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Assessment of product criticality at the corporate level presenting a newly developed method based on standard VDI 4800 Part 2

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ABSTRACT

Numerous unpredictable vulnerabilities are inherent in global supply chains for both raw materials and components. While methods to determine the criticality of raw materials exist and policies such as the EU's Critical Raw Materials Act are being implemented to improve supply chain resilience, companies often face challenges due to their dependence on components, for which criticality assessment methods are not yet well established. VDI 4800 Part 2 is the first standard developed for the assessment of raw material criticality and links the criticality assessment with life cycle sustainability aspects. However, it does not include the applicability for components. Therefore, this study explores the adaptation of VDI 4800 Part 2 method to components in a way that can be applied by companies. Thereby, criteria proposed in VDI 4800 Part 2 were modified to fit the context of components. The developed procedure, like the original method, evaluates the two dimensions *supply risk* and *vulnerability* by addressing nine and eleven individual criteria, respectively. As a case study, the adapted method was applied by a company to analyse the criticality of an electrolyser showing the criticality of nine different components. The application of the method enabled the company to identify and mitigate potential supply chain weaknesses. This study presents a new method for the criticality assessment of components applicable by companies that aligns with VDI 4800 Part 2 and can be used as a guide for strategic decisions in risk management.

1. Introduction

In today's globalised world, the economy is profoundly interconnected and as a result, supply chains are threatened by a wide variety of potential disruptions. This relates to raw materials as well as components and products. In this study, the term *raw material* refers to a basic, natural or unprocessed substance used to produce goods, while *component* refers to a part that has already been manufactured from raw materials and is used to assemble a final product. When it comes to critical raw materials, the EU relies heavily on imports to meet its ever growing demand (European Commission, 2024). In response, governments have intensified efforts in recent years to diversify their supply chains and strengthen their strategic autonomy. Measures include expanding domestic production, promoting recycling and reducing material consumption (European Commission, 2020; HM Government, 2022; Exec. Order No. 13817, 2017). A central element of the EU's strategy is the Critical Raw Materials Act, introduced in 2023 and adopted in March 2024 (University of Cambridge Institute for Sustainability Leadership and Wuppertal Institute, 2023; Council of the European Union, 2014). One of the main drivers behind these efforts is the need to secure access to raw materials for domestic industries, ensuring the production of essential goods and safeguarding economic stability.

Against this background, it becomes increasingly important to systematically assess the criticality of raw materials within a given reference system in order to recognize and mitigate supply risks. To this end, a range of methods has been developed and tested (Gandenberger et al., 2010; Erdmann et al., 2011; Schneider et al., 2014; Graedel et al., 2015; Bach et al., 2016; Kolotzek et al., 2017). Some of these methods have since been revised (Gemechu et al., 2015; Santillàn-Saldivar et al., 2022; Santillàn-Saldivar et al., 2022), while others have been adapted for the application at the corporate level (Yavor et al., 2021). Several reviews provide insights into the landscape of these methods. Sonderegger et al. (2020), for example, provide a comprehensive overview of approaches for evaluating the impacts of mineral resource use. Additional studies focus on integrating criticality assessment with Life Cycle Assessment

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methodologies (Hackenhaar et al. 2022, Jabra et al 2025). These reviews show that most methods are based on a set of common criteria, including production capacity, the use of primary raw materials, the concentration of reserves and production, corporate concentration, price volatility, demand growth, the feasibility of exploration projects, political stability and co-production.

VDI Standard 4800 Part 2 (VDI 4800/2) is the first standard designed for the purpose of assessing the criticality of raw materials within a reference system, e.g. a company (VDI, 2018). It includes the above aspects used in other methods together with other geological, technical and structural criteria. As a VDI standard, it was created by the participation of various stakeholders. Regular review and, if necessary, revision of the method are part of the development of VDI standards, which provide assurance that users are following recognised rules of technology. VDI 4800/2 evaluates the criticality of a raw material regarding two dimensions: *supply risk* and *vulnerability*. Each dimension consists of several criteria. The supply risk dimension focuses on the specific raw material and takes criteria such as the ratio of reserves to global annual production, the country concentration of reserves as well as production, and the level of demand growth into account. The vulnerability dimension, on the other hand, examines the susceptibility of the reference system to supply disruptions of the raw material by analysing the internal consumption, the availability of procurement strategies and the ability to pass on raw material prices to customers, among other factors. VDI 4800/2 provides not only a method for assessing criticality, but also one for evaluating resource efficiency. However, it is relatively complex and the criticality assessment relies on data that is often only obtained with great effort. VDI 4800/2 was developed as a VDI guideline within a national context taking the state of the art into account. It should be noted that it does not represent an international standard. Instead, it primarily considers German and European requirements and may not account for differing requirements from other regions.

As of now, there is only one publication presenting the application of VDI 4800/2, in which Kranich et al. (2019) assessed the raw material criticality for an electric vehicle driving system. The necessary data was collected by breaking down the module into components, parts, materials, and raw materials step by step. This resulted in absolute and relative weight data regarding raw materials at the component and part levels. Based on these outputs, the raw material criticality was assessed using the VDI 4800/2 method.

Own criticality assessments were performed by the authors in two different research projects, the results of which have been incorporated into this paper. The aim of the ***iNEW2.0*** project was to develop innovative and efficient electrolysis processes for use in sustainable Power-to-X value chains (Wuppertal Institut, 2021). The *Life Cycle Impact Zero* (LCIZ) project supports the implementation of a sustainable production at Enapter, which manufactures electrolysers (Wuppertal Institut, 2022). In the project iNEW2.0, a criticality analysis using the VDI 4800/2 method was conducted by the authors. Herein, the criticality of different raw materials was evaluated in the early development stage of an electrolyser as an initial resource analysis in order to establish feedback loops with technical developers. Through this approach, development risks can be reduced and possible alternatives might be explored. However, a challenge that was encountered when employing the VDI 4800/2 method for analysing product criticality is its limitation to the assessment of raw materials. As such, it is necessary for companies to exactly determine the contained raw materials of their components as done by Kranich et al. (2019). This is usually a demanding endeavour which requires a complete life cycle inventory and draws on data that companies often do not have. Furthermore, the bottlenecks in supply chains for companies often concern obtaining certain components rather than raw materials. This was not only communicated by the partners in the iNEW2.0 project, but also in the LCIZ project, which aimed to assess the criticality of an electrolyser that had already been developed. Often, there is a high concentration of manufacturers and the substitution possibilities for components are poor. Initiatives such as the European Chips Act show the importance of considering international supply chains at the product level (Regulation 2023/1781). If the criticality analysis is only focused on raw materials, such possible supply issues and vulnerabilities might go unrecognised.

Methods are already being used in various areas to analyse the risk of such supply chain disruptions (Pournader et al., 2020). However, these methods are often very specific to individual product groups or companies (Singhal et al., 2011; Heckmann et al., 2014). Furthermore, various overview studies show that the approaches differ significantly from the criticality assessment for raw materials (Ho et al., 2015; Fan & Stevenson, 2018). Only in recent years have they been increasingly linked to environmental or sustainability aspects. Research at the intersection of sustainability and supply chain resilience is still in its early stages and is a consequence of the observed mutual influences. There is still a lack of clarity about concepts, methods and metrics for sustainable and resilient supply chains. It appears that the concept of sustainable supply chains is better established and there is greater agreement on its fundamentals than is the case for supply chain resilience (Negri et al. 2021). More recent analyses also show that only a few of the criteria currently considered in criticality assessments are taken into account in the assessment of supply chain risks (Sultana et al. 2024). VDI 4800/2 is a standard that attempts to consider both aspects of sustainability in the life cycle and aspects of security of supply in the form of a criticality assessment. However, this criticality assessment is currently limited to raw materials. This raises the question of whether a method intended for broader application, such as VDI 4800/2, can also be used with regard to the criticality of components. The aim of this study was therefore to develop a method that closely aligns with VDI 4800/2 to assess not only the criticality of raw materials but also that of components and that is applicable by companies. At present, there are no publications regarding this extended application of VDI 4800/2. Accordingly, the following research question was derived:

Can the method of VDI 4800/2 be successfully transferred and applied to components in order to determine criticality at the product level?

The new method was developed and applied in the LCIZ project and aims to help companies in identifying potential supply risks and taking appropriate measures to strengthen their supply chains.

Section 2 below presents the approach used to develop the method. Subsequently, the method is described in Section 3 by the outline of criteria for determining supply risk and vulnerability. Section 3 further shows the results of the method's application in the case study of the LCIZ project. Section 4 contains a discussion of the application of the method as well as on the method itself and its development. Finally, a conclusion is drawn in Section 5.

2. Methods

The following section describes the approach for the development of the method for determining the criticality of components based on the principles outlined in VDI 4800/2. The guideline takes 13 criteria for the determination of supply risk and 12 criteria for the determination of vulnerability into account. All criteria have a four-stage evaluation framework with the indicator values of 0, 0.3, 0.7 and 1, with 0 indicating the lowest and 1 the highest criticality. Analogue to VDI 4800/2, the criticality of the newly developed method comprises the two dimensions supply risk and vulnerability. Within each dimension, each criterion suggested by VDI 4800/2 was transferred from raw materials to components. Therefore, the decision tree presented in Fig. 1 was used.

Within the adaptation process, some criteria, which are part of the VDI 4800/2 framework for raw materials, were deemed irrelevant for components and thus excluded from the new method. The specific reasoning for the exclusion of each criterion is found in the result section. For the other criteria, the four-stage evaluation framework of VDI 4800/2 was adopted wherever possible. However, certain criteria that were quantitatively determined for raw materials were replaced by a qualitative evaluation in the form of an expert assessment due to the lack

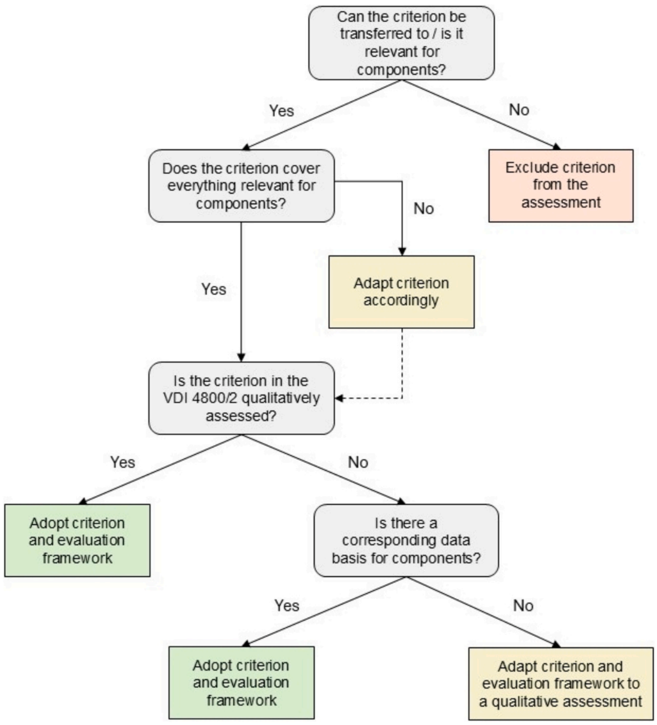

Fig. 1. Decision tree for the adaptation process of the criteria presented in VDI 4800/2 for raw materials to components.

of data. In these cases, a new evaluation framework was developed by the authors, whereby values of 0, 0.3, 0.7, and 1 were assigned. The frameworks were defined individually for each criterion and are based on the ones of VDI 4800/2. They are presented in the result section of the respective criterion. In this way, a total of nine criteria for determining the supply risk and eleven criteria for assessing vulnerability were identified.

3. Results

3.1. Presentation of the developed method

In the following two sections, the criteria and their respective evaluation framework for determining component criticality are presented.

3.1.1. Criteria for determining supply risk

3.1.1.1. R-strategies. Originally in VDI 4800/2, this criterion refers to the recycling of raw materials. For the supply risk analysis of components, it was modified to include all circularity strategies, also known as R-strategies.

There are several R-strategies, which are upstream of recycling and should be integrated first, if possible. They have a higher level of circularity and thus lead to fewer natural resources being used, as well as less environmental pressure (Potting et al., 2017). It is important to assess whether R-strategies are established for the component and to what extent they lead to quality losses. The existence of R-strategies within the company not only saves resources, but it also increases the number of available products and therefore decreases supply risk.

The evaluation framework of VDI 4800/2 was adapted in a way that the indicator value of 0 denotes that R-strategies are established without any major quality losses, while 0.3 means that R-strategies are established with low quality losses. The indicator 0.7 is assigned when R-strategies are established with high quality losses. An indicator value of 1 signals that R-strategies are not established at all.

3.1.1.2. Logistic constraints. Logistic constraints for components refer to the economic efficiency and general possibility of matters such as transport distances and means of transport. These factors influence price and global availability (VDI, 2018). The evaluation framework of the criterion was adopted from VDI 4800/2.

For the assignment of an indicator value of 0, storage and/or transport should be unproblematic and economically viable. An indicator value of 0.3 means that storage and/or transport is complex, but economically justifiable, while a value of 0.7 means that storage and/or transport is only feasible at high costs. An indicator value of 1 denotes that storage and/or transport is problematic and not economical.

3.1.1.3. Country concentration of global production. The *country concentration of global production* refers to the number of countries producing the component in relevant quantities. If the production is concentrated in only a few countries, it might lead to market power and one-sided dependencies (VDI, 2018).

In VDI 4800/2, this criterion is calculated for the respective raw material on the basis of global production statistics, such as the data provided by the U.S. Geological Survey (1994-2020), using the Herfindahl-Hirschman-Index (*HHI*) (Rhoades, 1993). Since there are no adequate global production statistics for components available, the analysis was modified to a qualitative assessment, which does not require the calculation of the *HHI* and can be conducted by purchasing experts within the company. The number of countries (n) for the corresponding indicator values of the new evaluation framework was determined from the indicator values proposed in VDI 4800/2 and adding the assumption that all countries have the same production volumes, which results in the following dependency: $n = 1/HHI$. In order to account for the production of components rather than raw materials, upstream chains of the component's production are taken into account as well.

An indicator value of 0 denotes that the component is produced in relevant quantities by numerous countries (approx. $>$ 20), while 0.3 means that the component is produced by several countries (approx. 8–20) in relevant quantities. An indicator value of 0.7 signals that the component is produced only by a few countries (approx. 5–7) in relevant quantities. When the component is produced by a small number of countries (approx. $<$ 5) in relevant quantities, an indicator value of 1 is assigned.

3.1.1.4. Geopolitical risks of global production. Political instability of the producing countries significantly affects the availability of goods and might lead to major supply disruptions (VDI, 2018). Analogue to VDI 4800/2, the geopolitical risk of global production is determined by assessing whether production facilities and upstream chains of the respective component are predominantly located in countries with high political risk. The political country risk indicator (PCI) is based on two of the Worldwide Governance Indicators (Kaufmann & Kraay, 2024) and calculated by using formula (3).

$$PCI_i = 1 - \frac{x_i + y_i}{200} \quad (3)$$

x_i denotes the percentile ("Percentile Rank among all countries") for the indicator *voice and accountability* and y_i the percentile for the indicator *political stability and absence of violence* for the respective country i. The PCI takes values between 0 and 1, where 0 signifies the lowest possible political risk and 1 the highest possible political risk of a country (VDI, 2018).

The calculations for the political risk of the individual countries were adopted from VDI 4800/2. However, the overall geopolitical risk of the production of the component was modified to be assessed qualitatively, as global production statistics, which are necessary for a quantitative assessment, are not available for components.

When the component is produced predominantly in countries with very low political risk (PCI < 0.15), the indicator value of 0 is assigned. An indicator value of 0.3 denotes that component production predominantly takes place in countries with moderate political risk ($0.15 \leq$ PCI < 0.5), while 0.7 means that production mainly takes place in countries with high political risk ($0.5 \leq$ PCI < 0.85). If the component is predominantly produced in countries with high political risk (PCI ≥ 0.85), it is denoted by an indicator value of 1. ($0.15 \leq$ PCI < 0.5), while 0.7 means that production mainly takes place in countries with high political risk ($0.5 \leq$ PCI < 0.85). If the component is predominantly produced in countries with high political risk (PCI ≥ 0.85), it is denoted by an indicator value of 1.

3.1.1.5. Regulatory risks of global production. Supply security is not only dependent on political stability, but also on political decision-making and regulatory measures (VDI, 2018). The regulatory risk of global production is determined by assessing whether production facilities and upstream chains of the respective component are predominantly located in countries with high regulatory risk. The regulatory country risk indicator (RCI) is based on four of the Worldwide Governance Indicators (Kaufmann & Kraay, 2024) and calculated by using formula (4).

$$RCI_i = 1 - \frac{v_i + w_i + x_i + y_i}{400} \tag{4}$$

v_i denotes the percentile ("Percentile Rank among all countries") for the indicator *rule of law,* w_i the percentile for the indicator *regulatory quality,* x_i the percentile for the indicator *control of corruption* and y_i the percentile for the indicator *government effectiveness* for the respective country *i*. The RCI takes values between 0 and 1, where 0 signifies the lowest possible regulatory risk and 1 the highest possible regulatory risk of a country (VDI, 2018).

The calculations for the regulatory risk of the individual countries were adopted from VDI 4800/2. However, similar to the determination of geopolitical risk (see above), the overall regulatory risk of the production of the component was modified to be assessed qualitatively. The reason for this approach lies in the non-existent global production statistics for components, which are necessary for a quantitative assessment.

An indicator value of 0 denotes that component production predominantly takes place in countries with very low regulatory risk (RCI $<$ 0.15), while 0.3 signals that component production mainly takes place in countries with moderate regulatory risk ($0.15 \leq$ RCI < 0.5). An indicator value of 0.7 is assigned when the component is predominantly produced in countries with high regulatory risk ($0.5 \leq$ RCI < 0.85). In the case that component production mainly takes place in countries with very high regulatory risk (RCI ≥ 0.85), an indicator value of 1 is selected.

3.1.1.6. Company concentration of global production. The company concentration of global production provides information about the number of companies which produce the component in relevant quantities. When there are only a few suppliers, the risk of supply disruption increases. Additionally, substantial market shares being owned by individual companies might lead to price increases due to market power (VDI, 2018).

The company concentration of global production for raw materials can be found in the raw material fact sheets of the Deutsche Rohstoffagentur (DERA, 2024). Since there is no similar data available for components, this criterion was modified to be assessed qualitatively by purchasing experts of the company. Furthermore, the consideration of upstream chains was added to the assessment. The number of companies for the corresponding indicator values was determined analogously to the criterion *country concentration of global production* (see above).

An indicator value of 0 denotes that the component is produced by more than 20 companies in relevant quantities, while a value of 0.3 indicates component production taking place in about 8–20 countries in relevant quantities. When the component is produced in approximately 5–7 companies in relevant quantities, an indicator value of 0.7 is assigned. An indicator value of 1 signals that the component is produced by less than 5 companies in relevant quantities.

3.1.1.7. Global demand impetus. In this criterion, the demand trend for the component is compared to the general economic growth. If demand rises disproportionally quickly, price increases may ensue and supply might not be sufficient to meet the demand. This is especially relevant for a disruptive growth in demand, which can occur as a result of fundamental technological advances (VDI, 2018). The evaluation framework of the criterion was adopted from VDI 4800/2.

A value of 0 indicates that the change in demand for the component is smaller than the change in global economic growth. When the demand grows in parallel with global economic growth, an indicator value of 0.3 is assigned, while 0.7 signals that the demand grows disproportionately in relation to economic growth. If the demand for the component grows disruptively, it is denoted by an indicator value of 1.

3.1.1.8. Substitutability. An important factor influencing the criticality of a component is the question of how well it can be substituted in its main applications. The better the substitution possibilities, the lower the supply risk, since the dependency on the specific good decreases (VDI, 2018). Substitution possibilities are assessed with regard to functional as well as economic aspects. The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 for this criterion means that the component is easily and fully substitutable in its main applications without additional cost, while 0.3 indicates that substitution is possible at low cost. A value of 0.7 denotes that the component is substitutable in its main applications only at high cost and/or with a functionality loss, while 1 means that the component is not substitutable at all.

3.1.1.9. Price fluctuations. The last criterion for the supply risk dimension concerns the price fluctuations of the component in the last 5 years. Strong price fluctuations indicate supply uncertainty and show that demand and supply of a product differ at times. This complicates planning and compromises the long-term security of supply (VDI, 2018).

Originally, in VDI 4800/2, this criterion refers to the price volatility of raw materials. In order to make the assessment more efficient, it was modified to determine the price fluctuations instead of the price volatility, since there is no available data on price volatility of components and conducting one's own calculations is very time-consuming. The price fluctuations are estimated qualitatively by the purchasing experts of the company.

The assessment of price fluctuations takes the last 5 years into account. If there have been almost no fluctuations, an indicator value of 0 is assigned. A value of 0.3 denotes that there have been moderate price fluctuations, while 0.7 refers to high fluctuations in the last 5 years. An indicator value of 1 signals that there have been very high price fluctuations in the last 5 years.

3.1.1.10. Excluded criteria. Four criteria, which are part of the VDI 4800/2 framework, were excluded from the supply risk analysis of components. The *static range* refers to the ratio of reserves to global annual production of a raw material. This criterion was left out of the analysis because there are no reserves of products in the same way as there are reserves of raw materials. Aspects such as stockpiling and storekeeping, which might be considered reserves of products, are already covered by the criterion *appropriate inventory levels/stockpiling* in the vulnerability dimension. The criterion *co–/by-product dependency* of VDI 4800/2 refers to whether the raw material is predominantly produced as the main product or a co–/by-product, such as in the case of copper and gold. As this does not happen in the same way during the manufacture of components, this criterion was omitted in the assessment. The criterion *constraints due to natural disasters* is analysed by looking at the geographical distribution of biotic raw material cultivation areas. It is irrelevant for mineral and fossil raw materials and thus also irrelevant for components, as there are no cultivation areas. Finally, the *country concentration of reserves* is based on the distribution of reserves across different countries. Since there are no reserves of components as there are of raw materials, this criterion was also taken out of the analysis.

3.1.2. Criteria for determining vulnerability

3.1.2.1. Share of risk-exposed product in total contribution margin. An important aspect for the assessment of a company's vulnerability consists of determining the share of the risk-exposed products in the total contribution margin. The contribution margin is calculated by subtracting the variable costs from the total sales revenue. A positive contribution margin is needed to cover the fixed costs of a company. When a high share of the contribution margin is dependent upon the risk-exposed products, the company becomes increasingly vulnerable to economic hardships when supply disruptions occur (VDI, 2018). The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 denotes that the contribution margin of the products affected by the supply risk is less than 2 % of the company's total contribution margin. If the share is between 2 % and 10 %, an indicator value of 0.3 is assigned, while 0.7 indicates the share is between 10 % and 25 %. A value of 1 means that the share is higher than 25 % of the company's total contribution margin.

3.1.2.2. Importance of the component to the product function/substitutability in the product. This criterion analyses to what extent it is possible to substitute the component without loss of function of the product. The substitution could be realised by the same component with other technical specifications, by another component or by changing the overall process. While the criterion analysing substitutability in the supply risk dimension focuses on the general substitutability of the component in its main applications, this criterion refers to the specific substitutability of the component in the considered product. The more substitution possibilities are available, the less vulnerable a company is to disruptions of supply (VDI, 2018). The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 denotes that the component is replaceable, achieving the same functionality and comparable or slightly inferior product quality. If the function of the product is retained, but quality declines when the component is replaced, an indicator value of 0.3 is assigned. A value of 0.7 means that the function of the product relies strongly on the component and a substitution would lead to major malfunctions and quality losses, while 1 signals that the function of the product is not given without the component and substitution is impossible.

3.1.2.3. Consumption relative to global annual production. The company's consumption of the component is put into proportion to the global annual production. The greater the company's share in a global good, the higher the vulnerability (VDI, 2018). Due to a lack of global production data of components, this criterion is assessed qualitatively rather than quantitatively as done in VDI 4800/2.

If the quantities of the component used are so small that an offset against the annual global production is no longer meaningful, an indicator value of 0 is assigned. A value of 0.3 means that the company's consumption is smaller than 2 % of the global annual production of the component, while 0.7 corresponds to a share between 2 % and 10 %. A value of 1 denotes that the company's consumption of the component is higher than 10 % of the global annual production.

3.1.2.4. Purchase value of the component relative to the total purchase value. In this criterion, the purchase value of the component is put into proportion to the total purchase value of the company. This reveals information about the required amounts for the company itself, as well as about the potential for negotiation with suppliers. Furthermore, it allows for conclusions about the value of the required component. The higher the share of the purchase value, the more vulnerable a company is to possible supply disruptions (VDI, 2018). The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 denotes that the share of the purchase value of the component is less than 5 % of the total purchase value, while a value of 0.3 corresponds to a share between 5 % and 50 %. If the share lies between 50 % and 75 % of the total purchase value, an indicator value of 0.7 is assigned. A value of 1 means that the share of the component is higher than 75 % of the total purchase value.

3.1.2.5. Access to and feasibility of substitution solutions. While the criterion *importance of the component to the product function/substitutability in the product* is used to analyse the technical substitutability of the component, this criterion is concerned with access to and feasibility of the substitution solutions. Substituting a component with another one might require new certification processes and conformity declarations. This is an aspect that does not apply to raw materials in the same way and was therefore added to the original evaluation framework of this criterion. Patents may also hinder the implementation of technically possible substitutions. Constraints can be related to economic and logistic issues as well, such as an increase in production costs or restricted access to suppliers (VDI, 2018). All of those changes take time, which can influence the temporal feasibility. The evaluation framework of the criterion was adopted from VDI 4800/2.

If there is free access to substitution solutions without or with negligible constraints, an indicator value of 0 is assigned. A value of 0.3 denotes that access to substitution solutions is available and solutions can be implemented with a minor financial effort, within a short time or with minor R&D effort. A value of 0.7 means that access to substitution solutions can be gained, but the solution can only be implemented with a major financial effort, comprehensive R&D efforts, takes a lot of time, or requires a new certification process. If substitutions are not feasible at all, a value of 1 is assigned.

3.1.2.6. Ability to innovate. Vulnerability to supply risks can be mitigated by a high capacity for innovation within a company (VDI, 2018). Analogue to VDI 4800/2, it is measured by factors such as the number of inventions and patent applications or the proportion of total sales spent on R&D. The corporate culture and their general openness to innovation should be considered as well. A high capacity for innovation might lead to developing new products, driving technological advancements or implementing completely new business models. The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 corresponds to a continuous development of new products, processes and business activities, as well as an open corporate culture. If there is high inventiveness and/or a large number of invention disclosures, sufficient R&D budget to implement ideas and motivation and empowerment of employees, a value of 0.3 is assigned. A value of 0.7 indicates that there are hardly any in-house inventions, few patent applications, a small R&D budget and little employee empowerment. A value of 1 signals that there are no inventions or patents, no R&D budget and no employee empowerment at all.

3.1.2.7. Availability of a procurement strategy. The implementation of procurement strategies reduces the company's vulnerability by providing additional protection against supply disruptions. Such strategies could be to either have long-term contractual ties or joint ventures with producers, or to have multiple independent suppliers and manufacturers at hand to minimise dependencies (VDI, 2018). Another possibility is the securement of supply through R-strategies. Companies can also build their own production facilities in order to reduce their dependence on manufacturers. The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 for this criterion signals that detailed procurement strategies are available and largely implemented. If procurement strategies are existing and partially implemented, a value of 0.3 is assigned, while 0.7 corresponds to contemplated but not implemented procurement strategies. A value of 1 means that no procurement strategies are available.

3.1.2.8. Ability to pass through prices. If it is possible for the company to pass on price fluctuations to customers, the company is less vulnerable to economic hardships caused by price increases of the purchased goods (VDI, 2018). This ability is assessed by examining if it has been possible to pass on price fluctuations of the component in the past. It is heavily dependent on the existing competition in the market. The evaluation framework of the criterion was adopted from VDI 4800/2.

If passing on price fluctuations has always been possible, an indicator value of 0 is assigned, while 0.3 denotes that passing on has frequently been possible and/or to a large extent ($> {}^2/_3$ of price increase). A value of 0.7 signals that passing on price fluctuations has rarely been possible and/or to a small extent only ($< {}^2/_3$ of price increase). A value of 1 indicates that it has not been possible to pass on price fluctuations to customers.

3.1.2.9. Bargaining potential/market power vis-à-vis suppliers. The bargaining potential and market power vis-à-vis suppliers is determined by analysing whether it is possible for the buying company to determine prices and other delivery conditions, which is dependent on the market share of the company (VDI, 2018). The higher the market share of the buying company is for a component, the stronger the ability to influence delivery conditions. The vulnerability decreases as a result of high market power vis-à-vis suppliers. The evaluation framework of the criterion was adopted from VDI 4800/2.

If the company's own demand in the total market is higher than 50 %, it controls the demand market. Therefore, an indicator value of 0 is assigned. A value of 0.3 means that influencing delivery conditions is regularly possible to a major extent, while an influence in individual cases to a minor extent corresponds to an indicator value of 0.7. A value of 1 signals that influencing delivery conditions is hardly possible at all.

3.1.2.10. Availability of price hedging instruments. Price hedging can be utilised to protect the company against price fluctuations, which may impede planning and financial security. Possible instruments include fixed price agreements, stockpiling and supplier contracts, but also derivatives such as futures and options. It is important to note whether there are regulated stock markets or whether hedging instruments are only available on an individual basis from a limited number of suppliers. Companies are the most vulnerable if there are no hedging instruments available at all and they have no possibility to protect themselves against the market volatility (VDI, 2018). The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 for this criterion denotes that there are standardised hedging instruments available in regulated stock markets with a high market liquidity. A value of 0.3 signals that hedging instruments are available as off-floor transactions with a high liquidity from many providers or as standardised instruments on exchange markets with a medium market liquidity. A value of 0.7 means that hedging instruments are only available on a very individual basis from few counter-parties with low market liquidity. If there are no instruments available to hedge against the market volatility of the respective prices at all, an indicator value of 1 is assigned.

3.1.2.11. Appropriate inventory levels/stockpiling. This last criterion considers the inventory level of the component at the respective company or upstream companies. The higher the inventory level, the less vulnerable a company is to possible supply risks, especially considering short-term supply disruptions. If there is a continual purchasing of the company in order to replenish its stock, the average purchasing prices over a period will be more stable compared to the prices when only buying on immediate demand. However, if large areas are needed for storage, that might be a limiting factor (VDI, 2018). Furthermore, if the component's prices are high, a sufficient credit line to finance the inventory is needed. The inventory cycle time may be an appropriate measure to use for determining the adequate inventory level for a component. The evaluation framework of the criterion was adopted from VDI 4800/2.

An indicator value of 0 signifies that there is optimal inventory taking into account availability and economic viability as a function of the strategic importance. If there is sufficient inventory, but certain constraints regarding short-term and direct access to the volumes required, a value of 0.3 is assigned, while 0.7 means that there is a medium inventory level, but it is mostly held by upstream companies without direct access. A value of 1 indicates that there is no or only a very low inventory level of the component.

3.1.2.12. Excluded criteria. The criterion *internal consumption*, which is part of the VDI 4800/2 framework, compares the consumption of the respective raw material with the total raw material demand of the company. As products are typically not compared by their mass but by their value, which is covered by the criterion *purchase value of the component relative to the total purchase value*, the criterion was excluded from the vulnerability assessment.

3.1.3. Aggregation of the criteria

To apply the method to a component, all of the above criteria of the supply risk and vulnerability dimension are taken into account. Subsequently, a degressive addition of the individual values to the base 3, analogous to the VDI 4800/2 method, is used to evaluate the supply risk and vulnerability of each component. Therefore, the n values of the individual criteria are first sorted in descending order. Each value is then multiplied by a normalised weighting factor $i(i = 1, \ldots, n)$ which is calculated as shown in formulas (1) and (2).

$$G_i = \frac{2^{(i-1)}}{3^i} \cdot K_n \tag{1}$$

$$K_n = \frac{1}{\sum_{i=1}^{n} G_i} \tag{2}$$

Finally, the single multiplied values are added up to one result value.

The result of this assessment yields the criticality of the component in both dimensions, with higher values indicating greater criticality and thereby an increased risk for the overall system. The results can be depicted on a two-dimensional grid, with the supply risk on one and vulnerability on the other axis.

3.2. Presentation of case study results

The developed method was applied in the LCIZ project, which included a criticality analysis of an electrolyser for a company. The project was initiated by a pre-selection of potentially critical components, conducted by experts within the project team in order to reduce the necessary time investment and mitigate complexity. The team of experts was formed by the company's sustainability manager and two senior scientists from Fraunhofer UMSICHT and the Wuppertal Institute working in the fields of sustainable technology and circular economy. In the pre-selection process, components made of conventional plastics and cardboard or components made of metals that are part of the housing were categorised as non-critical by the experts, as these parts are generally easy to substitute, the supply chains are less complex and there is a wide choice of producers. Functional and electronic components, on the other hand, were prioritised as potentially critical. The pre-selected components were then evaluated by employees of the company with regard to the respective criteria in the dimensions of supply risk and vulnerability. For improved applicability, the criteria were compiled in Tables A.1 and A.2 (see Appendix), including a leading question for each one. Depending on the use case, some of the criteria may be excluded or deemed irrelevant for the assessment. For instance, since the company was only recently founded, the criteria *ability to innovate* and *ability to pass through prices* were excluded from the assessment. Another reason for excluding a criterion may be if the knowledge or data required to evaluate the criterion is not available. However, it should be kept in mind that the more criteria are taken into account, the more reliable the result will be.

Fig. 2 shows the criticality results of the method application in the LCIZ project (Enapter GmbH et al., 2024). The graph is separated into nine areas with dividing lines at x = 0.3, x = 0.7, y = 0.3 and y = 0.7, analogous to the indicator values of the evaluation framework. In total, six components of the electrolyser were identified as having a high supply risk and a medium vulnerability risk. Additionally, the analysis revealed that two other components face a medium risk for both supply and vulnerability, while one component has a medium supply risk and low vulnerability. While the usage of critical components within the electrolyser entails the risk of a supply shortage and vulnerability that could jeopardise the company's business operations, the assessment revealed bottlenecks and thus enabled the company to take countermeasures to reduce this risk. For example, it was shown that the company is already counteracting the risk of vulnerability by stockpiling critical components and implementing procurement strategies. However, room for improvement was identified by introducing R-strategies for critical components, thereby helping to increase the company's independence from global supply chains.

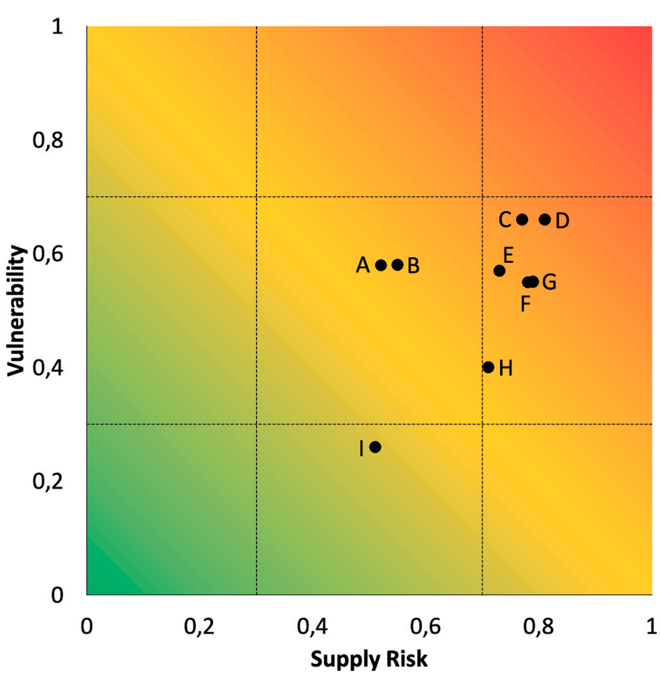

Fig. 2. Results of the criticality assessment of preselected electrolyser components (A-I), based on the dimensions of supply risk and vulnerability (A: Catalyst loaded beads; B: Nickel foam; C: Power supply unit 24 V; D: Power supply unit 48 V; E: Condenser; F: Power connector; G: Power line filter; H: Ferrite core; I: Heater).

4. Discussion

4.1. Discussion of the case study

Overall, the method was successfully implemented in the LCIZ project and delivered comprehensible results. Using the prepared Tables A.1 and A.2 in the appendix), which guide the evaluation of the criteria through specific questions, the company could apply the method on its own. As this method is particularly interesting for companies that want to strengthen their supply chain, this is an important finding. The independent assessment of the criteria raises further awareness of the various aspects that contribute to criticality, which offers considerable added value to the company. Easy accessibility and practicability should therefore also be kept in mind when further developing the method.

However, during the development and application, various points arose both on individual criteria and on the method in general, which are discussed below. Some of these were inherited from the method of VDI 4800/2 and some are unique to the newly developed method.

4.2. Discussion of the developed method

4.2.1. Discussion of the adaptation process

The newly developed method builds upon an established approach originally designed for evaluating the criticality of raw materials. The general transferability of this method from raw materials to components proved to be largely straightforward. This is particularly true for the vulnerability dimension, where the criteria focus primarily on the reference system and could therefore be more closely aligned with the VDI 4800/2 guideline. As a result, these criteria did require almost no changes to the evaluation frameworks.

By contrast, adapting the supply risk dimension presented more challenges. Originally tailored to specific raw materials, the criteria for supply risk had to be reformulated to reflect the characteristics of components, which often consist of multiple materials and are sourced through more complex supply chains. Therefore, various criteria required an inclusion of upstream supply chain elements. This extended chain introduces additional complexity and risk factors, which were not as prominent in the original method. Another difficulty was the lack of available production data for components. While such data is typically accessible for raw materials, its absence for components necessitated a shift from quantitatively to qualitatively assessed criteria.

4.2.2. Discussion of the method

With regard to the method as a whole, it can be said that the method is quite intricate and time-consuming, potentially necessitating a preliminary selection of components. However, establishing criteria or guidelines for this selection process is difficult. Instead, good knowledge of the products under consideration, as it is often provided by the purchasing department in companies, helps to pre-select and exclude non-critical components from the assessment.

Moreover, high values are frequently entered for criteria such as *price fluctuations* and *substitutability* in both methodologies, whereas the latter is potentially even counted twice in the vulnerability assessment due to the distinguishment of technical substitutability and its feasibility. Combined with degressive addition, this tendency could result in an overestimation of criticality, warranting caution in interpretation. This also becomes apparent when comparing the results of criticality assessments at the raw material level using VDI 4800/2 with the results of other criticality assessments such as those carried out by the EU (European Commission et al., 2017).

Furthermore, the aforementioned lack of data for the quantitative assessment of certain criteria necessitates a qualitative assessment. This qualitative nature may result in not all questions being fully answerable. As a consequence, distorted results may ensue, since the robustness of the findings improves with an increased number of answered criteria. Further exploration of the qualification requirements for experts providing qualitative assessments would also enhance the clarity and reliability of results. On the other hand, it should be noted that the method was developed for a self-assessment by companies, which is why a qualitative assessment is often preferred over a quantitative evaluation as it is easier to implement and has a lower data requirement. In addition, depending on the data quality, quantitative calculations might only lead to an estimate as well, even though they involve a lot more effort.

In terms of individual criteria, it was noted that the inclusion of *substitutability* as a criterion for supply risk requires further discussion, as components are generally difficult to substitute in their main applications, leading to overall high criticality values. This challenge mirrors the issue in VDI 4800/2 regarding the substitutability of raw materials in their main application.

Furthermore, the criterion of *global demand* presents a significant challenge due to the absence of adequately specific production statistics. This issue is not unique to the developed method, but also pertains to the VDI 4800/2 approach, as relying on production quantity may not fully capture the complexity of demand dynamics. Thus, the lack of a robust data foundation for evaluating the global demand remains a constraint in both methodologies. In these cases, qualitative assessments may also be preferred to quantitative calculations.

Unique to the developed method is the aspect of information about the component's global production. The lack of comprehensive data may lead to an incomplete representation of the entire supply chain. This limitation affects the criteria of *company concentration* and *country concentration* as well as *geopolitical risks of global production* and *regulatory risks of global production*. For example, the assessment of geopolitical risks may focus primarily on the country of the supplier, as the location of the manufacturer is often unknown. In this regard, adapting the method to directly inquire about suppliers may address this issue, but it would overlook potential risks in the upstream supply chains.

5. Conclusion

Criticality will remain an important issue in the future, as dependence on a small number of supplier countries for many strategic raw materials is extremely high. This circumstance is the reason for various international activities to determine and reduce the criticality of raw materials. However, similar dependencies exist for numerous components. Therefore, a new method was developed that aligns with VDI 4800/2 and allows the assessment of criticality of a component rather than raw material. In the adaptation process, some quantitative assessments suggested by VDI 4800/2 were replaced by qualitative evaluation due to the unavailability of data and some criteria were omitted. Overall, however, there is a high degree of agreement between the new and the original method, which fulfills the aim of developing a method that aligns with VDI 4800/2 and thereby embodies criticality assessment as well as life cycle sustainability aspects. It was hence shown that the VDI 4800/2 method can be transferred to components.

Furthermore, the case study within the LCIZ project showed the applicability of the method to components in order to determine criticality at the product level. The case study further suggests that the method can be used by experts within the company itself. The application enabled the company to estimate the supply risk for components as well as the vulnerability at a corporate level. Thereby, the method can serve as a guide for strategic decisions in risk management. However, the use of a high number of criteria showed that the assessment involves considerable effort. Moreover, the availability of data and the expertise of the professionals carrying out the assessment are decisive criteria for a valuable implementation. Therefore, this method should not be viewed as an isolated tool, but rather as an integral part of a comprehensive approach to risk management and strategic planning.

CRediT authorship contribution statement

Silvia Proff: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation. **Saskia Heinemann:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Michael Ritthoff:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization.

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Declaration of competing interest

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

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Appendix A

Table A1
Criteria for determining the supply risk.

Criteria	Question	Value range
R-strategies	To what extent are R-strategies (reuse, refurbish, recycle, etc.) of the component established?	1 = not established 0.7 = established with high quality losses 0.3 = established with low quality losses 0 = established without any major quality losses
Logistic constraints	Is storage and/or transport problematic or associated with high costs?	1 = problematic and not economical 0.7 = only feasible at high costs 0.3 = complex, but economically justifiable 0 = unproblematic and economically viable
Country concentration of global production	Are production facilities and upstream chains of the component concentrated in a few countries?	1 = produced in relevant quantities in a small number of countries (approx. < 5) 0.7 = produced in relevant quantities in a few countries (approx. 5–7)

(*continued on next page*)

Table A1 (*continued*)

Criteria	Question	Value range
		0.3 = produced in relevant quantities in several countries (approx. 8–20) 0 = globally produced in relevant quantities (approx. > 20 countries)
Geopolitical risks of global production	Are production facilities and upstream chains concentrated in countries with high political risk?	1 = predominantly in countries with very high political risk (PCI ≥ 0.85) 0.7 = predominantly in countries with high political risk (0.5 ≤ PCI < 0.85) 0.3 = predominantly in countries with moderate political risk (0.15 ≤ PCI < 0.5) 0 = predominantly in countries with very low political risk (PCI < 0.15)
Regulatory risks of global production	Are production facilities and upstream chains concentrated in countries with high regulatory risk?	1 = predominantly in countries with very high regulatory risk (RCI ≥ 0.85) 0.7 = predominantly in countries with high regulatory risk (0.5 ≤ RCI < 0.85) 0.3 = predominantly in countries with moderate regulatory risk (0.15 ≤ RCI < 0.5) 0 = predominantly in countries with very low regulatory risk (RCI < 0.15)
Company concentration of global production	Are the component and its preliminary products produced in relevant quantities by only a few companies?	1 = produced by a small number (approx. < 5) of companies 0.7 = produced by a few (approx. 5–7) companies 0.3 = produced by several (approx. 8–20) companies 0 = produced by numerous (approx. > 20) companies
Global demand impetus	Is global demand for the component rising faster than global economic growth?	1 = disruptive demand growth 0.7 = disproportionate demand growth relative to global economic growth 0.3 = demand growth in parallel with global economic growth 0 = change in demand is smaller than the change in global economic growth
Substitutability	To what extent can the primary product be substituted in its main application?	1 = no substitutability 0.7 = substitutability at high cost and/or with a functionality loss 0.3 = substitutability at low cost 0 = easy and complete substitutability without additional costs
Price fluctuations	How high were the price fluctuations of the component in the last 5 years?	1 = very high price fluctuations 0.7 = high price fluctuations 0.3 = moderate price fluctuations 0 = almost no price fluctuations

Table A2
Criteria for determining vulnerability.

Criteria	Question	Value range
Share of risk-exposed product in total contribution margin	How high is the share of the company's contribution margin accounted for by the product affected by the supply risk?	1 = share higher than 25 % 0.7 = share between 10 % and 25 % 0.3 = share between 2 % and 10 % 0 = share less than 2 %
Importance of the component to the product function/substitutability in the product	To what extent is it possible to technically substitute the component (by the same component with other technical specifications/by another component/by changing the overall process) without loss of function of the product?	1 = function of the product not given without the component, hence substitution is not possible 0.7 = substitution with other components would lead to major malfunctions and quality losses 0.3 = function of the product is retained if the component is replaced, but quality declines 0 = component is replaceable; substitution achieves the same functionality and comparable or slightly inferior product quality
Consumption relative to global annual production	How high is the company's consumption of the component in comparison with the global annual production?	1 = higher than 10 % 0.7 = between 2 % and 10 % 0.3 = less than 2 % 0 = quantities of component used are so small that an offset against the annual production no longer meaningful
Purchase value of the component relative to the total purchase value	What share has the purchase value of the component in the total purchase value of the company?	1 = higher than 75 % 0.7 = between 50 % and 75 % 0.3 = between 5 % and 50 % 0 = less than 5 %
Access to and feasibility of substitution solutions	To what extent are technical substitution solutions feasible due to legal, economic, logistic, time or certification constraints?	1 = not feasible 0.7 = access to substitution solutions can be gained, but can only be implemented with major financial effort, comprehensive R&D efforts, takes a lot of time, or requires new certification process 0.3 = access to substitution solutions available and solutions can be implemented with minor financial effort, within a short time, or with minor R&D effort

(*continued on next page*)

Table A2 (*continued*)

Criteria	Question	Value range
		0 = free access to substitution solutions without or with negligible constraints
Ability to innovate	What is the company's capacity for innovation (based on the number of inventions and patent applications, the proportion of total sales spent on R&D, or the openness of the corporate culture to innovation)?	1 = no inventions or patents; no R&D budget; no employee empowerment 0.7 = hardly any own inventions; few patent applications; small R&D budget; little employee empowerment 0.3 = high inventiveness and/or large number of invention disclosures; sufficient R&D budget to implement ideas; motivation and empowerment of employees 0 = continuous development of new products, processes, business activities; open corporate culture
Availability of a procurement strategy	Are procurement strategies in place for the component (e.g., long-term contractual ties with producers, joint ventures with producers, building own production facilities, securing supply through recycling strategies, multiple independent suppliers/ manufacturers)?	1 = not available 0.7 = contemplated but not implemented 0.3 = existing and partially implemented 0 = detailed procurement strategies available and largely implemented
Ability to pass through prices	Has it been possible to pass on price fluctuations of the component to customers in the past?	1 = has not been possible 0.7 = has been rarely possible and/or to a small extent (<2/3 of price increase) 0.3 = has been frequently possible and/or to a large extend (>2/3 of price increase) 0 = has always been possible
Bargaining potential/market power vis-à-vis suppliers	Is it possible to influence prices and other delivery conditions?	1 = hardly possible 0.7 = possible in individual cases to a minor extent 0.3 = regularly possible to a major extent 0 = own demand in total market > 50 %; company controls the demand market
Availability of price hedging instruments	Are hedging instruments against price fluctuations of the component available?	1 = not available 0.7 = only available on a very individual basis from few counter-parties, low market liquidity 0.3 = available as off-floor transactions with a high liquidity from many providers or as standardised instruments on exchange markets with a medium market liquidity 0 = standardised instruments available in regulated stock markets with a high market liquidity
Appropriate inventory levels/ stockpiling	Is the component stored/held in reserve in the own or upstream company?	1 = no or very low inventory level 0.7 = medium inventory level, but mostly held by upstream companies without direct access 0.3 = sufficient inventory but certain constraints regarding short-term and direct access to the volumes required 0 = optimal inventory taking into account availability and economic viability as a function of the strategic importance

Data availability

The data that has been used is confidential.

References

Bach, V., Berger, M., Henßler, M., Kirchner, M., Leiser, S., Mohr, L., Rother, E., Ruhland, K., Schneider, L., Tikana, L., Volkhausen, W., Walachowicz, F., Finkbeiner, M., 2016. Integrated method to assess resource efficiency – ESSENZ. J. Clean. Prod. 137, 118–130. https://doi.org/10.1016/j.jclepro.2016.07.077.

Council of the European Union (2024, 18 March). Strategic autonomy: Council gives its final approval on the critical raw materials act [Press release]. https://www.consilium.europa.eu/en/press/press-releases/2024/03/18/strategic-autonomy-council-gives-its-final-approval-on-the-critical-raw-materials-act/.

Deutsche Rohstoffagentur. Rohstoffe. https://www.deutsche-rohstoffagentur.de/DERA/DE/Rohstoffinformationen/Rohstoffe/rohstoffe_node.html;jsessionid=10D.

Enapter GmbH, Fraunhofer UMSICHT, Wuppertal Institut, & Fachhochschule Münster (2024). Life Cycle Impact Zero: Abschlussbericht.

Erdmann, L., Behrendt, S., & Feil, M. (2011). Kritische Rohstoffe für Deutschland: Identifikation aus Sicht deutscher Unternehmen wirtschaftlich bedeutsamer mineralischer Rohstoffe, deren Versorgungslage sich mittel- bis langfristig als kritisch erweisen könnte. Im Auftrag der KfW Bankengruppe. Abschlussbericht.

European Commission (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability. COM(2020) 474 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474.

European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Pennington, D., Tzimas, E., Baranzelli, C. et al. (2017). Methodology for establishing the EU list of critical raw materials: Guidelines. Publications Office. https://data.europa.eu/doi/10.2873/769526.

European Commission (2023). Study on the Critical Raw Materials for the EU 2023 – Final Report.

Exec. Order No. 13817, 82 FR 60835 (2017). https://www.govinfo.gov/content/pkg/DCPD-201700922/pdf/DCPD-201700922.pdf.

Fan, Y., Stevenson, M., 2018. A review of supply chain risk management: definition, theory,and research agenda. Int. J. Phys. Distrib. Logist. Manag. 48 (3), 205–230.

Gandenberger, C., Marscheider-Weidemann, F., Tercero, L., 2010. Kritische Rohstoffe aus europäischer Sicht. Die Volkswirtschaft 11, 12–15.

Gemechu, E.D., Helbig, C., Sonnemann, G., Thorenz, A., Tuma, A., 2015. Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessment. J. Ind. Ecol. 20, 154–165.

Graedel, T.E., Harper, E.M., Nassar, N., Nuss, P., Reck, B.K., 2015. The Criticality of Metals and Metalloids. Proc. Natl. Acad. Sci. 112 (14), 4257–4262. https://doi.org/10.1073/pnas.1500415112.

Hackenhaar, I., Alvarenga, R.A.F., Bachmann, T.M., Riva, F., Horn, R., Graf, R., Dewulf, J., 2022. A critical review of criticality methods for a European Life Cycle Sustainability Assessment. Procedia CIRP 105, 428–433. https://doi.org/10.1016/j.procir.2022.02.071.

, 2022HM Government (2022). Resilience for the Future: The United Kingdom's Critical Minerals Strategy. https://assets.publishing.service.gov.uk/media/62f36bafe90e07714288b188/resilience_for_the_future_the_uks_critical_minerals_strategy.pdf.

Ho, W., Zheng, T., Yildiz, H., 2015. Supply Chain Risk Management: A Literature Review. Int. J. Prod. Res. 53 (16), 5031–5069. https://doi.org/10.1080/00207543.2015.1030467.

Jabara, M., Wu, J., De Franceschi, S., Manzardo, A., 2025. Assessing Mineral and Metal Resources in Life Cycle Assessment: An Overview of Existing Impact Assessment Methods. Sustainability 17 (4), 1692. https://doi.org/10.3390/su17041692.

Kaufmann, D., Kraay, A., 2024. The Worldwide Governance Indicators: Methodology and 2024 Update. Policy Research Working Paper Series 10952. The World Bank.

Kolotzek, C., Helbig, C., Thorenz, A., Reller, A., Tuma, A., 2017. A company-oriented model for the assessment of raw material supply risks, environmental impact and

social implications. J. Clean. Prod. 176, 566–580. https://doi.org/10.1016/j.jclepro.2017.12.162.
Kranich, S., Krommes, S., Rieder, R., 2019. Bewertung der Rohstoffkritikalitäts-Methode nach VDI 4800 im Produktentwicklungsprozess: Fallstudie eines elektrischen Fahrzeugantriebssystems. NachhaltigkeitsManagementForum 27, 53–63. https://doi.org/10.1007/s00550-018-0481-z.
Negri, M., Cagno, E., Colicchia, C., Sarkis, J., 2021. Integrating sustainability and resilience in the supply chain: A systematic literature review and a research agenda. Bus. Strateg. Environ. 30 (7), 2858–2886. https://doi.org/10.1002/bse.2776.
Potting, J., Hekkert, M.P., Worrell, E., Hanemaaijer, A., 2017. Circular economy: measuring innovation in the product chain. In: Planbureau voor de Leefomgeving, p. 2544.
Pournader, M., Kach, A., Srinivas, T., 2020. A Review of the Existing and Emerging Topics in the Supply Chain Risk Management Literature. Decis. Sci. 51 (4). https://doi.org/10.1111/deci.12470.
Regulation 2023/1781. Regulation (EU) 2023/1781 of the European Parliament and of the Council of 13 September 2023 establishing a framework of measures for strengthening Europe's semiconductor ecosystem and amending Regulation (EU) 2021/694 (Chips Act) (Text with EEA relevance). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.229.01.0001.01.ENG.
Rhoades, S.A. (1993). The Herfindahl-Hirschman Index. Federal Reserve Bulletin, Mar, 188-189. https://EconPapers.repec.org/RePEc:fip:fedgrb:y:1993:i:mar:p:188-189:n:v.79no.3.
Santillàn-Saldivar, J., Gemechu, E.D., Muller, S., Villeneuve, J., Young, S.B., Sonnemann, G., 2022. An improved resource midpoint characterization method for supply risk of resources: Integrated assessment of Li-ion batteries. International Journal of Life Cycle Assessment 27, 457–468.
Schneider, L., Berger, M., Schüler-Hainsch, E., Knöfel, S., Ruhland, K., Mosi, J., Bach, V., Finkbeiner, M., 2014. The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. Int. J. Life Cycle Assess. 19, 601–610. https://doi.org/10.1007/s11367-013-0666-1.
Singhal, P., Agarwal, G., Mitall, M.L., 2011. Supply chain risk management: review, classification and future research directions. International Journal of Business Science and Applied Management 6 (3), 15–42.
Sultana, S., Paul, N., Tasmin, M., Dutta, A.K., Khan, S.A., 2024. Analyzing Supply Chain Risks and Resilience Strategies: A Systematic Literature Review. Engineering Proceedings 76 (1), 41. https://doi.org/10.3390/engproc2024076041.
University of Cambridge Institute for Sustainability Leadership, & Wuppertal Institute (2023). Embracing circularity: A pathway for strengthening the Critical Raw Materials Act. Cambridge, UK: CLG Europe. https://www.corporateleadersgroup.com/files/cisl_embracing_circularity_report_v5.pdf.
U.S. Geological Survey, Mineral Commodity Summaries (1996-2023). U.S. Geological Survey (U.S. Geological Survey, 1996-2023 [yearly publication]). https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries.
U.S Geological Survey, Minerals Yearbook (1994-2020). U.S. Geological Survey (U.S. Geological Survey, 1994-2020 [yearly publication]. https://www.usgs.gov/centers/national-minerals-information-center/minerals-yearbook-metals-and-minerals.
Vdi, 2018. Resource efficiency: Evaluation of the use of raw materials. DIN Media, Berlin.
Wuppertal Institut (2021). iNEW 2.0: Incubator Sustainable Electrochemical Value Chains. Wuppertal Institut für Klima, Umwelt, Energie. https://wupperinst.org/en/p/wi/p/s/pd/1981.
Wuppertal Institut (2022). ImpactZero: Life Cycle Impact Zero. Wuppertal Institut für Klima, Umwelt, Energie. https://wupperinst.org/en/p/wi/p/s/pd/2037.
Yavor, K.M., Bach, V., Finkbeiner, M., 2021. Adapting the ESSENZ method to assess company-specific criticality aspects. Resources 10 (6), 56. https://doi.org/10.3390/resources10060056.