. Schrijvers et al. 2020; Talens Peiró et al. 2018; Tercero Espinoza 2021), which is not necessarily true but a reasonable and useful approximation from the European perspective with its large amount of materials in use and potentially recyclable. In order to account for this European potential, the ideal recycling rate to use is the share of raw material supplied from European recycling from European scrap (i.e., neither dependent on foreign scrap for recycling in the EU nor using European scrap for recycling elsewhere). The reasoning and build-up of this recycling indicator is discussed in Blengini et al. (2017a) and in more detail by Talens Peiró et al. (2018). In the following, this recycling rate is denoted as EU EoL RIR (EU end-of-life recycling input rate).

Figure 15 shows the flows used to estimate the EU EoL RIR. The definition outlined above is in fact quite restrictive and has high data requirements. In particular, the high data requirements mean that estimates of the EU EoL RIR are only available for a selection of all raw materials considered in the criticality exercise. This is the case of raw materials for which MSA (material systems analysis) studies have been commissioned by the European Commission (e.g., Bio by Deloitte 2015; Passarini et al. 2018; Torres de Matos et al. 2020) or for which equivalent information is available from the scientific literature (e.g., Soulier et al. 2018) or from industry sources (e.g., Oakdene Hollins 2017). This problem can only be solved with more research into raw material cycles at the EU level. In the meantime, is appears useful to clearly identify what recycling rate is being used to enable a better understanding of the sourcing of each raw material.

For the purpose of the criticality calculations, the different recycling rates have to continue to be taken as equivalent and are denoted generically as "recycling rate" in the following. Figure 16 (top) shows the values for the recycling rate used in the latest EU criticality exercise. These are, unfortunately, mostly low values below 10%, but there is a significant minority with higher recycling

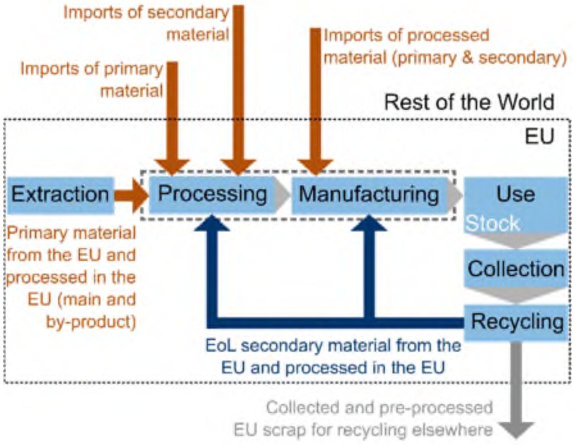

Figure 15: Flow data necessary for calculating the recycling rate (EU EoL RIR) used in the EU criticality methodology. Flows in blue go into the numerator and denominator, while flows in dark orange go into the denominator only (Talens Peiró et al. 2018; Tercero Espinoza 2021). The flow in gray is not included in the calculation.

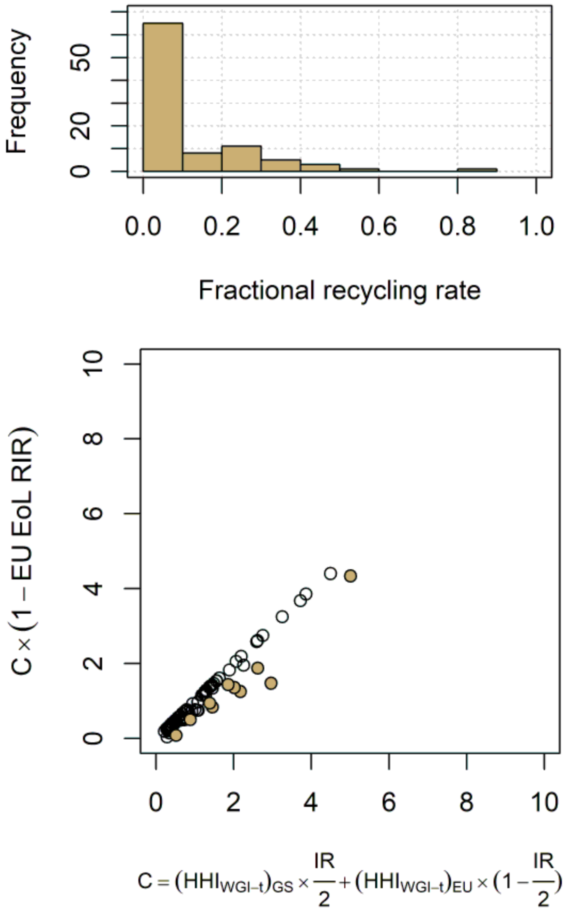

Figure 16: (top) Distribution of recycling rates used in the latest EU criticality exercise (cf. European Commission 2023a), and (bottom) the indicator for concentration of supply (denoted by "C" in the legend for convenience, cf. Figure 14) before (horizontal axis) and after accounting for recycling (vertical axis). Data from European Commission (2023a). Raw materials for which the risk score is significantly reduced are highlighted in light brown.

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rates. For many of these, the effect on the risk scoring is large, as shown in Figure 16 (bottom).

Accounting for substitutability

A final adjustment to the risk score based on concentration of supply is accounting for substitutability. Substitutability can be seen to affect both axes of the criticality matrix, as it affects both the supply of the function provided by a particular raw material as well as the impact a physical shortage may have. To account for these two effects, Blengini et al. (2017a) introduced two separate assessments for substitution for the two axes, each covering the aspects more relevant to the dimension in focus. In the case of the "supply risk" dimension, the substitutability scoring focuses on the availability of the substitute raw material following three questions: (1) Are there sufficient amounts of the substitute raw material available? (2) Is the substitute raw material itself critical? (3) Is the substitute raw material a co-product or by-product of another raw material? The answers to these questions help to assess whether substitution would be possible to a significant extent. The extent of the substitution is also part of the formula, accounted for by the extent to which the target raw material may be substituted in a particular application ("subshare") and the proportion of that application in EU demand for that raw material ("share"). Overall, the equation is (Blengini et al. 2017a):

$$SI_{SR} = \sum_m \left[\sqrt[3]{Prod_m \times Crit_m \times Coprod_m} \times \sum_a \left(Subshare_{m,a} \times Share_a\right) \right]$$

where SI_{SR} is the substitution index to be used in the supply risk axis, $Prod_m$ is the level of production, $Crit_m$ the criticality and $Coprod_m$ the co-production for a substitute raw material m that could substitute the target raw material in one or more applications a (which itself has $Share_a$ in demand for the target raw material) to the extent $Subshare_{m,a}$. In other words: for each substitute raw material, take the geometric average of its availability (given by scores for production, criticality and co-production) and weigh that by the proportion of demand for the target raw material that the substitute could take over.

An advantage to this approach is that it provides a consistent framework for thinking about and assessing the impact of substitution on the supply risk dimension. A disadvantage is that it requires much data and, in the absence of data, many assumptions.

In terms of values, the level of production ($Prod_m$) assumes a value of 0.8 if the global annual production of the substitute material is higher than the material in question, and 1.0 otherwise. Substitute criticality $Crit_m$ is 0.8 if the substitute material was not critical or not screened in the previous assessment, and 1.0 otherwise. Finally, substitute co-production $Coprod_m$ takes the value of 0.8 if the substitute is extracted as a primary material, 0.9 if it is extracted both as a primary and as by-/co-product, and 1.0 otherwise (Blengini et al. 2017a). Therefore, $SI_{SR} \leq 1$ such that the risk scoring is reduced to the extent that substitution of a part of the demand for the target raw material is feasible in terms of the availability of the substitutes as estimated by the equation above.

Figure 17 shows that the substitution index SI_{SR} can take values well below 1 (top left of the graph), which leads to a significant lowering of the risk score following the supply risk equation (cf. Figure 5). However, most SI_{SR} values are

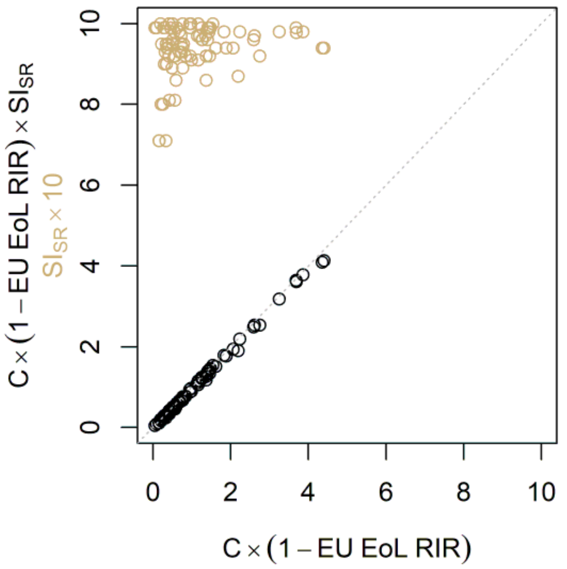

Figure 17: Values of the substitution index for the supply risk dimension in the latest criticality exercise (in light brown, top left of the graph) and their effect on the supply risk score (horizontal axis without including substitution, vertical axis after considering substitution). "*C*" is defined in Figure 16 and represents the country concentration term of the supply risk equation (cf. Figure 5) considering both global and EU sourcing, trade restrictions and governance of the producing countries. Data from European Commission (2023a).

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above 0.9 and the lowest values correspond to raw materials with very low country concentration (horizontal axis). In sum, substitution scores had a very limited influence on the supply risk scoring in the last criticality exercise.

The economic importance score – in depth

The assessment of economic importance is less complex but no less important than that of the supply risk. The economic importance axis corresponds to the impact dimension of classical risk assessment (Glöser et al. 2015). In other words, it attempts to quantify what could be at stake if there were to be a physical bottleneck in raw material supply.

Value added of European industries using raw materials

The EU methodology approximates economic importance of a raw material to the EU economy by matching demand for a raw material to EU industry sectors and using the value added of those sectors (cf. Figure 4 and Figure 18).

A key problem is that there is an obvious mismatch between the value contribution of a raw material and the value added by a sector using this raw material. Nevertheless, the EU criticality methodology assigns the entire value added of a sector to the use of a raw material in that sector. Therefore, the value of raw materials is exaggerated by the criticality methodology. Moreover, the value contribution of the raw material to the value added in the sector will vary between applications. As a result, the value of raw materials to the European economy is exaggerated *to different extents* for different raw materials in the criticality methodology. This is clearly a problem, but one currently without a satisfactory solution in the criticality literature.

Furthermore, assigning the value of a sector neglects the value of the industries possibly depending on the products of that sector. This problem would be solvable using input-output (I/O) analysis, were the I/O-tables differentiated and up-to-date enough. They are not. The EU methodology therefore turns to data on industrial production from the Structural Business Statistics database (SBS; Eurostat 2023), which classifies economic activities using the NACE classification. This data is available at a finer granularity than I/O tables, even when used at the 2-digit level. Focusing on mining and manufacturing activities, 29 2-digit NACE codes are used to quantify the economic importance of raw materials. Figure 19 shows the relative value of these sectors in terms of their value added.

Using the value of the sectors allows for the creation of a ranking using scores between 0 and 10 to match the scores

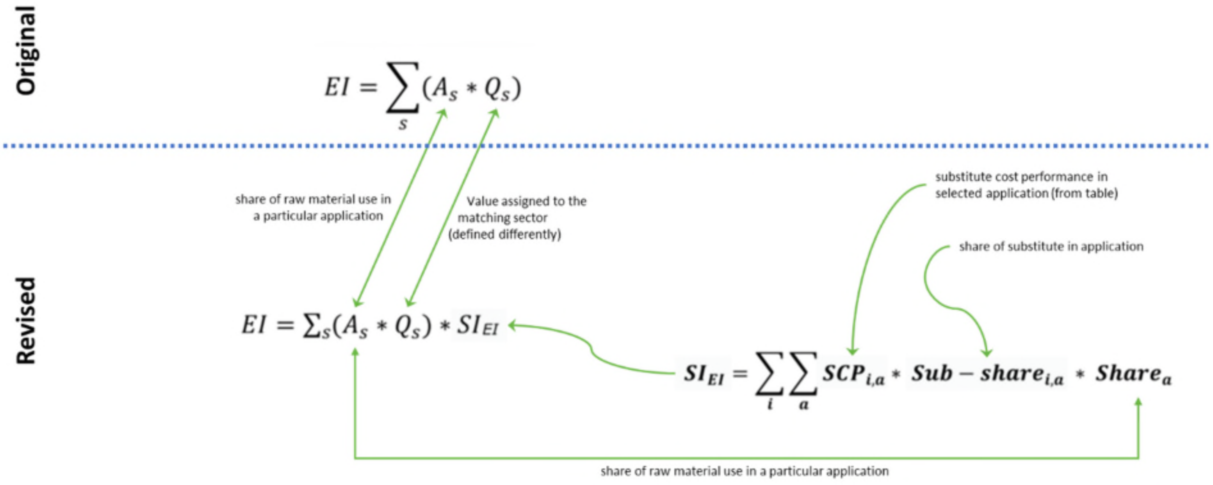

Figure 18: Calculation of the economic importance score in the original and revised EU methodologies (Blengini et al. 2017a; Blengini et al. 2017b; European Commission 2010, 2017b). *EI* = economic importance; A_S = share of raw material use in a particular sector; Q_S = gross value added of the sector using the raw material; SI_{EI} = substitutability index for the economic importance dimension, based on the substitute cost performance in each application ($SCP_{i,a}$) as well as the share of the raw material in a given application and the sub-share that the substitute may achieve.

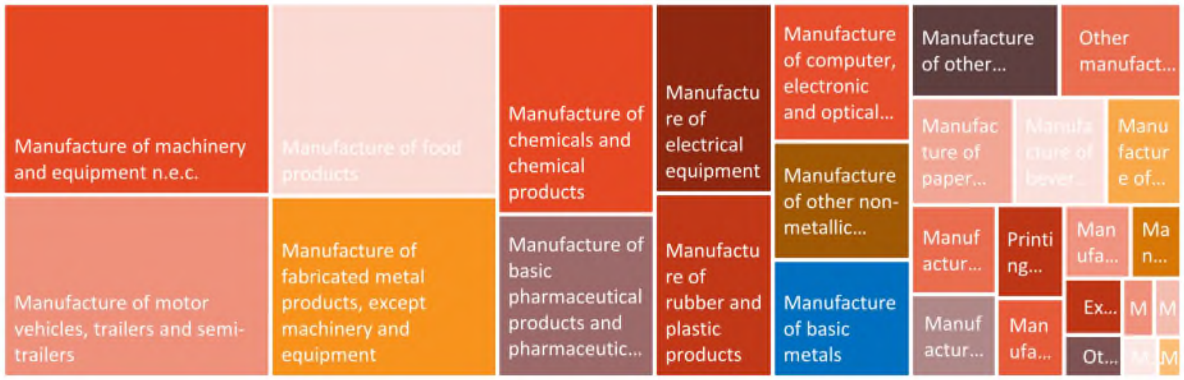

Figure 19: Value added of 2-digit NACE sectors used in the calculation of the economic importance axis in the last criticality exercise. Data from European Commission (2023a) and Eurostat (2023).

of the supply risk. To fit the values into this range, all values of gross value added (GVA) for 2-digit NACE sectors are divided by GVA of the largest sector and multiplied by 10 (i.e. 100% assignment to the largest sector results in a score of 10 before accounting for substitution). The threshold value for this dimension is set at 2.8 in this scale (i.e., 28% of the GVA of the largest sector, before accounting for substitution).

In the simplest case, of 100% of a raw material being used by a single 2-digit NACE sector, an assignment to C24 "Manufacture of basic metals" (marked in blue in Figure 19) and any larger sector (above and to the left of C24 in Figure 19) will ensure that the score for economic importance is greater than the threshold value for this axis before considering substitution. Such a raw material is aggregates, assigned 100% to C23 "Manufacture of other non-metallic mineral products" (European Commission 2023a). Conversely, a 100% assignment to a smaller sector (to the right of C24 "Manufacture of basic metals" in Figure 19) will mean the value of economic importance for that raw material is below the threshold.

In all other cases, the score is based on the weighted sum of the GVA of the sectors using a particular raw material, with the share of raw material going into that sector as the weight. This can lead to some strange results depending on the assignment of raw materials use to NACE sectors. For example, magnesium (Mg) has a much higher score than copper (Cu), cf. European Commission (2023a). This follows from Mg being assigned mostly to C29 (2nd largest sector, 48% of Mg use) and C25 (4th largest sector, 49% of Mg use) whereas Cu with its wider range of uses also includes assignments to small sectors like C32 ("Other manufacturing", below the threshold, 21% of Cu use) and its main use as a conductor is assigned to C27 ("Manufacture of electrical equipment", 7th largest sector in Figure 19, 38% of Cu use). Nevertheless, the score for Cu is well above the threshold value for economic importance, as is the score for a majority of candidate raw materials (see below).

Accounting for substitution

Substitution in the economic importance axis intends to reflect the reduced impact of a possible supply shortage if there are readily available options to supply the same function/products using different raw materials. In this sense, the relevant aspects are the relative performance and costs of the substitution options vs. current practice. These are captured through a numerical score ranging from 0.7 to 1.0 and assigned based on Table 1.

Table 1: Substitute cost performance (SCP) evaluation matrix from Blengini et al. (2017a).

		Performance		
		Better	Similar	No substitute
Costs	Much higher	0.9	1.0	1.0
	Slightly higher	0.8	0.9	1.0
	Similar or lower	0.7	0.8	1.0

Similar to the supply risk dimension, the extent of the substitution is also part of the formula, accounted for by the extent to which the target raw material may be substituted in a particular application ("sub-share", estimate based on expert judgement) and the proportion of that application in EU demand for that raw material ("share", from market data). Overall, the equation is (Blengini et al. 2017a):

$$SI_{IE} = \sum_{m}\sum_{a}(SCP_{m,a} \times Subshare_{m,a} \times Share_{a})$$

where SI_{IE} is the substitution index to be used in the economic importance axis, $SCP_{m,a}$ is the substitute cost performance value for substitute raw material m in application a (which itself has $Share_a$ in demand for the target raw material) and may substitute for the target raw material to the extent $Subshare_{m,a}$. In other words: for each substitute raw material, take the numerical assessment of the substitute's cost and performance and weigh that by the proportion of demand for the target raw material that the substitute could take over. Figure 20 shows the values of the substitution score and their effect on the economic importance score based on the gross value added of the sectors using the candidate raw materials.

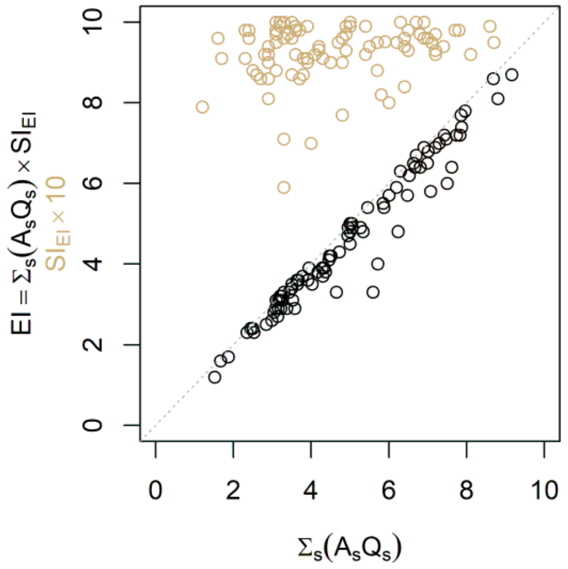

Figure 20: Gross value added attributed to the candidate raw materials (horizontal axis) and their corresponding economic importance score after considering substitution (vertical axis). The substitution scores themselves are also shown in light brown. A_S = share of raw material use in a particular sector; Qs = gross value added of the sector using the raw material; SI_{EI} = substitutability index for the economic importance dimension.

At first glance, the distribution of values for SI_{EI} appears broader than that for SI_{SR} (cf. Figure 17). However, the difference is very small: SI_{EI} = 0.93 ± 0.07 vs. SI_{SR} = 0.95 ± 0.07. The difference appears larger because some of the lower values of SI_{EI} affect some of the mid-to-high values of $\sum_s A_s\, Q_s$ and therefore, affect the scoring to a much larger extent than SI_{SR}.

Creating the list of Critical Raw Materials

Having determined scores for both the supply risk and economic importance dimensions, the last step in creating a list of Critical Raw Materials is the introduction of threshold values. Note that threshold values in criticality studies are the product of a decision: there is no derivation that can deliver "the right" threshold value for each dimension. Furthermore, not only the value of the threshold but also its shape is the product of a decision (cf. Glöser et al. 2015).

In the case of the EU criticality studies, the threshold value for the supply risk axis is set to 1.0 and that on the economic importance axis to 2.8 on the respective scales. Materials with scores at or above both thresholds are considered "critical". Figure 21 shows the results of the latest EU criticality study with some diagnostic additions.

First, notice that the thresholds for economic importance and supply risk divide the plot into four unequal quadrants:

- Raw materials below both thresholds are in the bottom left quadrant. Only 8 of the 70 circles in the graph are located here.
- Raw materials in the bottom right quadrant have a sufficiently high economic importance score to be in the list of Critical Raw Materials but their supply risk score is below the threshold such that they are considered "non-critical". 40% of raw materials fall in this quadrant, including copper and nickel, which are considered Strategic Raw Materials and are therefore added to the list of Critical Raw Materials despite their low supply risk score.
- Raw materials in the top left quadrant have supply risk scores above the threshold but a low economic

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importance score. This is the most sparsely populated quadrant with only two raw materials.

- Raw materials in the top right quadrant are considered "critical" because their scores are simultaneously at or above the thresholds for both criticality dimensions. The 32 CRM together with copper and nickel (strategic) constitute the List of Critical Raw Mateirals for the EU.

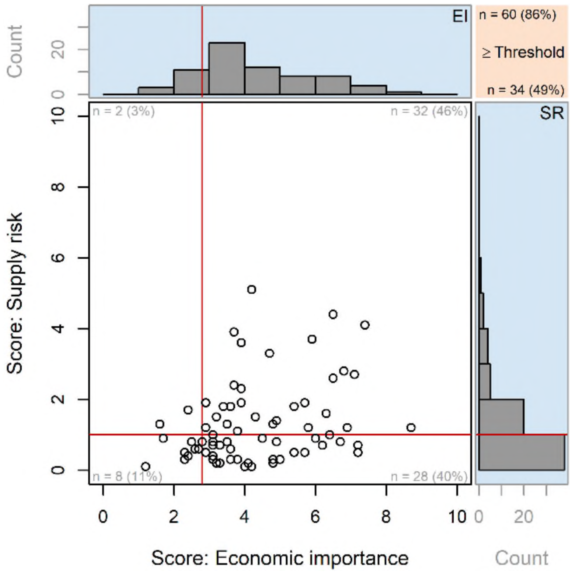

Figure 21: Results of the 2023 criticality study, with some diagnostic additions (data from European Commission 2023a).

Closer examination of the results shows that the economic importance score is a much weaker selector than the supply risk score: 60 out of 70 candidate raw materials (groups) are at or above the economic importance threshold where are "only" 34 out of 70 candidate raw materials are at or above the threshold for supply risk.

The histograms on the top (for economic importance) and to the right (supply risk) of Figure 21 differentiate this further. The distribution of supply risk scores decays monotonically towards higher scores while the distribution of economic importance scores has a clear peak to the right (i.e., above) the threshold value.

Conclusion

The description above presents a compact yet complete walk-through of the EU methodology for the identification of Critical Raw Materials. It shows the data and procedures, highlights decisions behind indicators and effects of the different variables on the scoring of both dimensions of criticality, namely supply risk (likelihood) and economic importance (impact).

Given that lists of Critical Raw Materials are heavily dependent on the perspective of the people producing them, the transparency in data and calculations is an asset of the EU methodology. With the exception of the indicator for substitution in the supply risk axis, which had essentially no effect on the results in the latest criticality exercise, all aspects under consideration meaningfully affect the scoring and yield a CRM list that can be well interpreted and understood in terms of the priorities and decisions behind it, as described in this Working Paper.

There remain both methodological difficulties (i.e. how to better capture the value of raw materials for the EU economy) as well as data limitations (e.g., quantifying net imports of raw materials, estimating recycling rates) that affect the results. Some of these difficulties are also articulated herein, in principle or with concrete data.

The content of this Working Paper is based mostly on the reports by Blengini et al. (2017a), Blengini et al. (2017b), and European Commission (2023a), enriched with the author's own analysis and experience. It is meant to provide quick and meaningful insight into an existing methodology. The hope is to make the methodology more understandable and accessible to an expanding community of people from industry, governments and academia who are now joining the conversation on Critical Raw Materials in the EU in the wake of the proposed Critical Raw Materials Act.

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