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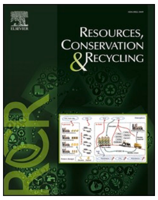

Integrated conceptual framework for resilience and criticality assessments for raw material supply chains

Lars Wietschel [a,*], Christoph Helbig [b], Martin Hillenbrand [b], Andrea Thorenz [a]

[a] Resource Lab, Institute of Materials Resource Management, University of Augsburg, Germany
[b] Ecological Resource Technology, University of Bayreuth, Bayreuth, Germany

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ABSTRACT

The global need for decarbonization strains critical raw material supply, reflected in increasing disruptions and threats. This demonstrates the need to enhance criticality towards integrated, time-dynamic assessments of criticality and resilience. This study reviews criticality, resilience, and raw material resilience literature. While we identify high conformity between *vulnerability* in criticality and *performance degradation* in resilience assessments, criticality additionally includes the likelihood of disruptions, and resilience emphasizes the required capacities to recover. The two concepts have not yet been integrated, wherefore we propose a time-dynamic indicator-based framework that considers three dimensions: the likelihood of disruption, the effect of disruption, and recovery from disruption. We illustrate the relevance by a Gallium case study from the perspective of the EU, faced with a hypothetical export ban. Our study contributes to a more comprehensive understanding of supply chain risks and mitigation opportunities and provides a foundation for the quantitative integration of criticality and resilience.

1. Motivation

Modern society bases its prosperity on a massive demand for raw materials, which are unevenly distributed around the globe (Bloodworth, 2014). Therefore, the questions of raw material availability and importance to the economy frequently is assessed in criticality assessments from a corporate, regional, or national perspective (Graedel et al., 2012). In 2008, the NRC introduced the criticality matrix to map the likelihood of supply disruptions of scarce minerals over the potential impact of a disruption on the U.S. industry (U.S. National Research Council, 2008). Numerous raw material criticality assessments have recently been published with varying goals, actor perspectives, scopes, and material choices (Helbig et al., 2021a; Schrijvers et al., 2020a). Prominently, this includes the lists of Critical Raw Materials of the European Commission (European Commission, 2023a) and of Critical Minerals for the USA (Nassar and Fortier, 2021). Most published criticality assessments are static and currently do not systematically investigate dynamic aspects, such as a complex system's reaction to a disturbance (Dewulf et al., 2016; Frenzel et al., 2017; Ioannidou et al., 2019; Sprecher et al., 2015). A static perspective can provide important insights into the likelihood of disruption due to geographical and political factors (Mancheri et al., 2018). However, the dynamics of how a complex system, such as a national economy, responds to raw material disruptions by potential abilities to absorb shortages, restore its original functionality, or adapt to new conditions is not yet covered in criticality assessments (Dewulf et al., 2016).

Quantitative resilience assessments allow the investigation of a system's reaction to disruptions over time (Bruckler et al., 2024). The so-called *resilience curve* maps the performance course dynamically, thereby facilitating the evaluation of a system's capacities to absorb disturbances, restore affected system components in the aftermath of disruptions, or adapt to change to maintain the original functionality (Bruckler et al., 2024). The subfield *supply chain resilience* is concerned with the economic and timely management of preparedness for supply chain disruptions by managing the abilities to respond, recover, and maintain a positive state in the aftermath (Ribeiro and Barbosa-Povoa, 2018). Therefore, both criticality studies and resilience assessments concern 'shocks' in supply chains (SC). However, other than criticality assessments, resilience considerations usually ignore the probability of a disrupting event, complicating the judgment about whether it is worth investing in resilience capacities.

Different preceding works considered the concept of resilience well

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* Corresponding author.
E-mail address: lars.wietschel@uni-a.de (L. Wietschel).

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suited to analyze how a system responds to criticality (Dewulf et al., 2016). Sprecher et al. (2015) is the first work investigating the concept of resilience in the context of raw material supply chains for the case of rare earth elements and defines it as "*the capacity to supply enough of a given material to satisfy the demands of society and to provide suitable alternatives if insufficient supply is available*". Several studies build upon this work by refining the initially proposed system dynamics approach and expanding to other minerals such as tantalum, cobalt, or antimony (Brink et al., 2022, 2020; Mancheri et al., 2018). The works have considerable efforts in analyzing and understanding the historical particularities of certain material supply chains in common. However, general conclusions on the relationship between criticality assessments and resilience considerations remain vague. A second relevant methodological stream on raw material resilience originates from the Joint Research Center, which builds upon the indicator-based EU criticality methodology and complements it with forward-looking aspects (Blagoeva et al., 2016). While the work includes relevant aspects of resilience, it is an open collection of indicators without an in-depth analysis of cause-effect chains. The European Critical Raw Materials Act of 2024 continues the evolution of criticality towards resilience by putting *critical raw material resilience* as one of three general objectives of the regulation at the forefront (European Commission, 2023b).

Based on the most relevant literature, we identify several research gaps: traditional criticality assessments are suited to estimate the disruption likelihood and its potential immediate effect, however, due to their static nature, they fail to cover the response dynamics of complex systems. Furthermore, several existing studies mix indicators that assess the current risk for supply disruptions (e.g., concentration of mining) with indicators that reflect a potential future reaction to a shortage (e.g., potential to substitute) (Dewulf et al., 2016), which raises the need for a clear separation into indicators that asses the supply risk, the vulnerability, and the resilience (Schrijvers et al., 2020a). The concept of supply chain resilience considers the dynamic process of dealing with a disruption and the subsequent recovery, however, it mostly disregards the disruption likelihood. 'Resilient' raw material supply chains are particularly necessary if there is a high perturbation likelihood with high impacts on the system, which reveals the need for integrating both concepts. Works from the field of critical raw material resilience provide essential steps toward integrating criticality and resilience for specific material supply chains but remain vague in discussing the concepts' commonalities and contrasts, which would be the basis for a generalizable integrated framework. Against this background, this work investigates the following questions:

- *RQ1: What are the commonalities and contrasts of raw material criticality assessments and supply chain resilience considerations?*
- *RQ2: How can the two concepts be merged into an integrated framework?*
- *RQ3: What are the advantages of applying the integrated approach?*

The article first reviews state-of-the-art resilience considerations, raw material criticality assessments, and both in the context of critical raw materials. Emerging from this, an integrated concept for the resilience and criticality assessment of raw materials is proposed and applied in a brief case study on Gallium from an EU perspective. Finally, we discuss the resilience terminology in the European Critical Raw Materials Act and the limitations of our work.

2. State-of-the-Art

2.1. Supply chain resilience

The term *resilience* originates from the Latin term *resilire,* which could be translated to *rebound*. The term is popular in several research fields, such as psychology, livelihood, and human, animal, social, economic, or ecological systems, with the commonality that resilience is the *process of dealing with a disturbance*. Existing literature within the field of economic and ecological systems can be divided into *engineering resilience* and *ecological resilience* (Holling, 1996; Meerow and Newell, 2015). The more traditional engineering resilience puts stability around an equilibrium state at the center and covers how well a system absorbs and recovers from disturbances (Holling, 1996). It is a *reactive concept* centered around capacities that take effect after a disruptive event. Ecological resilience concentrates on ever-changing systems with multiple stable states, such as the ecosystem.

Supply Chain Resilience (SCR) is a rather new concept that can be ascribed to the concept of engineering resilience. It was most likely established by Fiksel (2003) and has been refined by several works since then (Bruckler et al., 2024; Poulin and Kane, 2021). It is usually defined as a combination of preparedness for a disturbance and the ability to respond, recover, and maintain a positive equilibrium state within reasonable costs and time (Pires Ribeiro and Barbosa-Povoa, 2018), Bruneau et al. (2003) introduced a conceptual framework that mapped a system's performance degradation due to a disturbance and the subsequent development over time. This enables to quantitatively study how a system deals with disruption, resulting in the so-called resilience curve depicted in Fig. 1, primarily applied in SCR research.

Through a comprehensive literature study, Bruckler et al. (2024) synthesized metrics to quantitatively describe the curve, thereby setting a state-of-the-art for quantifying supply chain resilience. Even though the literature applies various terms, there is a broad consensus that supply chain resilience is determined by a system's *absorptive, adaptive*, and *restorative* capacity (Bruckler et al., 2024). The absorptive capacity determines the system's ability to instantaneously absorb, withstand, or resist disturbances. In some publications, this capacity is directly linked to the system's vulnerability, which in resilience literature is defined as the amount by which the performance immediately degrades in light of perturbations (Bruckler et al., 2024). Chapter 2.2 discusses 'vulnerability' regarding raw material supply chains. The adaptive capacity determines the ability of a system to flexibly find adaptation options to recover from the negative effects of disturbances (Biringer et al., 2013; Vugrin et al., 2011). The restorative capacity refers to the system's ability to repair or restore efficiently and effectively to recover the effects of performance degradation(Biringer et al., 2013; Vugrin et al., 2011). In total, 17 quantitative metrics assess sub-aspects of resilience, including the time-based metrics, such as the *resistive duration*, the *absorb duration*, the *endure duration*, the *recovery duration*, performance-related metrics, such as the *depth of impact*, the *critical threshold*, the *residual capacity*, the *residual performance,* and the *restored performance*, rates, such as the *failure* and *recovery rate*, and time integrals such as the *cumulative absorptive performance* (Fig. 1 includes all metrics). The 'performance' of a system is key in SCR considerations. However, an unambiguous measure for 'performance' does not exist, and depending on the key indicators of an organization or a system, several perspectives on performance can exist (Bruckler et al., 2024). It could be the production volume of a manufacturer, the revenue, profit, or service provision to customers in absolute or relative terms. Concerning raw materials, performance might be expressed as the mining production capacity of a mineral, demand coverage, or the price of a material.

Leaving the field of supply chain resilience, scientific literature increasingly pays attention to the *transformative capacity*, which refers to the ability to leave existing paths to achieve required changes proactively (Reyers et al., 2022). Elmqvist et al. (2019) argues that resilience goes beyond merely considering absorption of and recovery from disturbances and pleads for additionally considering the capacity for proactive transformation to maintain a specific function. This perspective puts the *desired function* of a system at the core and goes beyond merely sustaining existing structures (Elmqvist et al., 2019). Applying this thinking to critical raw materials shifts the focus on maintaining desired functions relevant to society instead of ensuring the availability of specific raw materials. However, this would require value judgments as to which function is desirable for society and which is not. Often, such a desirable function is undefined or highly subjective, wherefore the

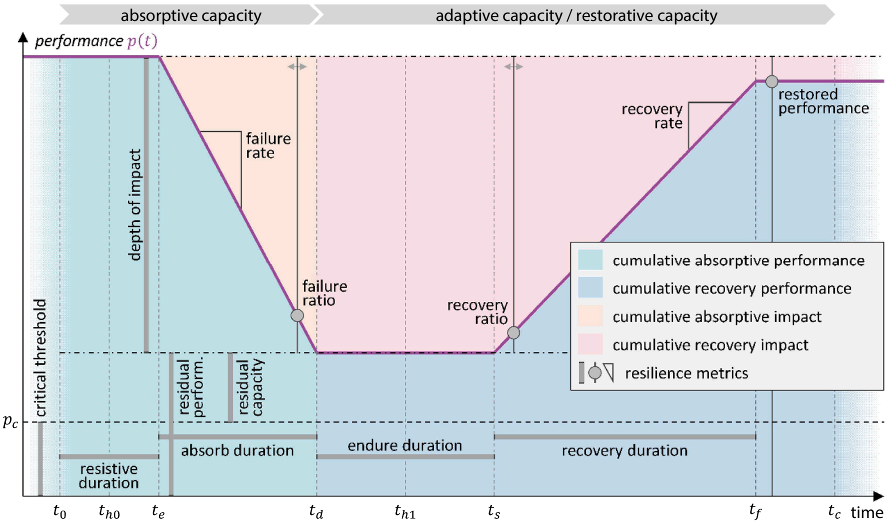


Fig. 1. Generalized resilience curve divided into the absorb and recovery phase with 17 resilience metrics that are either time-based (e.g., resistive duration), performance-related (e.g., depth of impact), rates (e.g., failure rate), and time integrals such as the cumulative absorptive performance (Bruckler et al., 2024).

transformative capacity cannot be assessed in those cases.

Supply chain resilience: In this work, the resilience definition is based on the SCR concept: The resilience is a property of a system that decides upon how its performance evolves over time – before, during, and in the aftermath of perturbations – and depends on the absorptive, adaptive, and restorative capacities.

2.2. Raw material criticality

The concept of criticality has gained attention due to the increasing dependence of modern society on specific raw materials and significant disruption events questioning the unlimited supply of these raw materials. The definition of Critical Raw Materials (CRMs), also referred to as Critical Minerals, is that they are essential for various applications and, therefore, are highly economically important and are facing a high risk of supply disruptions. Raw material criticality assessments can determine lists of CRMs and also quantify gradual levels of criticality (Gunn, 2014). To account for potentially changing global dynamics, CRM lists are often periodically updated, e.g., by national bodies like the European Commission and the United States Geological Survey. These lists are often the cornerstone for policy decisions, research and development prioritization, and investment strategies, e.g., resource efficiency, substitute development, and circularity strategies (Helbig et al., 2021b).

Criticality assessments: tools to identify and prioritize materials requiring attention typically consisting of two dimensions (Dewulf et al., 2016; Helbig et al., 2016b, 2021a; Kullik, 2024): supply risk and vulnerability to supply disruptions, as shown in Fig. 2. Those two dimensions are assessed from a global, national, sector/industry, or technology-focusing perspective by a variety of different indicators (Schrijvers et al., 2020a).

Supply risk: expresses the likelihood of a supply disruption. The ten most used indicator groups for supply risk are market concentration, scarcity, political instability, regulation risks, by-product dependence, dependence on primary production, lack of substitution options, demand increase, price volatility, and import dependence (Helbig et al., 2021a). Market concentration is the degree to which a few countries or companies dominate the supply. High concentration increases the risk of supply disruptions due to geopolitical or economic factors. Scarcity refers to the physical availability of the material, often measured by the reserves-to-production ratio, indicating how long known reserves can meet current production levels. Political instability indicates supply disruptions due to political unrest or policy changes in producing regions, often based on the Worldwide Governance Indicators. Regulation risks address potential impacts from changes in environmental regulations, trade policies, or mining laws that could restrict the production and trade of a material. By-product dependence refers to materials mainly produced as by-products of other mining processes that are less responsive to changes in demand and, therefore, dependent on their host material. Dependence on primary production is the reliance on primary production for a material compared to secondary production. The lack of substitution options describes the difficulty of replacing a material with a viable substitute. Demand increase assesses the additional material demand growth due to future technologies. Price volatility is the fluctuation of market prices of a material, which can indicate underlying supply risks. Import dependence is a specific indicator for nation-perspective assessments and describes the ratio to which a

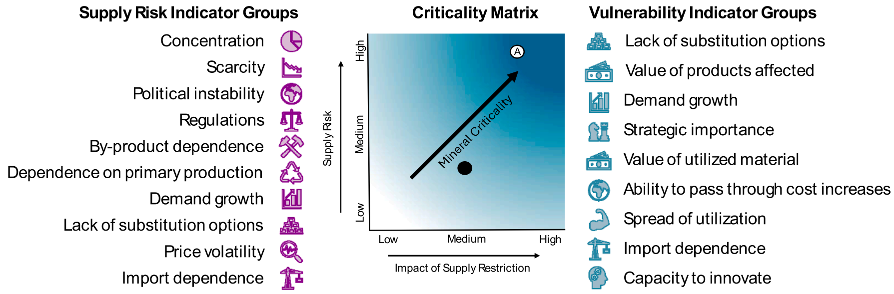


Fig. 2. Criticality matrix and frequently used indicator groups for supply risks and vulnerability. Figure adapted based on National Research Council (2008); Helbig et al. (2016b); Helbig et al. (2021a), and Schrijvers et al. (2020a).

country relies on imports for the supply. Higher imports are considered to pose higher supply risks.

Vulnerability: expresses the scale of the effect of a supply disruption on the investigated system, wherefore the required approach depends on the chosen perspective (Dewulf et al., 2016; Helbig et al., 2021b). A global perspective focuses mainly on the overall availability and distribution of materials, considering the interconnected nature of global supply chains. From a national perspective, countries assess criticality based on the material's importance to their economy. Using the added value to industry sectors is a possible measure of raw materials' economic importance and vulnerability, especially in the downstream supply chain. Taking a sector or industry perspective, industries often estimate the potential damage caused by the disrupted supply of a material resource, e.g., by quantifying the revenue of products or through higher prices, through the inability to pass on cost increases to the customer, which makes the production activity less profitable. When a technology perspective is taken, certain technologies may rely heavily on specific materials, making those materials critical to the technology's continued development and deployment.

Frenzel et al. (2017) suggest that supply risk should be calculated as the integral of the product of likelihood and vulnerability over supply disruption scale and time. Unfortunately, even more than five years after the concepts' publication, it remains challenging to obtain reliable data to accurately predict supply risks and vulnerabilities.

2.3. *Critical raw material resilience*

Since 2015, a few scientific works have been published that attempt to establish a link between raw material criticality and resilience. As Table 1 shows, most published works assess only a single or very few elements, with a clear focus on materials for decarbonization, such as Rare Earth Elements (REE), cobalt, and lithium. The restriction on single elements within one study is most notable in works that apply system dynamics. In the identified literature, two main approaches can be distinguished.

The most prominent research stream consists of several works based on or extending the work of Sprecher et al. (2015), who were the first to introduce a framework for assessing resilience in critical raw material supply chains. They investigated which mechanisms in NdFeB supply chains provide resilience and what policy recommendations can be drawn from the insights to improve resilience. The authors assume resilience as the "*sum of several generic system dynamics*", wherefore the work is based on expert interviews to gain insights on the NdFeB supply chain to set up a *system dynamics model*. They identified *resistance, rapidity*, and *flexibility* as the most important mechanisms to overcome disruptions like natural disasters, trade embargoes, and stock depletion in NdFeB supply chains. Sprecher et al. (2017) studied the resilience of CRM supply chains in the case of REE. They suggested evaluating mechanisms like supply diversity, substitution, change of material property, and stockpiling to overcome disruptions (e.g., socio-political tensions or natural disasters). Similarly, Mancheri et al. (2018) applied this approach to analyze the resilience of the tantalum SC, focusing on the same mechanisms. Mancheri et al. (2019) explored the impacts of Chinese policies on REE supply chain resilience, considering factors like trade restrictions and Chinese influence on supply chain dynamics. Brink et al. (2020) extended the knowledge of individual mines, refineries, and trade flows of cobalt and applied network analysis to identify powerful companies in the cobalt supply chain. Brink et al. (2022) studied the antimony SC in light of resilience. Shao and Jin (2020) and Liu et al. (2023) set up a comprehensive system dynamics model to evaluate the resilience of the Chinese lithium and cobalt SCs and revealed China's low resilience towards reductions of cobalt imports.

The second research stream on critical raw materials resilience builds upon the publication of Blagoeva et al. (2016), who used an indicator-based framework. They considered an upstream and downstream dimension of material supply chains to assess the EU's resilience. The approach is based on the EU criticality methodology and complements it with forward-looking aspects (European Commission, 2014). The approach incorporates, for example, the EU's financial capacity to react to supply bottlenecks. Indicators such as the investment potential indicate the EU's restorative capacity by potential upstream supply chain expansion, and the purchasing potential indicates the

Table 1
Literature review of works on critical raw material resilience.

Short	Year	Title	Method	Element
Sprecher et al.	2015	Framework for Resilience in Material Supply Chains, With a Case Study from the 2010 Rare Earth Crisis	System Dynamics	REE
Sprecher et al.	2017	Novel Indicators for the Quantification of Resilience in Critical Material Supply Chains, with a 2010 Rare Earth Crisis Case Study	Event Sequence Analysis	REE
Mancheri et al.	2018	Resilience in the tantalum supply chain	System Dynamics	Tantalum
Mancheri et al.	2019	Effect of Chinese policies on rare earth SC resilience	System Dynamics	REE
Brink et al.	2020	Identifying supply risks by mapping the cobalt SC chain	SC Network Analysis, indicator framework	Cobalt
Shao and Jin	2020	Resilience assessment of the lithium supply chain in China under impact of new energy vehicles and supply interruption	System dynamics	Lithium
Brink et al.	2022	Resilience in the antimony supply chain	System Dynamics	Antimony
Liu et al.	2023	Resilience assessment of the cobalt supply chain in China under the impact of electric vehicles and geopolitical supply risks	System Dynamics	Cobalt
Blagoeva et al.	2016	Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU	Indicator framework	Several
Yan et al.	2020	Rethinking Chinese supply resilience of critical metals in lithium-ion batteries	Indicator framework	Lithium, Cobalt
Yu et al.	2022	International trade network resilience for products in the whole industrial chain of iron ore resources (in Chinese)	Interrupt simulation methods	Iron ore
Yu et al.	2023	Resilience assessment of international cobalt trade network	Interrupt simulation methods	Cobalt
Song et al.	2024	Resilience assessment of trade network in copper industry chain and the risk resistance capacity of core countries: Based on complex network	Complex network methods	Copper
Gervais et al.	2025	Tracing the propagation of disruptions in supply chain scenarios: A case study of photovoltaics diversification	(non-)linear programming	PV-SC

ability of individuals to pay higher prices for products in case of price peaks due to supply shortages. Yan et al. (2020) built upon the JRC methodology to study the Chinese supply resilience of critical raw materials in lithium-ion batteries. The indicator-based framework of Blagoeva et al. (2016) allows the analysis of several elements within one study.

Furthermore, three works apply a complex network theory approach and study the import and export relations between countries based on *network indicators*. Song et al. (2024) evaluate the global copper supply network by six indicators: degree (trade flow intensity between countries), path length (minimum average number of sides in a trade relation), density (degree of prosperity in trade between countries), clustering coefficient (trade connections in the trade network), hierarchy (number of trade relationships of a country), and matching (tendency of countries in the network to establish trade relations). Yu et al. (2023) apply an interrupt simulation method and consider three indicators: *degree of hierarchical distribution* (total number of trade connections of a country), *degree of matching association* (preferred relationships between countries), and *agglomeration - average clustering coefficient* (clustering of connections). Yu et al. (2022) investigate the resilience of 20 global economies for the iron ore supply.

Gervais et al. published 2025 a novel mathematical programming approach for determining risk-optimized photovoltaic supply chain configurations from raw materials over intermediates to the final modules through diversification strategies. Compared to most other works, they investigate a whole product supply chain and particularly evaluate the effect of export restrictions on each SC stage from a national perspective under different diversification scenarios (Gervais et al., 2025).

While Sprecher et al. (2015) identified resistance, rapidity, and flexibility as the main drivers of raw material resilience, a review on supply chain resilience showed that most SCR publications refer to the *absorptive capacity* when discussing the ability to resist disturbances, *restorative capacity* when discussing the ability to rapidly restore the original functionality, and *adaptive capacity* when referring to the ability to adapt to new conditions flexibly (Bruckler et al., 2024). To harmonize terms of closely related research fields, we apply the terms absorptive, restorative, and adaptive when referring to a system's resilience capacities. Resilience *drivers,* also referred to as *actions, measures, mechanisms,* or *strategies,* determine these capacities (Bruckler et al., 2024; Sprecher et al., 2017). If a driver is in the sphere of influence, it may proactively be controlled by decision-makers before a disturbance occurs. Well-developed absorptive, restorative, and adaptive capacities increase the ability to *react* rapidly and effectively. The transformative capacity accounts for the ability to *proactively* leave a path of low resilience (Elmqvist et al., 2019). Table 2 allocates drivers identified in the analyzed literature to the addressed capacity and shows an estimated temporal scope.

Table 2
Drivers of critical material resilience based on the analyzed literature.

Driver of resilience	Description	Temporal scope	Reference
Absorptive capacity – Reactive			
Strategic Stockpiles	Instantly available raw materials to buffer supply disruptions	Short	Sprecher et al. (2015)
Ability to pass-through cost increase	Competitive situations (or other factors) that might allow passing-through cost increases	Short	Duclos et al. (2008)
Purchasing power	Individual purchasing power of citizens indicates a potential to pay a higher price for a product	Short	Blagoeva et al. (2016)
Diversification	Diversified supply chains are less susceptible to the collapse of a supplier	Short	Gervais et al. (2025)
Restorative capacity – Reactive			
Investment potential	Higher investment. potential indicates a possible expansion of the material SC upstream	Medium	Blagoeva et al. (2016)
Preparation to build/expand primary production	Preparations may include accepted permits, finalized building plans, availability of required land, etc.	Medium – long	Adapted from Sprecher et al. (2017), (Koese et al., 2025)
Qualified reparation staff	Reparation of specific processes or transportation modes by qualified staff	Short – Medium	Vugrin et al. (2011)
Adaptive capacity – Reactive			
Material efficiency	Improvement of material efficiency by changing properties, dimensioning, etc.	Medium – Long	Adapted from Sprecher et al. (2017)
Substitutability	Unique material properties lead to 'price of substitution' (performance, availability, cost,..). Good substitutability indicates low detriments through using substitute	Short – Medium	Duclos et al. (2008); Graedel et al. (2012); Sprecher et al. (2017)
Recyclability	Indicates the potential feasibility of recyc-ling a material. Good recyclability means low cost, availability of technology, etc.	Medium	Graedel et al. (2012); Sprecher et al. (2017)
Innovation potential	Indicates how quickly a system is able to adapt to a supply restriction by innovations	Short-Long	Graedel et al. (2012)
Exploration	Successful exploration projects speed up the buildup of new primary production	Medium - Long	Adapted from Sprecher et al. (2017)
Backup supplier	General availability, already established business relations, contracts, etc., with potential backup supplier	Short – Medium	Hosseini et al. (2019)
Transformative capacity – Proactive			
Innovation potential	Indicates how quickly a system is able to adapt to a supply restriction	Medium	(Graedel et al., 2012)

Absorptive capacity: decides upon a system's ability to absorb, withstand, or resist perturbations instantaneously. Drivers of the absorptive capacity are characterized by their immediate availability. *Strategic stockpiling* of raw materials allows instant buffering of supply disruptions, as mentioned in various works on CRM resilience. Stockpiles may come at high costs and are always limited depending on the material prices. The *ability to pass through cost increases* in used criticality assessments to account for a competitive situation, which allows passing-through raw material cost increases, thereby offsetting supply shortages. Similarly, the *purchasing power* of individuals can be used to account for a potential readiness to pay higher prices for products.

Restorative capacity: refers to the system's ability to repair or restore efficiently and effectively to recover the effects of performance degradation. Drivers are characterized by their contribution to restoring original functionalities. The *investment potential* accounts for the ability of vertical backward integration to ensure the supply of materials. Sprecher et al. (2015) used the *buildup of new primary production* as a measure to increase the diversity of supply. This measure would help restore performance in case of supply disruptions; however, in our opinion, it cannot be termed a *driver* to strengthen a capacity. If new primary production is built before a disruption, we argue that this measure reduces the supply risk and, in turn, the criticality. Instead, actions that lay the foundations for a rapid buildup or expansion in case of disturbances, such as executing approval procedures, acquiring permits, or feasibility assessments, increase the restorative capacity. Therefore, we use the *preparation to build/expand primary production*. The ability to rapidly repair disrupted parts of a supply chain strengthens the restorative capacity (Vugrin et al., 2011). However, this ability is very context-specific since reparation capacities can only be answered concerning a specific item of the supply chain (e.g., a specific process or transportation mode)

Adaptive capacity: determines the ability of a system to flexibly find adaptation options to recover from the negative effects of disturbances. Drivers are characterized by their contribution to increasing adaptation flexibility. *Increasing material efficiency* in light of disruption can partly offset a performance decline; however, implementation usually takes several years. *Substitutability* is mentioned in several studies and refers to the capacity to replace a material with a substitute in case of disruption. It can be assumed that a material usually has unique properties, wherefore substitution comes at costs, such as a lower performance, limited availability, or a higher price. Research and development on potential substitutes and their integration into product systems increase the substitutability. *Recyclability* refers to the ability to recycle material in terms of economic feasibility, quality, availability of technology, availability of recycling capacity, and availability of End-of-Life materials for recycling. It differs from the actual recycling already done, which impacts the criticality of a material. The *innovation potential* can indicate the ability to quickly adapt to supply disruptions by new solutions without further detailing how a solution might look.

Transformative capacity: focuses on maintaining function by proactive transformation, potentially by entirely new solutions (Elmqvist et al., 2019). The *innovation potential* indicates a system's ability to identify entirely new materials or technologies that outperform (in terms of cost, availability, quality, etc.) currently available alternatives in providing a specific function. Furthermore, it indicates the potential for providing completely new functions that possibly displace other functions. Innovation can take place without the pressure of a disrupted supply chain, wherefore it might allow a proactive switch to a better alternative and, therefore, has a *transformative* character (Elmqvist et al., 2019). Besides the *reactive* absorptive, restorative, and adaptive capacities, the innovation potential is characterized by its *proactive* character. It does not consider the supply chain of a specific material but puts function at its core.

3. Integrated concept for criticality and resilience assessment

3.1. Methodological foundation

While the supply risk in criticality assessments indicates the likelihood of a disruption, resilience assessments usually neglect the probability of such events. On the other hand, resilience science considers the process of recovery from disruption and the capacities facilitating it, which is mostly disregarded in criticality assessments. Given the assumption that it will particularly be necessary to build up resilience capacities if there is a high likelihood of disturbances together with high impacts on the system, the need for integrated approaches becomes obvious.

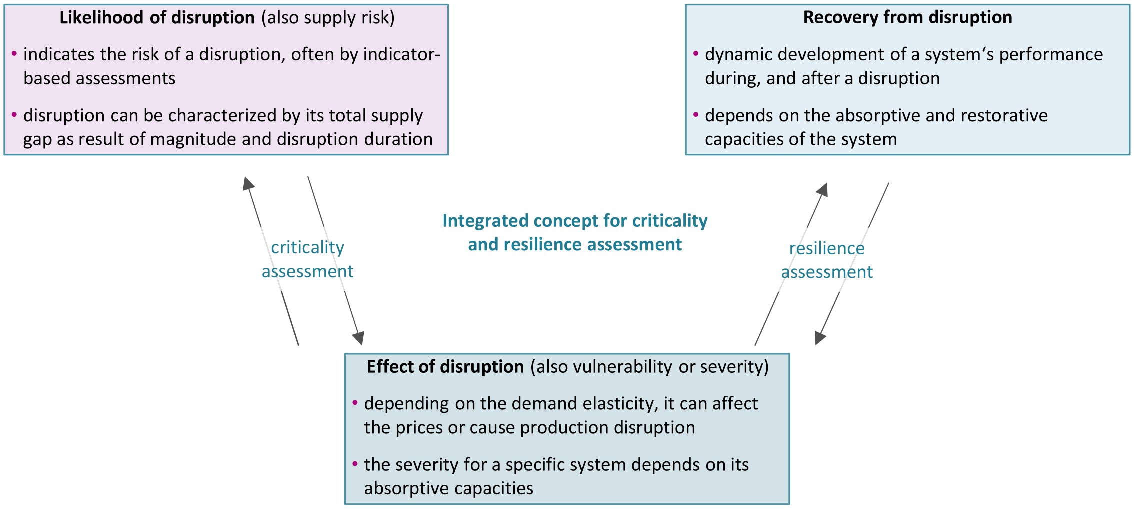
We find a high commonality between the effect (or scale) of damage due to a supply disruption, which in criticality assessments is usually termed 'vulnerability' or 'level of severity', and the 'performance degradation', which in resilience research frequently quantifies the absorb phase (e.g., depth of impact or cumulative impact). The effect of disruption thus constitutes the link between those two concepts. Fig. 3 shows the nexus of raw material supply security, the effect of disruption, and the subsequent recovery.

One prominent exception in criticality assessments is the concept of Frenzel et al. (2017), who considered raw material criticality as the integral over supply disruptions of varying scale (x) over time (t) with the likelihood $p(x,t)$ of a disruption of that scale x at time t multiplied with a vulnerability factor $v(x,t)$ for each of these possible disruption scales at all times, as shown in following equation (Frenzel et al., 2017):

$$C = \int dt \int dx\, p(x,t)\cdot v(x,t)$$

In theory, this concept addresses criticism about criticality assessments (Kullik, 2024): It is time-dynamic, includes multiple possible scenarios and their likelihood, and introduces a vulnerability factor that can be interpreted as the systems' performance equivalent to integral-based metrics in resilience assessments. However, one must acknowledge that the double integral will hardly ever be solved as the data for each supply disruption scale and point in time are scarce.

Additionally, Fig. 4 shows that the vulnerability factor does not mark the end of the supply disruption effect chain: the disrupting event reduces the available supply, and the combination of scale and duration characterizes this event. The disruption scale can, for example, be quantified as a percentage of global or domestic production capacity that is temporarily unavailable. The duration of supply disruption is the total time passed between the event and supply restoration back to the


Likelihood of disruption (also supply risk)
- indicates the risk of a disruption, often by indicator-based assessments
- disruption can be characterized by its total supply gap as result of magnitude and disruption duration

Recovery from disruption
- dynamic development of a system's performance during, and after a disruption
- depends on the absorptive and restorative capacities of the system

Effect of disruption (also vulnerability or severity)
- depending on the demand elasticity, it can affect the prices or cause production disruption
- the severity for a specific system depends on its absorptive capacities

Fig. 3. Qualitative link of raw material criticality and resilience assessments in an integrated concept with the 'effect of disruption' constituting the linking element.

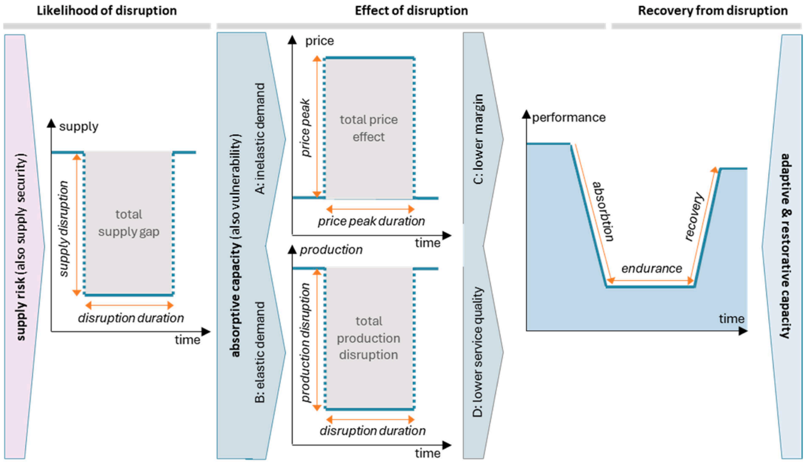


Fig. 4. Supply disruption effect chain, including the likelihood of disruption, its effect pathways, and the subsequent recovery phase. The likelihood of disruption refers to the traditional 'supply risk' and should provide information on the disruption scale and duration. The effect of disruption is determined by the absorptive capacities and depending on the demand elasticity results in lower margins or lower service quality or a mix of both. The recovery is determined by the time and scale of adaptive and restorative capacities.

original level. Multiple empiric characterizations of historic supply disruption events for critical raw materials have been carried out so far (Hatayama and Tahara, 2018; Kühnel et al., 2023; Santillán-Saldivar et al., 2021).

As has been discussed by Frenzel et al. (2017) and by Helbig et al. (2016a), the effect of such a supply disruption can differ depending on the market dynamics. If demand is very inelastic, a supply disruption will cause a price increase (Fig. 4, A). If demand is very elastic, then the same supply disruption will cause a decline in production (B). Of course, both effects are possible simultaneously to different extents, and the effects superpose each other. Frenzel et al. (2017) highlight that monetary cost is one of the various options for measuring vulnerability. Within the criticality framework, the likelihood of potential supply disruptions of varying scale and duration combined with a direct vulnerability-based effect of such a disruption expressed in reduced production or increased prices is an expression of raw material criticality.

This is where resilience comes into play with its time-dynamic perspective. Those dynamics are essential in the event assessment, and the direct impact of a disruption to prices or production volume might not be the ultimate performance measure. As Fig. 4 shows, an increasing raw material price might affect the margins of businesses (C), and if production volumes are decreased, it may affect service quality (D). Both direct effect pathways can impact the business or sector performance. However, affected systems are not necessarily unprotected against such disruptions. Still, they can proactively strengthen their capabilities to absorb disturbances and rapidly recover in the aftermath, thereby partly or fully restoring the original performance. Additionally, some supply disruptions may very well be permanent. Even if prices never return to normal or production volumes are reduced indefinitely, a resilient system may recover its performance through material substitution, product changes, or adaptations to business models.

Similar to Schrijvers et al. (2020a), we plead for an integrated concept of criticality and resilience that considers three dimensions: the likelihood of disruption, its effect, and subsequent recovery from disruption. Table 3 comprises indicators with a clear causal link to each of the three dimensions. Table A1 of the appendix describes each indicator in detail and discusses its causal relation to the respective category. In previous studies, several indicators have been ascribed to one of the dimensions where we do not see a causal relationship. Table A2 of the appendix also discusses those indicators and provides reasoning for their exclusion from the respective dimension. Although we attempt to provide a comprehensive list of available indicators, it is not necessarily exhaustive. Neither do all these indicators have to be used in assessments simultaneously.

Likelihood of disruption: indicators of this category must be causally related to the likelihood of disruption, which must be confirmed by a rational explanation for the qualitative or quantitative relationship. Table 3 shows the identified indicators for the likelihood of disruption, based on the reviews of Helbig et al. (2021a) and Schrijvers et al. (2020). Indicators such as a high concentration of mineral deposits, physical scarcity expressed by the depletion time, or political instability in producing countries are causally linked to the disruption likelihood through varying mechanisms. Other frequently mentioned indicators for the supply risk do not have a causal link: both *lack of substitution options* and *recyclability* neither increase nor reduce the likelihood of a supply disruption of a given material directly. Lacking substitutes rather indicates that substitution is not an available option to recover from disruption. Similarly, recyclability expresses the ability to recycle an element; however, without upscaled processes or missing facilities, it will hardly influence the likelihood of disruption. Instead, both can be options for recovering from a disruption. Short- or long-run physical resource scarcity results in rising commodity prices (Schischke et al., 2023; Tilton et al., 2018), wherefore price volatility is more the result of shocks (e.g., physical supply disruptions or expected shortages) than their cause.

Effect of disruption: Indicators that are causally linked to the *effect of disruption* include strategic stockpiles, which can temporarily absorb supply disruptions, or the ability to pass through cost increases, which enables the purchase of resources even during disruption-induced price peaks without compromising the own profitability. Other frequently mentioned indicators reflect that the material is important within a given value chain due to a high internal demand, several dependent products, strategic importance, or a high dependent revenue (e.g., revenue impacted, population using the material, the use in emerging technologies, price vs. profit). Especially in this dimension, several indicators listed under the *effect of disruption* (also vulnerability) found in literature lack a causal link, however are related to the likelihood of disruption, such as demand growth, trade restriction, import dependency, future demand-to-supply ratio, import dependency, company concentration, change in imports, and mining production share. Even if a good substitutability for a material is given, a company has a high ability to innovate, or a material in principle is recyclable, it will take time to implement the required actions, wherefore an instantaneous disruption effect is not mitigated. Therefore, those indicators relate to the capacity to recover from a disruption (find a detailed discussion in

Table 3
Literature-based set of indicators potentially applied in integrated Critical Raw Material Resilience concepts. The table includes a list of all indicators with clear causal links to the respective dimension and the underlying references. Table A1 of the appendix includes a detailed description of each indicator, a explanation of the causal link, and a conclusion on the allocation to the respective dimension. Table A2 of the appendix provides a list of indicators that were allocated to one of the three dimensions by literature where no causal link exists (based on our assessment).

Indicator	References
Causal link to the likelihood of disruption	
Concentration of resources or refining, scarcity, political instability, regulations, by-product dependence, dependence on primary production, demand growth, import dependence, environmental or social regulations, mining/production efficiency, global production, environmental impact, exploration conditions, local natural environment, materialization capacity, production growth, mining technologies, natural disasters, resource competition, circularity metrics, degree of exploration, geological specificities, logistic restrictions, trade restrictions	(Helbig et al., 2021a; Schrijvers et al., 2020b)
Causal link to the effect of disruption	
Strategic stockpiles, ability to pass-through cost increase (also price sensitivity), purchasing power (regional scope), economic size of sector, internal demand, demand vs. world production, market power regarding suppliers, revenue impacted, population using the material, use in emerging technologies, price vs. GDP, availability of hedging options, apparent consumption, price vs. profit, procurement strategy, strategic importance, value of products affected, value of the utilized material, spread of utilization, consumption volume, diversification	(Blagoeva et al., 2016; Duclos et al., 2008; Gervais et al., 2025; Helbig et al., 2016b; Schrijvers et al., 2020a; Sprecher et al., 2015)
Causal link to the recovery from disruption	
Adaptive and restorative capacity: investment potential, preparation to build up or expand primary production, material efficiency, substitutability, recyclability, innovation potential, exploration, backup supplier, qualified reparation staff *Transformative capacity:* innovation potential or ability to innovate	(Blagoeva et al., 2016; Duclos et al., 2008; Graedel et al., 2012; Sprecher et al., 2017; Vugrin et al., 2011)

Table A2 of the appendix).

Recovery from disruption: Indicators linked to *recovery* are separated into adaptive and restorative ones, representing the ability to react to disturbances. Indicators are, among others, the investment potential, which shows the ability for vertical integration, the preparation to build up or expand primary production, or the substitutability and recyclability, which both can be understood as abilities that can come into effect when raw material prices increase, or physical shortages occur. Apart from reactive capacities, we additionally introduce a proactive transformative capacity with the indicator ability to innovate, which represents the capacity to proactively leave a high-risk path. Innovations of this kind can, for example, be material innovations that enable substituting materials with a high disruption probability by innovative ones with a low likelihood.

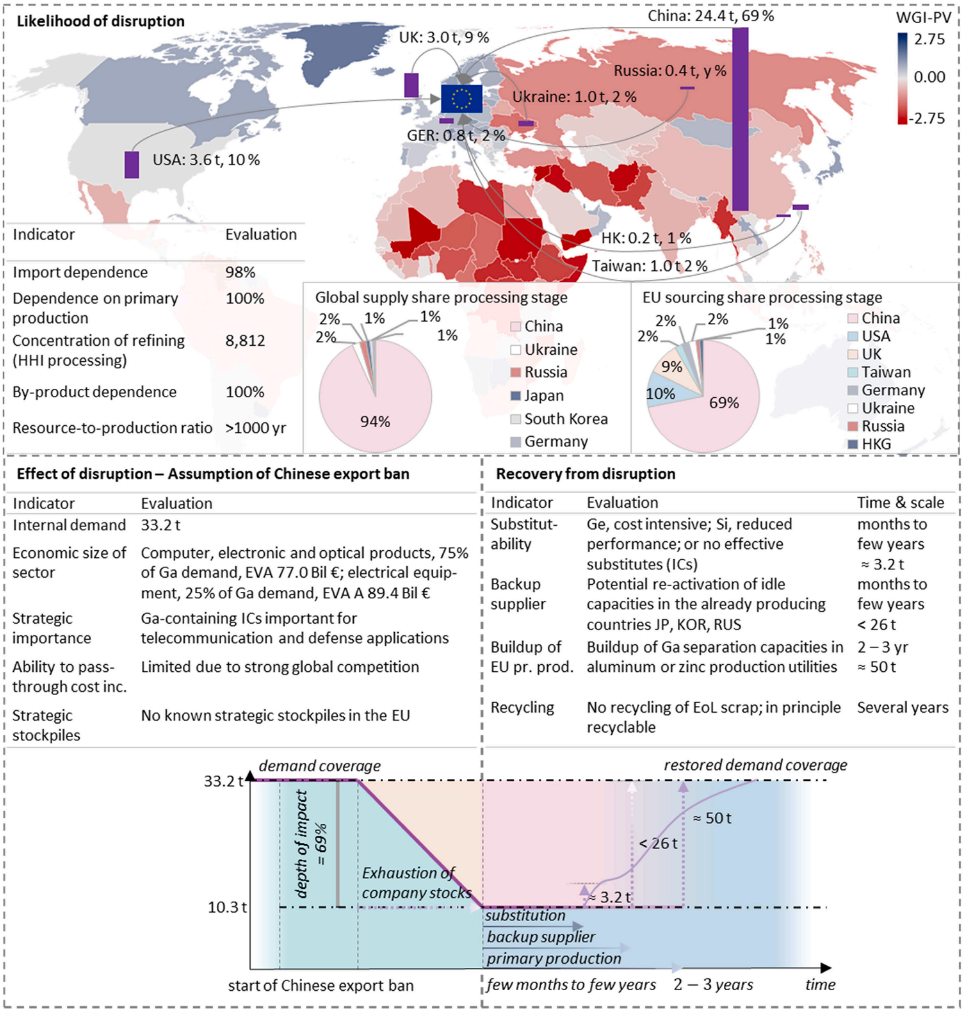
3.2. Gallium case study

In this section, we qualitatively apply the integrated framework to Gallium, which is frequently considered critical from the EU perspective (European Commission, 2023a). Gallium has recently also gained public attention because China imposed an export ban to the USA in late 2024 and a mandatory export registration (Lv and Munroe, 2024). This case study briefly illustrates the implication of applying the integrated framework from the perspective of the European Union. Gallium is a metal that is used for semiconductors like gallium arsenide and gallium nitride in integrated circuits (ICs), light-emitting diodes, and thin-film photovoltaics made out of copper indium gallium diselenides (SCREEN2, 2023). Gallium production nowadays is predominantly happening in China (USGS, 2024). Therefore, the evaluation of the criticality and resilience of the gallium supply chain from a European perspective is a relevant question. Fig. 5 illustrates a not necessarily conclusive collection of indicators for the likelihood of disruption, the fictive simulation of the effect of a Chinese export ban to the EU, and potential ways for recovering from disruption.

Likelihood of disruption: Gallium is only mined as a by-product of aluminum mining (Løvik et al., 2015). During the processing of aluminum, gallium needs to be separated. Otherwise, it either ends up in the waste by-product red mud or in aluminum alloys, both of which result in the material being permanently unavailable. Over the past two decades, China has become by far the largest gallium producer. This high market concentration with a Herfindahl-Hirschman-Index (HHI) above 8000 marks a significant supply risk for non-Chinese gallium users. Geopolitical tensions between China and the US, as well as previous events like the rare earth crises in the early 2010s and the price peaks observed for magnesium in 2022, for which similarly high concentrations of the market in China can be observed, illustrate that this market concentration induced supply risk is not only a theoretical risk, but a practical one. There are no significant post-consumer recyclate volumes available, therefore, the dependence on primary production is 100 %. For the European Union, 98 % of gallium supply is imported, again marking high supply risks. On the positive, while there are no quantitative estimates of gallium reserves available, physical scarcity is not a significant issue since resources are estimated to have a static reach of over 1000 years, which is more than sufficient (USGS, 2024). The Gallium trade ban to the USA established at the end of 2024 illustrates that an indefinite ban on Chinese exports to the EU is a realistic scenario. Although considerable efforts are made at different stages to avoid this, we will assume the scenario of a full ban of gallium commodity exports from China to the European Union to estimate the disruption effects and the potential subsequent recovery.

Effect of disruption: In the case of a sudden, unanticipated Chinese export ban, the by-far largest source of gallium for the EU would be disrupted. On average, between 2016 and 2020, the EU imported 71 % of its supply, or 24.4 t gallium, from China (SCREEN2, 2023). Europe used about 11 % of global gallium production (SCREEN2, 2023). To our knowledge, there are no strategic stockpiles of gallium in the EU that could instantaneously mitigate the effects. The sectors of gallium's application are the manufacture of computers, electronic and optical products, and electrical equipment, which are global sectors with high competition. The competitiveness of gallium users on the global market would significantly worsen due to a low ability to pass through cost increases. Some of the gallium-containing integrated circuits specifically have high importance for telecommunication and defense applications (Frenzel et al., 2016), further highlighting their strategic importance, which is exemplified in the identification of gallium as a Strategic Raw Material in the Critical Raw Materials Act.

Recovery from disruption: Substitution plays a subordinate role only since most applications hardly have substitutes or significantly reduce performance. Assuming a Gallium demand share of ICs at 70 % with a possible substitution of 6 % and a lightning share of 25 % with a possible substitution of 36 %, 3.2 t could be substituted (SCREEN2, 2023). Current non-Chinese supply is limited to a total production of 10 t in Japan, the Republic of Korea, and Russia and idle capacities of 36 t in those countries, yielding a maximum of 26 t for a re-activation from potential



Indicator	Evaluation
Import dependence	98%
Dependence on primary production	100%
Concentration of refining (HHI processing)	8,812
By-product dependence	100%
Resource-to-production ratio	>1000 yr

Effect of disruption – Assumption of Chinese export ban

Indicator	Evaluation
Internal demand	33.2 t
Economic size of sector	Computer, electronic and optical products, 75% of Ga demand, EVA 77.0 Bil €; electrical equipment, 25% of Ga demand, EVA A 89.4 Bil €
Strategic importance	Ga-containing ICs important for telecommunication and defense applications
Ability to pass-through cost inc.	Limited due to strong global competition
Strategic stockpiles	No known strategic stockpiles in the EU

Recovery from disruption

Indicator	Evaluation	Time & scale
Substitutability	Ge, cost intensive; Si, reduced performance; or no effective substitutes (ICs)	months to few years ≈ 3.2 t
Backup supplier	Potential re-activation of idle capacities in the already producing countries JP, KOR, RUS	months to few years < 26 t
Buildup of EU pr. prod.	Buildup of Ga separation capacities in aluminum or zinc production utilities	2 – 3 yr ≈ 50 t
Recycling	No recycling of EoL scrap; in principle recyclable	Several years

Fig. 5. Results of the Gallium case study clustered in the likelihood, effect, and recovery from disruption. For each dimension, a subset of possible indicators is shown and quantified. The countries are colored based on their Worldwide Governance Indicators in the category Political Stability and Absence of Violence (WGI-PV) score and lower values (red) refer to a higher risk.

backup suppliers (USGS, 2024). Since no detailed information on the idle capacities is available, we assume a fast re-activation is highly uncertain. The opportunity to expand primary production relates to the potential re-activation of European gallium separation capacities in aluminum or zinc production utilities. Due to the growing competition from China, previously large production volumes in countries like Germany have declined, and gallium processing has been stopped. Since 2023, when China announced export controls for gallium and germanium, companies and metal industry associations have repeatedly mentioned the possibility of restarting European gallium processing. However, investments might be faced with lacking cost-competitiveness on global markets due to higher energy and labor costs and a significant lead time (Koese et al., 2025). At the beginning of 2025, Metlen Energy & Metals SA announced an investment in a Gallium production capacity of 50 t annually at an already operating mine in Greece, seeking a production ramp-up in 2027, which would be sufficient to cover the whole European demand (Innovation Newsnetwork, 2025).

4. Discussion and conclusion

This work enhances the discussion on how the two concepts of *raw material criticality* and *resilience* can be integrated further. It builds upon the ongoing discussion initialized by Sprecher et al. (2015), who first applied resilience considerations for raw material supply chains and deemed resilience inverse to criticality by arguing that "*one can define the criticality of a material in terms of how resilient its supply chain is*". Dewulf et al. (2016) introduced the idea of resilience as a response to criticality, and Schrijvers et al. (2020) continued discussing whether a third 'resilience dimension' is needed to advance the criticality concept. Our work investigated similarities and differences between the two concepts by reviewing the scientific literature on supply chain resilience, criticality, and critical raw material resilience assessments. We found high conformity between the scale of damage due to a supply disruption, which in criticality assessments usually is termed 'vulnerability' or 'level of severity', and the 'performance degradation', which in resilience research frequently is applied to quantify the absorb phase. This means that the disruption effect can be considered as the already existing link between these two concepts.

Similarly to Dewulf et al. (2016), we, therefore rather, see the two concepts as complementary and not inverse. Combining them results in a three-dimensional assessment model with the first dimension indicating the likelihood of a disruption, the second dimension indicating the effect of disruption, and the third dimension indicating the capacity for recovering from disruption. Similarly to Schrijvers et al. (2020a), we recognize vague cause-effect mechanisms between several indicators and the supply risk or vulnerability dimension they aim to explain. Many of the applied indicators in one of the two traditional 'criticality dimensions' instead refer to the system's capacity to react to disruptions (whether physical disruptions or price increases), which additionally emphasizes the need for a third 'resilience dimension' that covers a system's reaction on disruptions. The pilot case study on Gallium exemplifies a path towards elaborate implementation of the integrated framework. It explicitly differentiates between the (1) likelihood of disruption, which is high for Gallium from the EU perspective due to several reasons, (2) the instantaneous effect on the EU, which is high for gallium-using sectors due to a strong dependence on Chinese exports and no known strategic stockpiles, and (3) potential options for recovery, which includes minor Gallium volumes that could be substituted at lower performance, highly uncertain re-activation of idle capacities from potential backup suppliers, and the looming buildup of EU primary production, which could cover the entire domestic market in a few years. Although the case study is exemplary, the strengths of the integrated framework are already evident: the range of available levers and their mechanisms are revealed and presented in a temporal order. The EU's dependence on Chinese gallium exports is expected to decrease in the foreseeable future, and with it, the likelihood of supply disruptions. However, until production is ramped up, an export ban will have massive effects, which could be reduced by dedicated resilience actions such as strategic stockpiling to enhance the absorptive capacity. The framework thereby enables political and corporate decision-makers to transparently assess the capacities and weaknesses of their raw material supply chain. If the analysis shows high supply disruption likelihood, low absorptive capacities, or weak capacities to recover from disruption, targeted decisions can be made regarding which measures should be implemented to strengthen the supply chain. At the political level in the EU (Critical Raw Materials Act) and in the UK (UK Critical Minerals Strategy), it has been recognized that resilience should be included in the strategy to ensure the secure and sustainable availability of raw materials.

4.1. Resilience in the critical raw materials act

The Critical Raw Materials Act (CRMA) is a cornerstone regulatory framework within the EU's strategy to ensure secure and sustainable access to strategic and critical raw materials. It aims to mitigate supply risks and foster domestic primary and secondary production capacities (Hool et al., 2024). Article 1 of the CRMA states that its general objective is "*to ensure the Union's access to a secure, resilient, and sustainable supply of critical raw materials*". The CRMA defines strategic raw materials (SRMs) based on their strategic importance, large production scale, and geological scarcity. Key factors are the relevance and expected demand of those raw materials for strategic technologies, like decarbonization (renewable energy, electric mobility, decarbonized industry), digitalization, aerospace, and defense, within the EU. Further, the CRMA defines Critical Raw Materials to include all SRMs and materials that surpass predefined thresholds for both economic importance and supply risk, where both values are calculated based on the methodology developed by the EU (Blengini et al., 2017).

The CRMA sets ambitious goals, so-called benchmarks, regarding the domestic mining, processing, and recycling capacity, which shall be equivalent to at least 10 %, 40 %, and 25 %, respectively, of the EU's annual SRM consumption. Further, no third country shall account for more than 65 % of the Union's annual SRM consumption (European Commission, 2023b). To realize those goals, the regulation defines strategic projects, which are required to contribute meaningfully to the supply of SRMs. One-stop-shop solutions for the permitting process are planned to support the development of critical raw material projects, prioritize recognized strategic projects, and significantly shorten the time for approval. Within the framework, extraction projects must receive a permit within 27 months, while processing and recycling projects must be approved within 17 months (European Commission, 2023b). Environmental impact assessments of strategic projects ensure compliance with the EU's broader environmental goals. However, the public consultation period is limited to 90 days since strategic projects are of "*overriding public interest*" (Hool et al., 2024).

Besides strategic projects, the CRMA includes measures to monitor and mitigate CRM supply risks. Stress tests for each SRM are carried out at least every three years (European Commission, 2023b). Strategic stockpiles are reported and coordinated to buffer against sudden supply shortages. Large companies must carry out risk assessments of their raw materials supply chain of SRMs. Joint purchasing agreements among EU member states are promoted to strengthen collective bargaining power in international markets. The CRMA highlights the importance of establishing partnerships with like-minded countries to ensure a stable and diversified supply of CRMs.

Domestically, member states are encouraged to foster national resource exploration programs to identify and develop new domestic sources of CRMs. Those exploration and strategic projects must align with the UNFC classification to standardize and enhance the sustainability of raw material projects across member states. To also foster domestic secondary production, specific national measures to promote circularity for CRMs are suggested, including targets for the domestic recycling of SRMs (Hool et al., 2024).

In summary, the CRMA lays out many activities to proactively reduce the risks faced by the European industry regarding its raw material supply. It also provides a few features to limit the potential scale of damage caused by supply disruptions. However, despite the prominent mention of the term *resilience* in its key objective in Article 1, it remains unclear how the agencies will measure whether a potentially strategic project increases resilience. The CRMA mentions resilience only twice in its further articles. Article 37 defines that third countries could be prioritized for the conclusion of Strategic Partnerships if they "*contribute to the resilience of supply*". Further, Annex III specifies that strategic projects in a third country shall "*contribute to maintaining the resilience of the Union's supply of strategic raw materials*". The text leaves open how this resilience contribution is achieved and proven. Therefore, following the integrated methodology for criticality and resilience obtained in this article, we propose that policy and industry action follow the three pillars of reduction of supply disruption likelihood, reduction of the effect of supply disruption, and improved recovery from disruption.

4.2. Limitations of our work and future research

While we qualitatively develop an integrated concept for criticality and resilience and exemplarily apply it in a Gallium case study, this work is not meant to be a ready-to-use tangible quantitative approach. We know that quantifying various disruption scenarios in complex systems, such as global raw material markets and strategic sectors, is highly laborious. As the work of Gervais et al. (2025) shows for the case of photovoltaic supply chains under different diversification scenarios it requires a detailed understanding of each case, including technical and economic modeling. The global need for decarbonization will increase the demand for raw materials, potentially leading to unbalanced supply-demand situations and subsequent supply shortages (Hertwich et al., 2015). Political initiatives such as the CRMA demonstrate the urgent need for integrated critical raw material resilience assessments to equip sustainable development by clean technologies with the required resilience.

Future works should develop elaborate quantitative concepts for integrated assessments that consider the three dimensions: *the likelihood of disruption, the effect of disruption*, and *recovery from disruption*. The case study shows how the integrated framework can practically be implemented for analyzing critical raw material supply chains. Future work needs to cover a range of elements, consider different realistic disruption scenarios, and analyze the time and scale of recovery options in depth. Such quantitative models could be used to assess the current state of supply risk and the available resilience capacities from the perspective of specific nations, regions, or companies. It could further be evaluated at what supply risk or effect threshold it becomes necessary to strengthen the absorptive or adaptive capacities actively. Integrated model developers should focus on disclosing and arguing the causal links between indicators and dimensions. This will enable (1) a more precise estimation of the probability of a disruption occurring, (2) the quantification of its potential impact by considering the system's absorptive capacities, and (3) allow a targeted strengthening of the abilities to overcome shocks.

CRediT authorship contribution statement

Lars Wietschel: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Christoph Helbig:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Martin Hillenbrand:** Writing – review & editing, Writing – original draft. **Andrea Thorenz:** Writing – review & editing, Conceptualization.

Declaration of competing interest

Co-author Christoph Helbig serves as a Guest Editor in RCR's Virtual Special Issue "Establishing Resilient and Sustainable Supply Chain of Critical Materials for a Low-carbon Future".

Appendix

Table A1

Indicators with clear causal link; L: Likelihood of disruption, E: Effect of disruption, R: Recovery from disruption.

	Indicator	Explanation	Causal link	Conclusion
L	concentration of resources or refining	Market concentration is the degree to which a few countries or companies dominate the supply. The market concentration is measured via the Herfindahl-Hirschman-index (HHI), which ranges from low concentration with 0 to monopoly with 10,000. (Dewulf et al., 2016; Helbig et al., 2021a)	High concentration increases the risk of supply disruptions due to geopolitical or economic factors. (Dewulf et al., 2016; Helbig et al., 2021a	Potential cause of disruption - likelihood of disruption
L	scarcity	Scarcity refers to the physical availability of the material, often measured by the reserves-to-production ratio, indicating how long known reserves can meet current production levels. (Dewulf et al., 2016; Helbig et al., 2021a; Schrijvers et al., 2020a)	Although it is unlikely that physical scarcity will limit the accessibility to any material in the foreseeable future, it is a measure of the market pressure for further exploration and mining expansion and the dependency on exploration and expansion to meet demand. (Dewulf et al., 2016; Helbig et al., 2021a; Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
L	political instability	Political instability indicates supply disruptions due to political unrest or policy changes in producing regions, often based on the Worldwide Governance Indicators (WGI). (Dewulf et al., 2016; Helbig et al., 2021a)	A lack of sufficient political stability and governance in countries where a major part of the materials are sourced can increase the likelihood of supply disruption. (Dewulf et al., 2016; Helbig et al., 2021a)	Potential cause of disruption - likelihood of disruption
L	regulations	Regulation risks address potential impacts from changes in environmental regulations, trade policies, or mining laws. (Dewulf et al., 2016; Helbig et al., 2021a)	Those changes could restrict the production and trade of a material. (Dewulf et al., 2016; Helbig et al., 2021a)	Potential cause of disruption - likelihood of disruption
L	by-product dependence	By-product dependence refers to materials mainly produced as by-products of other mining processes. The by-product production is less responsive to changes in demand, as the production is mainly oriented at meeting the demand of the host material. (Dewulf et al., 2016; Helbig et al., 2021a)	Changing market conditions of the host material can affect the economic profitability of the by-product. Production capacity utilization will be managed and depend primarily on the host material. (Dewulf et al., 2016; Helbig et al., 2021a)	Potential cause of disruption - likelihood of disruption
L	dependence on primary production	Dependence on primary production is the reliance on primary production for a material compared to secondary production. (Schrijvers et al., 2020a)	Changes in the availability and supply of primary production are more likely to cause disruption. (Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
L	demand growth	Demand growth assesses the additional material demand increase due to future technologies. (Schrijvers et al., 2020a)	This increase might stress material supply if production is not increased likewise. (Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
L	import dependence	Import dependence is a specific indicator for nation-perspective assessments and describes the ratio to which a country relies on imports for the supply. (Helbig et al., 2016b)	Higher imports are considered to pose higher supply risks, as the supply chain is out of the hands of domestic policy and trade. (Helbig et al., 2016b)	Potential cause of disruption - likelihood of disruption
L	environmental or social regulations	Environmental regulations (e.g., REACH or RoHS) or socio-political regulations (e.g., Dodd-Frank-Act) define the framework within which production can take place. (Helbig et al., 2016b; Schrijvers et al., 2020a)	Increasing environmental or social regulations can delay or restrict resource extraction and processing operations. The truly accessible reserves are limited by those regulations. (Helbig et al., 2016b; Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
L	mining/production efficiency	Efficiency in mining or production determines the quantity of resources extracted with a given input of energy, labor, and capital. (Frenzel et al., 2017)	Declining ore grades or inefficient technologies can increase costs, reduce output, and increase the risk of supply shortages. (Frenzel et al., 2017)	Potential cause of disruption - likelihood of disruption
L	environmental impact	Environmental impacts cause a high or low probability of a supply disruption of a material due to potential regulations and the thereby limited (or enhanced) sourcing possibility of raw materials. (Graedel et al., 2012; Kolotzek et al., 2018)	Environmental impacts can lead to stricter regulations. (Graedel et al., 2012; Kolotzek et al., 2018)	Potential cause of disruption - likelihood of disruption
L	exploration conditions	Limited access to resources per capita and decreasing investment in exploration hinders the country's sustainable development. (Schrijvers et al., 2020a)	Limited access to resources per capita and decreasing investment in exploration hinders the country's sustainable development. (Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption

(continued on next page)

Table A1 (*continued*)

	Indicator	Explanation	Causal link	Conclusion
L	local natural environment	Local environmental impacts, such as pollution of soil and air, affecting human health or water scarcity and contamination, directly influence workers and local communities. (Helbig et al., 2021b)	This can result in workers strikes and the withdrawal of the social licences to operate. (Helbig et al., 2021b)	Potential cause of disruption - likelihood of disruption
L	materialization capacity	The materialization capacity refers to the ability to transform raw materials into finished products. Adapted from (Blagoeva et al., 2016)	Limited materialization capacity can cause supply chain bottlenecks, especially in high-demand scenarios (e.g. electric vehicles, net-zero). (Blagoeva et al., 2016)	Potential cause of disruption - likelihood of disruption
L	demand growth	The rate of increase in material production to meet demand. (Helbig et al., 2021b)	Slow production growth relative to demand spikes (e.g., due to new technologies, substitution of other materials, or policy changes) increases the likelihood of disruptions. (Helbig et al., 2021b)	Potential cause of disruption - likelihood of disruption
L	natural disasters	A mine or company may be affected by an accident or natural disaster. (Helbig et al., 2021b)	In any such cases, the higher the market concentration, the more prone the global market is to supply disruptions. (Helbig et al., 2021b)	Potential cause of disruption - likelihood of disruption
L	resource competition	Resource competition describes the (rising) demand by emerging economies and the competition between different resource-demanding economy sectors. (Schrijvers et al., 2020a)	Both can influence the likelihood of disruption in the case of supply shortages. (Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
L	degree of exploration	The degree of exploration refers to the level of effort and investment directed toward discovering new mineral deposits. A higher degree of exploration indicates greater effort and resources devoted to finding new reserves. (Achzet and Helbig, 2013)	The declining rate of discovering large deposits and the decreasing ore grade result in supply sources becoming increasingly scarce. This raises the likelihood of supply shortages and disruptions. (Achzet and Helbig, 2013)	Potential cause of disruption - likelihood of disruption
L	geological specificities	Mineral deposits are not equally or randomly distributed on earth. Some minerals are predominantly found in dense areas in a few countries, while others have more widely dispersed ore deposits. (Graedel et al., 2012)	Generally, the more concentrated the mineral deposits are, the higher the risk of supply restriction. (Graedel et al., 2012)	Potential cause of disruption - likelihood of disruption
L	logistic restrictions	Infrastructure bottlenecks (e.g., port capacity, road quality, transport accidents) or geopolitical conflicts can delay or restrict supply chains. (Mancheri et al., 2018)	Generally, the more concentrated the supply chain is, and the more logistic restrictions exist, the higher the likelihood of supply disruption. (Mancheri et al., 2018)	Potential cause of disruption - likelihood of disruption
L	trade restrictions	Trade restrictions might occur due to geopolitics ("haves" seeking to influence "have nots") and resource nationalism (state control of production), resulting in export/import bans / quota, tariffs, or compliance work. (Schrijvers et al., 2020a)	Trade restrictions might reduce the availability of resources on the international market and increase the likelihood of disruption. (Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
E	strategic stockpiles	Instantly available raw materials to buffer supply disruptions. (Helbig et al., 2021a; Sprecher et al., 2015)	Stockpiling can secure a stable supply of materials and products during times of disruption. Stockpiling can improve the resistance of a system because a stockpile can absorb sudden prices and secure a stable supply during times of fluctuations. (Helbig et al., 2021a; Sprecher et al., 2015)	Immediate effect - effect of disruption
E	ability to pass-through cost increase (also price sensitivity)	Competitive situations (or other factors) that might allow passing-through cost increases. (Duclos et al., 2008;Helbig et al., 2021a)	A low ability to pass through cost increase might result in damages and disruption of operation as customers are no longer willing to buy. (Duclos et al., 2008; Helbig et al., 2021a)	Immediate effect - effect of disruption
E	purchasing power (regional scope)	Individual purchasing power of citizens indicates a potential to pay a higher price for a product. The GDP at a country level and the GDP per capita are considered for this indicator. (Blagoeva et al., 2016)	A low purchasing power results in a low ability to pay higher prices. In competition with other market participants with a higher purchasing power this can result in supply disruption. (Blagoeva et al., 2016)	Immediate effect - effect of disruption
E	economic size of sector	The larger the economic contribution of a sector demanding the assessed materials, the bigger the disruption effect. (Helbig et al., 2021b)	The larger the economic contribution of a sector demanding the assessed materials, the bigger the effect of disruption. (Helbig et al., 2021b)	Immediate effect - effect of disruption
E	internal demand	Indicators that reflect that the material is used by the system under study. (Schrijvers et al., 2020a)	The more a material is used, the more vulnerable the system is to a supply disruption. (Schrijvers et al., 2020a)	Immediate effect - effect of disruption
E	demand vs. world production	The relationship between demand and production capacity determines material scarcity. (Schrijvers et al., 2020a)	High demand relative to production increases competition, driving up prices and potentially destabilizes demanding industries. (Schrijvers et al., 2020a)	?
E	market power regarding suppliers	Buyers that are very large or join forces and organize themselves in strategic partnerships can gain market power over suppliers. (Mancheri et al., 2019)	A high level of market power regarding suppliers can lead to an advantageous position in the supply of raw materials and the prices to be paid. At the same time, a competitor's market power can have a detrimental effect on its own supply. (Mancheri et al., 2019)	Immediate effect - effect of disruption
E	revenue impacted	Indicators that reflect the relative importance of the material compared to other materials used by the same system (e.g. via the revenue impacted by a supply disruption). (Schrijvers et al., 2020a)	A higher revenue impacted indicates a higher potential damage in case of a disruption. (Schrijvers et al., 2020a)	Immediate effect - effect of disruption
E	population using the material	Indicators that reflect that the material is used by the system under study. (Schrijvers et al., 2020a)	The more a material is used, the more vulnerable the system is to a supply disruption. (Schrijvers et al., 2020a)	Immediate effect - effect of disruption

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Table A1 (*continued*)

	Indicator	Explanation	Causal link	Conclusion
E	use in emerging technologies	Indicator for the relevance of the material for emerging technologies (e.g. Clean energy technologies). (Schrijvers et al., 2020a)	Sudden increases in demand can be caused by the relevance of material for emerging technologies and fast market penetration of those technologies resulting in potential supply disruptions. (Schrijvers et al., 2020a)	Immediate effect - effect of disruption
E	price vs. GDP	Indicators that reflect 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 and GDP that is impacted by a supply disruption). The country's GDP gives a broadly accepted proxy of its economic and financial performance. (Blagoeva et al., 2016; Schrijvers et al., 2020a)	If the GDP drops, indicating a lower economic and financial performance, or the price increases, indicating a stressed supply situation, the importance of the material and the vulnerability of the country to supply disruptions of this material is increased. (Blagoeva et al., 2016; Schrijvers et al., 2020a)	?
E	availability of hedging options	Hedging can enable a specific company to establish a stable supply of materials and products and minimize price fluctuations. (Helbig et al., 2021b)	If hedging options are available and get used the effects of disruption can be minimized. (Helbig et al., 2021b)	Immediate effect - effect of disruption
E	domestic demand growth	A rising domestic demand of the material under investigation. (Schrijvers et al., 2020a)	Rising domestic demand amplifies the local impact of global disruptions. (Schrijvers et al., 2020a)	?
E	apparent consumption	Indicators that reflects the amount of material that is used by the system under study. (Schrijvers et al., 2020a)	The more a material is used by a system, the more vulnerable the system is to a supply disruption. (Schrijvers et al., 2020a)	Immediate effect - effect of disruption
E	price vs. profit	The ratio of costs to overall profits determines if an operation will be feasible or unprofitable and vanish in the future. (Frenzel et al., 2017)	The smaller the profit margin compared to the material price is, the less flexibility facing price increases exist. (Frenzel et al., 2017)	Immediate effect - effect of disruption
E	procurement strategy	Strategies such as diversification or reliance on long-term contracts affect supply stability. (Sprecher et al., 2015)	Companies with limited supplier diversification are more exposed to disruption effects, leading to delays and higher costs. (Sprecher et al., 2015)	Immediate effect - effect of disruption
E	strategic importance	Materials described as of strategic importance are often materials of high importance to the defence, energy, or high-tech sectors, with a forecasted demand growth and a difficulty to increase production. (Helbig et al., 2016b)	Those materials have disproportionate disruption effects on strategic projects. (Helbig et al., 2016b)	Immediate effect - effect of disruption
E	value of products affected	The value of end products that rely on the material under investigation and are affected in the case of a supply disruption. (Duclos et al., 2008; Graedel et al., 2012; Helbig et al., 2016b)	If the value of the products affected is high, the impact of a disruption will also be high, as many products can't be produced. (Duclos et al., 2008; Graedel et al., 2012; Helbig et al., 2016b)	Immediate effect - effect of disruption
E	value of the utilized material	The value of the material under investigation. It will measure a supply shortage if it leads to increased raw material prices rather than a physical supply disruption. (Duclos et al., 2008; Graedel et al., 2012; Helbig et al., 2016b)	The higher the value of a utilized material is, the greater and more immediate the impact of disruption might be. This is especially because the material-demanding industries are dependent on high-value materials facing price spikes, supply shortages, and production disruption with limited short-term mitigation strategies. Market speculation can further amplify volatility, causing financial instability and cascading effects across key industries. (Duclos et al., 2008; Graedel et al., 2012; Helbig et al., 2016b)	Immediate effect - effect of disruption
E	spread of utilization	The extent to which a material is used by the population or across multiple industries and applications. (Graedel et al., 2012; Helbig et al., 2016b)	The widespread utilization of material across the population or multiple industries and applications leads to a greater and more immediate effect of disruption. A material used in diverse sectors creates simultaneous supply chain bottlenecks when disrupted, resulting in larger economic losses and price volatility.	Immediate effect - effect of disruption
E	consumption volume	The volume of a material consumed globally or within a specific sector. (Helbig et al., 2016b)	A larger consumption volume of material leads to a greater and more immediate effect of a disruption, as a supply reduction directly impacts large-scale/high-volume industries.	Immediate effect - effect of disruption
E	diversification	Diversification refers to the strategy to expand and diversify sourcing options to reduce dependency on one or few suppliers.	diversified supply chains are less susceptible to the collapse of a supplier.	Immediate effect – effect of disruption
R	investment potential	The investment potential indicates the relative investment potential of the EU compared to other major economies in the world that are considered potential competitors of the EU. (Blagoeva et al., 2016)	It is assumed that a higher investment potential can facilitate a possible expansion of the upstream material supply chain (vertical integration). Vertical integration can be a strategy to recover material supply in case of material disruption (Blagoeva et al., 2016)	Effect within medium to long term - Recovery from disruption (Adaptive and restorative capacity)
R	preparation to build up or expand primary production	Preparations may include accepted permits, finalized building plans, and availability of required land to increase the production of raw materials. Adapted from (Sprecher et al., 2017)	The build-up and expansion of primary production capacities effectively respond to supply disruptions. Without proper preparation (permits, finalized building plans, availability of required land, etc.), the process will be very lengthy. This measure, therefore, can be strengthened by proper preparation. Adapted from (Sprecher et al., 2017)	Effect within a month to several years - Recovery from disruption (Adaptive and restorative capacity)
R	material efficiency	Material efficiency refers to efficiently using material, minimizing waste, and maximizing output per unit of material input. It encompasses	Intensified research due to material scarcity or price peaks can improve material efficiency by changing	Effect within a month to several years - Recovery from disruption

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Table A1 (*continued*)

	Indicator	Explanation	Causal link	Conclusion
		technology, design, production processes, and recycling improvements to reduce material intensity. Adapted from (Graedel et al., 2012)	properties, dimensioning, material handling, etc. Adapted from (Graedel et al., 2012)	(Adaptive and restorative capacity)
R	substitutability	Substitutability refers to the ability to realize the substitution by another material. Every material has unique properties; therefore, substitution comes at certain costs, such as lower performance, limited availability, and higher costs. Substitution can be applied to material, component, assembly, or conceptual level. (Duclos et al., 2008; Graedel et al., 2012; Sprecher et al., 2017)	Good substitutability indicates few disadvantages to using substitutes, but it will always take time to implement material substitution, which is why substitution is an option for recovering from a disruption. (Duclos et al., 2008; Graedel et al., 2012; Sprecher et al., 2017)	Effect within a month to several years - Recovery from disruption (Adaptive and restorative capacity)
R	recyclability	The recyclability expresses the ability to recycle a material. (Graedel et al., 2012; Sprecher et al., 2017)	If recycling is technically and economically feasible, implementing secondary production capacities or increasing existing capacities can be an option for recovering from a disruption. (Graedel et al., 2012; Sprecher et al., 2017)	Effect within medium to long term - Recovery from disruption (Adaptive and restorative capacity)
R	innovation potential	The ability to innovate and the speed of adaptation as a system. It also describes the capability and capacity to innovate and leave a high-risk path proactively (before a disruption occurs). Adapted from (Graedel et al., 2012)	The innovation potential acknowledges that some systems (companies, countries, etc.) are more innovative than competitors. It is likely that in light of unexpected supply disruptions, those will also respond faster and, thereby, more quickly adapt and recover than others. Adapted from (Graedel et al., 2012)	Effect within a month to several years - Recovery from disruption (Adaptive and restorative capacity)
R	exploration	Indicated number and extent of exploration projects, prospected production capacity, or deposit size.	Successful exploration projects speed up the buildup of new primary production. Adapted from (Sprecher et al., 2017)	Effect within medium to long term - Recovery from disruption (Adaptive and restorative capacity)
R	backup supplier	The general availability of potential backup suppliers, with already established business relations to or contracts with potential backup suppliers. (Hosseini et al., 2019)	It can significantly speed up restoring the material supply after a disruption.	Effect within months - Recovery from disruption (Adaptive and restorative capacity)
R	innovation potential or ability to innovate	The ability to innovate and the speed of adaptation as a system. It also describes the capability and capacity to innovate and leave a high-risk path proactively (before a disruption occurs). Adapted from (Graedel et al., 2012)	The innovation potential acknowledges that some systems (companies, countries, etc.) are more innovative than competitors. It is likely that in light of unexpected supply disruptions, those will also respond faster and, thereby, more quickly adapt and recover than others. Innovation potential or the ability to innovate both strengthen the transformative capacity. Innovations can, for example, enable the development of innovative materials with low disruption likelihood. Adapted from (Graedel et al., 2012)	Preventive - Proactive adaptation to leave a high-risk path (Transformative capacity)

Table A2
Indicators that lack a clear or only have a vague causal link but are used in literature; L: Likelihood of disruption, E: Effect of disruption, R: Recovery from disruption.

	Indicator	Explanation	Causal link	Conclusion
L	lack of substitution options	The lack of substitution options indicates that substitution is not an option to recover from disruption. Instead, a lack of known substitutes indicates that substitution is not an option for recovering from a disruption. (Helbig et al., 2021a)	Lacking substitution options neither directly increases nor reduces the likelihood of a supply disruption. (Helbig et al., 2021a)	Substitution is effective within a month to several years - Recovery from disruption
L	price volatility	Frequent and/or unpredictable price fluctuations of resources. E.g., due to supply-demand imbalances, geopolitical factors, or speculation. (Helbig et al., 2021a)	In economic theory, short- or long-run physical resource scarcity (supply-demand gap with demand exceeding the supply) increases commodity prices. Therefore, the price indicates supply-demand gaps, and short-term price volatility is more the result of shocks (e.g., physical supply disruptions or expected shortages) than the reason for a higher likelihood of disruption. Other works (e.g., Helbig et al., 2019) have already questioned the usefulness of price volatility in indicating a likelihood of disruption. (Helbig et al., 2021a; Schischke et al., 2023; Tilton et al., 2018)	Potentially results from a disruption. No empirical evidence that price volatility influences the likelihood of a disruption - not recommended as an indicator within the framework
L	recyclability	The ease with which a material can be recycled and reprocessed into new products without significantly losing quality or functionality. (Helbig et al., 2021a)	The recyclability of a material neither increases nor reduces the likelihood of a direct supply disruption. It expresses the ability to recycle a material; without upscaled processes or missing facilities, it will not influence the likelihood of a disruption. Instead, if recycling is technically and	Effect within medium to long term - Recovery from disruption

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Table A2 (*continued*)

	Indicator	Explanation	Causal link	Conclusion
			economically feasible, increasing secondary production can be an option to recover from a disruption. (Helbig et al., 2021a)	
E	substitutability	Substitutability refers to the ability to realize the substitution by another material. Every material has unique properties; therefore, substitution comes at certain costs, such as lower performance, limited availability, and higher costs. Substitution can be applied to material, component, assembly, or conceptual level. (Duclos et al., 2008; Helbig et al., 2021a; Sprecher et al., 2017)	Good substitutability indicates few disadvantages from using substitutes, but it takes time to implement material substitution, which is why a "good substitutability" does not protect against the effect of a disruption. Instead, it helps to recover from a disruption in the longer term. Therefore, we ascribe substitutability as an indicator with a clear causal link to the recovery from a disruption. (Duclos et al., 2008; Helbig et al., 2021a; Sprecher et al., 2017)	Effective within a month to several years - Recovery from disruption
E	market price	The market price is the price of a resource in the commodities market. (Schischke et al., 2023; Tilton et al., 2018)	Short- or long-run physical resource scarcity results in rising commodity prices. Therefore, the effect itself is higher market prices (and not the other way round: high market prices indicate a high effect (i.e., high vulnerability or high economic importance) on the system). Based on this, we come to the conclusion that the market price of a commodity alone does not indicate the likelihood, effect, or recovery from a disruption. (Schischke et al., 2023; Tilton et al., 2018)	Potentially results from a disruption. No empirical evidence that it influences the effect of a disruption - not recommended as an indicator within the framework
E	demand growth	A growing demand of a resource is measured in additional mass being demanded by the market participants. (Schrijvers et al., 2020a)	Demand growth indicates that the supply situation can increasingly be strained through a resulting supply-demand gap, resulting in price increases or physical shortages if supply is not expanded. Schrijvers et al. (2020) acknowledged that, if applied, this indicator is rather used to evaluate the supply risk. This indicator is clearly linked to the likelihood of disruption. (Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
E	trade restriction	Trade restrictions, e.g., due to geopolitics ("haves" seeking to influence "have nots") and resource nationalism (state control of production), might reduce the availability of resources on the international market. (Schrijvers et al., 2020a)	Trade restrictions might restrict the export of materials, negatively impacting the supply situation. Schrijvers et al. (2020) acknowledged that, if applied, this indicator is rather used to evaluate the supply risk. The indicator is clearly linked to the likelihood of disruption. (Schrijvers et al., 2020a)	Potential cause of disruption - likelihood of disruption
E	import dependency	Import dependency indicates the amount of supply being imported compared to the amount produced domestically. (Helbig et al., 2021b)	A country that is highly dependent on imports faces a higher risk of supply disruptions due to low domestic production and low political ability to steer extraction activities. Schrijvers et al. (2020) acknowledged that, if applied, this indicator is rather used to evaluate the supply risk. The indicator is clearly linked to the likelihood of disruption. (Helbig et al., 2021b)	Potential cause of disruption - likelihood of disruption
E	price volatility	Price volatility is the degree of variation of the resource price over time, usually measured by the standard deviation of logarithmic returns. (Schrijvers et al., 2020a)	Price volatility results from shocks (e.g., physical supply disruptions or expected shortages) and market dynamics. There is no reasonable causal relation between the price volatility of a material and the vulnerability of a system that uses this material. Schrijvers et al. (2020) acknowledged that, if applied, this indicator is rather used to evaluate the supply risk. (Schrijvers et al., 2020a)	Potentially results from a disruption. No empirical evidence that it influences the effect of a disruption - not recommended as an indicator within the framework
E	future demand-to-supply ratio	The projected future demand for a resource and the supply ratio measure mass. (Helbig et al., 2016b)	If the projected future demand is higher than the current supply ratio, similar to demand growth, this indicator can indicate an increasing likelihood of a disruption. The indicator is clearly linked to the likelihood of disruption.	Potential cause of disruption - likelihood of disruption
E	change in demand share	The change in demand share refers to how the demand for a specific material of a system (company, country, etc.) changes compared with the global demand for this material over a certain period. This indicator looks at the specific demand share of a system. It does not consider if the absolute demand increases or decreases. (Helbig et al., 2016b)	In our opinion, it is questionable that the indicator has any causal relation to the effect of a disruption of the material, which questions the informative value of the indicator in this kind of assessment, and we do not recommend using it. (Helbig et al., 2016b)	Limited informative value - not recommended as indicator within the framework
E	target group's demand share	The demand share of a system (target group) for a certain material. (Helbig et al., 2016b)	Even if the target group's demand share is very high, the material might be relatively unimportant to the system. There is no causal relation between a high demand share and a high effect. Similarly to the indicator "change in demand share", we question the informative value of the indicator in this kind of assessment and do not recommend using it. (Helbig et al., 2016b)	Limited informative value - not recommended as indicator within the framework

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Table A2 (*continued*)

	Indicator	Explanation	Causal link	Conclusion
E	ability to innovate	The ability to innovate indicates the capacity to leave the current technology and development path. (Graedel et al., 2012)	It also indicates the ability to leave a high-risk path proactively. These can be, for example, material innovations that enable substituting materials with a high disruption probability by innovative ones with a low likelihood.	Effect within month to several years - Recovery from disruption
E	change in imports	The indicator change in imports measures the change in dependence on foreign resource suppliers. (Helbig et al., 2016b)	A country that is highly dependent on imports (and the dependency further increases) faces a higher risk of supply disruptions due to low domestic production and low political ability to steer extraction activities. Also, the review of Schrijvers et al. (2020) acknowledged that, if applied, this indicator is rather used to evaluate the supply risk. The indicator is clearly linked to the likelihood of disruption.	Potential cause of disruption - likelihood of disruption
E	company concentration	Company concentration is the degree to which a few companies dominate the supply. The concentration is measured via the Herfindahl-Hirschman-index (HHI), which ranges from low concentration with 0 to very high concentration with 10,000. (Helbig et al., 2021a)	A high supply concentration to a few companies (oligopoly) poses several supply risks: e.g., disruption to one or more companies has a large-scale impact on the supply situation. Furthermore, an oligopoly bears the risk of price cartels. The indicator thereby has a causal link to the likelihood of disruption.	Potential cause of disruption - likelihood of disruption
E	mining production change	The mine production change looks at how the mine production changed relatively during a period. (Helbig et al., 2016b)	It has a clear causal link to the likelihood of disruption.	Potential cause of disruption - likelihood of disruption
E	primary material price	The primary material price refers to the market cost of raw materials in their unprocessed or minimally processed form. (Helbig et al., 2016b)	It is questionable if there is any causal relation between material price and either of the three dimensions (also discussed before)	Is a potential effect of a disruption - not recommended as an indicator within the framework
E	recyclability	It expresses the ability to recycle a material (Helbig et al., 2021a)	The recyclability of a material neither increases nor reduces the effect of a supply disruption directly.	Effect within medium to long term - Recovery from disruption
E	resource efficiency potential	The resource efficiency potential refers to using raw materials more effectively, minimizing waste, and maximizing output per unit of material input. It encompasses technology, design, production processes, and recycling improvements to reduce material intensity. (Schrijvers et al., 2020a)	To gain resource or material efficiency or to realize a potential, intensified research is required, which takes time. Therefore, this indicator will not instantly decrease the effect of a disruption, so we allocate this indicator to the recovery from a disruption. (Schrijvers et al., 2020a)	Effect within a month to several years - Recovery from disruption (Adaptive and restorative capacity)

Data availability

All data used in the research is contained in the article.

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