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Materials Criticality Profiling Methodology at Product Level

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Abstract: *Strategic or critical material issues have recently drawn significant attention. While all materials are important to a certain degree, identifying critical ones remains essential due to time and resource constraints. This paper first provides a comprehensive diagnosis of material criticality at the product level, focusing on the following dimensions: Imbalance between demand and supply, Importance of the material to the object (e.g., product), Supply accessibility (including materials that cannot or should not be accessed), Dynamic factors or abrupt changes. Based on this diagnosis, the paper proposes a methodology to alert and evaluate critical materials in products, serving as a decision-making support tool for industries. A unique feature of this methodology is its product-level focus. Additionally, it enables personalization across different contexts by integrating dynamic factors into indicators and scenarios. A basic scenario example is included to illustrate how to derive calculation criteria from the diagnostic framework.*

Keywords: Critical Material; Criticality; Evaluation Methodology; Product; Decision Making

1. Introduction

Material crises have occurred at various times and in different countries. Notable examples include: The cobalt crisis in the late 1970s, triggered by the civil war in Zaire (the world's dominant cobalt producer at the time) [1-3]. The palladium crisis in the 1990s, caused by Russian export cuts [4]. The rare earth minerals crisis around 2010, resulting from Chinese export restrictions [5]. The oil shocks of 1973 and 1979, precipitated by Arab nations embargoing supporters of Israel [6].

Beyond these immediate triggers, material crises stem from complex interactions among multiple factors. For instance, while Zaire's civil war disrupted cobalt mining and rail transport, the country paradoxically achieved record cobalt production in 1978. Concurrently, surging global economic demand drove cobalt prices from $22.5/kg (1996) to $120/kg (1980, normalized to 1998 prices) [7]. Although substitutes for cobalt in ceramics and paints were readily available, critical applications like jet engine superalloys faced irreplaceable shortages.

The economic repercussions of such crises can be severe. The late-1990s palladium crisis, for example, cost a single U.S. automaker over $1 billion in losses—remarkable given that each vehicle contained under 28 grams of palladium. Similarly, the 2010 rare earth crisis disrupted numerous technology companies.

Therefore, studies on critical materials and resources are very important to the global industry and economy. Based on a review [8], there is a lack of a product-level evaluation methodology as well as a diagnosis of the parameters that influence material criticality. Currently, several evaluation methodologies for criticality have been developed:

for specific regions [5], [9], [10],
for specific groups of metals [11, 12],
for technologies with a specific perspective [1], [13],
and for material markets [4], [14].

For industry, the results from current evaluations and studies cannot be used directly if the goal is to determine which materials are critical for specific products. For example, beryllium was designated as a critical resource in the EU [5]. However, this information is not useful for companies that do not require beryllium in their products or that are not located in the EU. The list of critical materials was designated from a list of candidates in a European study. Hence, material criticality is a relative value that depends on context. For instance, different pools of candidates will result in different lists of critical materials. In addition, the focus of critical material studies at the product level is different from that conducted for specific regions or for specific groups of materials. While existing studies have assessed material criticality at regional, sectoral, and market levels [4], [5], [12], they lack a product-specific evaluation framework, creating a gap this study aims to address.

The objectives of this study are to develop an evaluation methodology for determining the criticality of materials at the product level. We conducted an analysis of the impact parameters affecting criticality of materials at the product level (i.e., diagnosis of criticality). Based on this theoretical framework, we developed a methodology that is suitable for different scenarios and an evaluation model for a basic scenario.

2. Materials and Methods

2.1 Diagnosis of impact parameters of criticality at the product level

In this part, we analyzed parameters that influence the criticality of materials at the product level, which is a necessary phase before the development of a criticality evaluation model. This process can be called the "diagnosis of criticality." The methods for the diagnosis are as follows: first, searching for key information on "critical," "strategic," and "important" from dictionaries and scientific publications; second, reviewing existing critical material studies; third, asking the question "which parameters can influence the criticality of materials at the product level"; fourth, reflecting on information in the previous three steps to identify key criteria of criticality; fifth, establishing an embryonic form of how criticality is influenced; sixth, examining the quantitative and qualitative indicators used in existing studies to see if they can be added to the embryonic form from the previous step; seventh, brainstorming parameters in terms of technological, social, environmental, political, and geographical aspects to reinforce the embryonic form; and eighth, establishing the mechanism of impact parameters on criticality.

As a result, we focused on two material supply crises from the past as case studies to verify the conformity of the criticality mechanism. The two material supply crises are the cobalt crisis in the late 20th century and the rare earth elements crisis around 2010. Even though these two case studies are not at the product level, they offer useful information to extract the impact parameters of material criticality. The resulting impact parameters from the diagnosis process are shown in Figure 1.

As shown in Figure 1, we identified four dimensions of criticality for materials at the product level: imbalance between demand and supply, accessibility to supply, importance, and dynamic factors. These dimensions were further broken down into more detailed levels. The final component of each dimension was termed an "impact parameter" of criticality.

2.1.1 Importance of materials

This dimension represents the importance of materials to the product and consists of three factors: functionality, substitutability, and economic influence. The functionalities of all materials contribute to the performance of a product. Thus, we prioritize the functionalities offered by the material over the material itself [4]. This reflects the significance of a material for a product. At the same time, functionality can be obtained from other materials if they offer an acceptable price, mature production technology, and sufficient supply. A material becomes less important the more easily it can be replaced.

Finally, we assess economic impact based on price. For example, rare earth elements used as catalysts in petroleum refining illustrate this point. Around 2010, the price of rare earth materials rose sharply. However, rare earth catalysts remained in use even though alternative catalysts containing no rare earth elements were already available. This occurred because the price increase of rare earth materials had minimal influence on the final price of petroleum, given the low usage of rare earth materials in refining production [9].

From this case, we derive the importance of the three impact parameters:

1. Functionality (rare earth elements' catalytic properties),
2. Substitutability (availability of rare-earth-free catalysts), and
3. Economic influence (the price increase had little effect on refining costs).

2.1.2 Accessibility to supply

We divided this dimension into two parts. The first part concerns supply that is restricted due to environmental or legislative barriers, such as limits on hazardous materials. For example, mercury in compact fluorescent lamps is capped at 5 mg, and the use of lead, cadmium, and hexavalent chromium is similarly regulated [15]. Traditional lamps were phased out in Europe due to their mercury content and inefficiency [16], reflecting tightening environmental policies. As public awareness grows, legislative restrictions on polluting materials will likely increase, potentially rendering even currently acceptable materials inaccessible in the future. The second part examines situations where materials are unavailable due to physical or economic constraints, which we categorized into supplier-related factors and broader geopolitical or market conditions. Supplier considerations include diversity, location, pricing, relationships, and internal stability. External factors involve competition from sectors like defense, reliance on by-products from primary mining, the scale of economically viable global reserves, and geopolitical tensions—such as China's 2010 rare earth export halt to Japan or historical oil embargoes. Supplier country instability, as seen in the 1970s Zaire conflict disrupting cobalt supply [7], along with domestic demand, labor strikes, or legislative shifts, can further restrict access. Additionally, imbalances between global demand and supply intensify scarcity, while recycling rates influence the potential recovery of materials from urban mines.

2.1.3 Imbalance between demand and supply

The demand and supply in this dimension is the amount directly related to the actor – the company who produces the product. The demand amount here means the needed amount of each material to satisfy the target production amount of the product. The supply amount here means the amount that the specific company can have access directly at that moment, including the actual supply amount and the potential supply amount from its actual suppliers and potential suppliers. Any material with a greater supply than its demand is significantly less worrisome than a material with a small demand but less supply. Hence, it is the imbalance between demand and supply that needs to be considered for criticality rather than demand or supply individually.

2.1.4 Dynamic aspect or abrupt changes

The suddenness of changing situations is often more disruptive than the situations themselves. Here, "situation" refers to the complete set of prevailing conditions at a given time - including price, reserve quantities, reserve locations, geopolitical relationships between involved nations, and all other factors affecting a material's criticality. While solutions typically emerge given sufficient time and markets do respond to material criticality issues, timing remains crucial. For instance, following the cobalt crisis, Zambia and Australia substantially increased their cobalt production, while Zaire's market share plummeted from 70% in 1978 to 31% by 2004. During this period, cobalt substitutes were developed for applications like magnets, cutting tools, ceramics, and paints [7], [17]. However, the time required for markets to reach equilibrium and for companies to adapt proves critical, as some organizations may not survive prolonged material crises.

Material criticality projections vary significantly across different time periods and contexts. The 2010 rare earth crisis had fundamentally different triggers than the palladium crisis of the 1990s. To address this variability, we propose maintaining a comprehensive pool of all potential impact parameters affecting criticality (Figure 1). While one material crisis might stem from parameters A, B, and C, another might involve parameters D, E, and F - all contained within the same master list. This allows selection of the most severe parameters for any given situation while monitoring others. Our first approach to interpreting dynamic factors involves scenario analysis, where different situations may incorporate distinct parameter combinations from this pool. This represents the first criticality evaluation methodology offering flexible parameter selection during assessment.

Previous research has acknowledged dynamic considerations [1], [18]. Our second analytical approach examines dynamic indicators, recognizing that some indicators inherently evolve over time [1]. Certain parameters represent latent risks, such as environmental regulations potentially triggering bans or consumer opposition. The third approach involves adjustable weightings and thresholds within evaluation models. Users might calculate criticality assuming 20% or 30% of candidates qualify as critical, or apply expert-defined thresholds. The model includes customizable parameters for user-defined weightings and thresholds, supported by implementation guidelines.

Ultimately, material criticality represents a relative measure reflecting: (1) the material's importance to the subject, (2) supply-demand imbalances, and (3) accessibility constraints. Criticality intensifies when abrupt changes outpace stakeholders' adaptive capacity. All materials possess some importance, but "relative" emphasizes focusing on those whose unavailability would cause severe damage, require urgent attention, or exceed adaptation capabilities. The "subject" concept embodies criticality's dynamic nature - whether analyzing a specific product, material group, technology, company, or nation. Similarly, "stakeholders" refers to relevant organizations; for a product, this includes manufacturers and supply chain participants who must respond to disruptions. This framework simultaneously establishes the study's scope while accommodating dynamic criticality assessments.

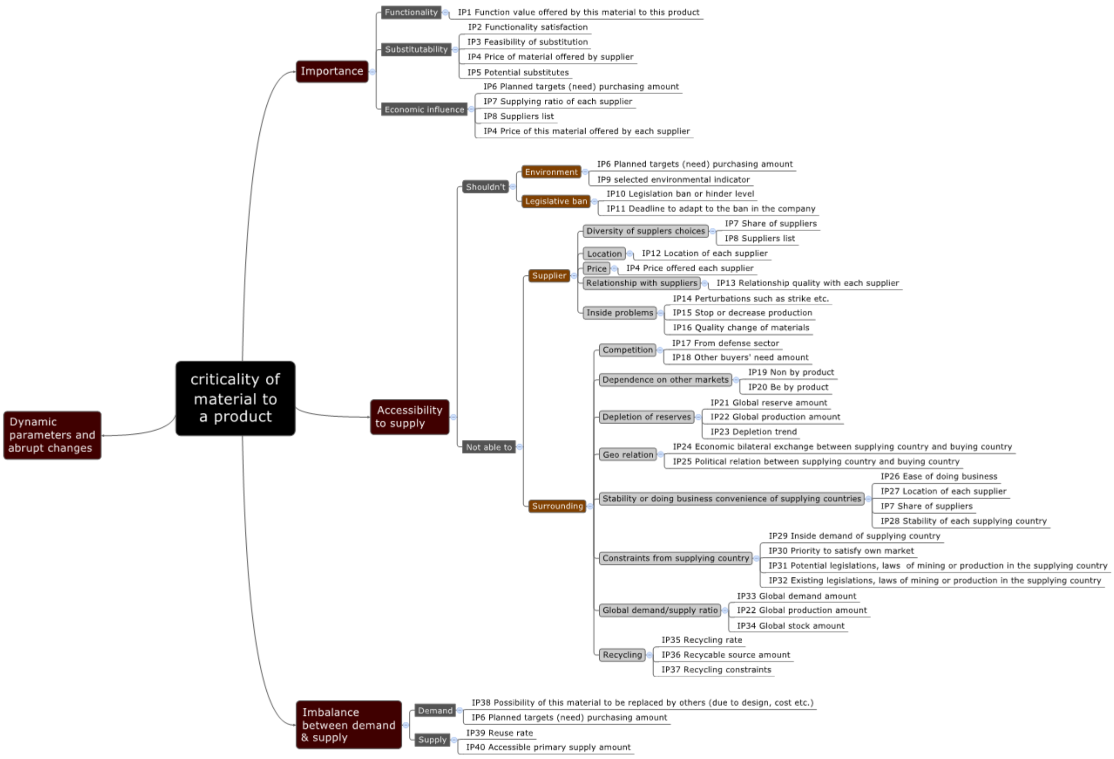

Figure 1. Impact parameters from the diagnosis part

2.2 Overview of evaluation methodology (basic concept)

The criticality evaluation methodology that we developed is destined for production industries at the product level. The guidelines of how to implement this methodology are shown in figure 2 below:

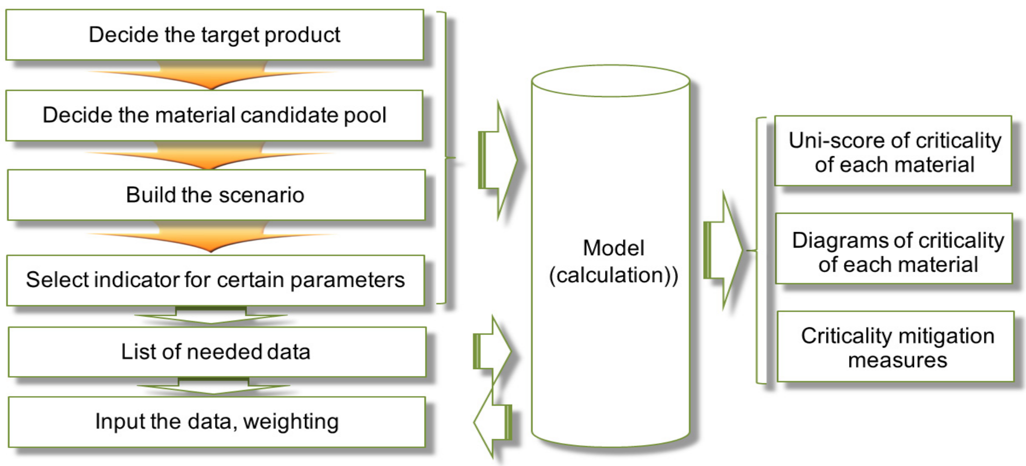

Figure 2. Guidelines on how to implement the criticality assessment methodology

The first step is to identify the target product for analysis, such as a battery, permanent magnet, light-emitting diode, etc. The second step is to define the material candidate pool. As one product might consist of thousands of materials, an analysis might require too much time or too many resources. Thus, this step allows the selection of materials of interest without exceeding available capacity (e.g., budget or human resources required for the criticality evaluation). We can also analyze all materials demanded by the product if possible. The third step is to build the scenario. We can consider the following scenarios as examples: Basic, Forecast, Potential Risk, Environment, Legislative, Economic, and Innovation, etc. These scenarios are related to the company's strategies. For example, if the company's financial situation is poor, it might create the Economic scenario where the impact parameters related to the economy are highlighted and given bigger weights. On the contrary, if the company is in a very good financial position and wants to project a better environmental or innovative image, it can create an Environment or Innovation scenario. Each type has its own priority, which consists of a list of selected impact parameters (IPs) (which might lead to different criteria) or weightings of criteria (see the following paragraph). The scenarios allow for multi-criteria decision making and determine criticality of materials under the corresponding priority. Scenario building reflects the scope of the assessment. The fourth step is the selection of indicators for certain impact parameters, as there are many indicators available to evaluate impact parameters. The objective of this step is to allow users to adapt their studies to specific situations, and this step can improve the methodology over time with more accurate or additional indicators. When data on an indicator are not available, users can choose another one. This also allows for the comparison of different results under different indicators. For example, eco-toxicity and climate change give completely different results in assessing the environmental friendliness of a material. After these four steps, the model, including the calculation module, provides a list of inputs. The fifth step involves entering the data as well as the weightings required by the calculation model, after which the model will offer three outputs: a general score of criticality for each material, a diagram showing the details for all materials (indicating what contributes more to criticality), and mitigation measures for corresponding issues. The mitigation measures can be extracted from existing studies and added by experts in the corresponding domains.

The criticality in the final diagram is represented by "criteria", which are different from impact parameters. A criterion can represent criticality by combining appropriate impact parameters. A criterion might contain more than one impact parameter, and one impact parameter might be associated with more than one criterion. The impact parameter and criterion are differentiated to make the model adaptable to different situations. For example, the IP "supplying ratio of one supplier" influences both the criterion "quality of relationship with suppliers" and the criterion "geo-relationship". However, this IP is not appropriate to assess criticality as an individual criterion. When the input of the supplying ratio changes, the calculation formula of the above two criteria does not need to be changed. Instead, one can simply change the input data. Figure 3 below shows how the impact parameters are connected to the criteria in the basic scenario that we developed.

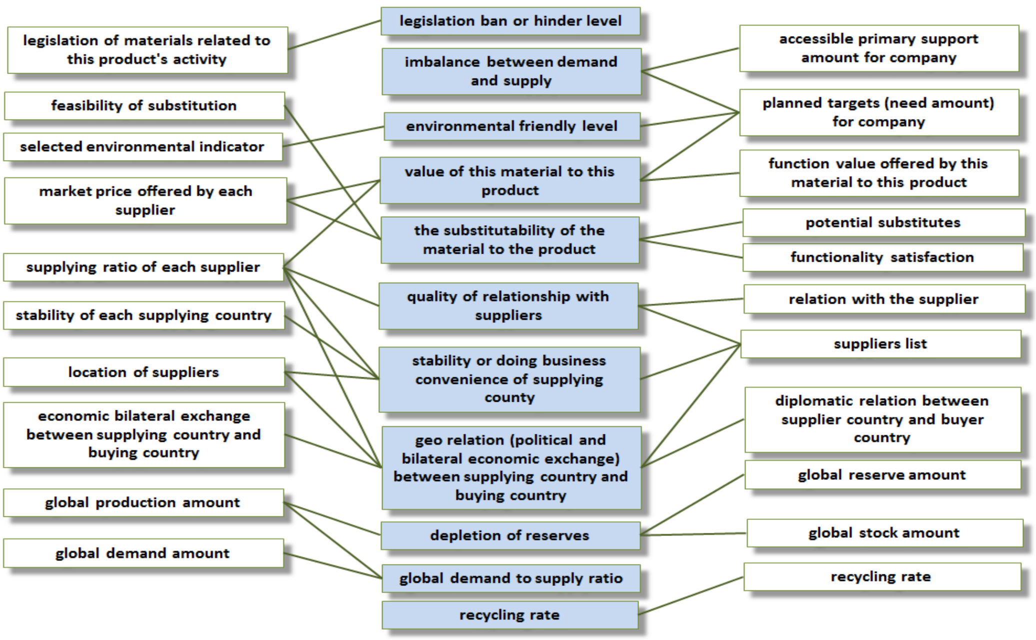

Figure 3. Connections between impact parameters and criteria in the basic scenario

2.3 Calculation of the criteria of the basic scenario

As stated in Section 2.2, we developed different scenarios based on the situation. This paper presents a baseline scenario covering the most influential impact parameters in use today. Readers may consider the baseline scenario as an example for developing others by adding or removing indicators.

First, the model's calculation incorporates five variables for scenario creation: Materials in the candidate pool, Suppliers of materials, Substitutes, General functionality, and Specific functionality.

General functionality and specific functionality are differentiated because multiple hierarchical levels are needed to understand the functionalities of complex products. The extraction of variables is carried out to automate the model. The dependency of a given company on its required materials in each specific situation can thus be determined. Below are the mathematical symbols for these variables, which are used both for calculating criteria and for the framework of the model.

M_i , $_i = 1$ to N ; Materials in the candidate pool to be analyzed. There are N materials in total.
S_j , $_j = 1$ to X ; Suppliers of materials. There are X suppliers in total.
Stt_k , $_k = 1$ to Y ; Substitutes. There are maximum Y substitutes of materials.
GF_L , $_L = 1$ to Z ; General functionality offered by materials for the product. There are Z general functionalities in total.
F_l , $_l = 1$ to H ; Functionality offered by materials to the product. There are H functionalities in total.

In detail, N, X, Y, Z, and H are the numbers of each variable. For example, if there are two materials to be analyzed, then N = 2 with the two materials represented by M_1 and M_2.

Secondly, some inputs are in the form of text to give information:

CL : Company location
P : Product name
$\mathrm{M_i}$: The $\mathrm{i^{th}}$ Material's name
$\mathrm{R_{(M_i)}}$: The $\mathrm{i^{th}}$ Material's mass ratio in the product
$\mathrm{S_j}$: The $\mathrm{j^{th}}$ supplier's name
$\mathrm{L_{(S_j)}}$: The $\mathrm{j^{th}}$ supplier's location (city and country)
$\mathrm{F_{(M_i)}}$: The functionality offered by the $\mathrm{i^{th}}$ Material
$\mathrm{F_l}$: The $\mathrm{l^{th}}$ functionality
$\mathrm{GF_L}$: The $\mathrm{L^{th}}$ general functionality
$\mathrm{Thh.U_{(F_l)}}$: The threshold's unit of lth functions

2.3.1 Criterion 1: Imbalance between demand and supply

This criterion is calculated based on the ratio between the amounts of supply and demand for a material. We used the following symbols to represent their meanings in the calculations.

$SR_{(S_j-M_i)}$: Supplying ratio of S_j for M_i
$D_{(M_i)}$: Demand amount of M_i
$S_{(M_i)}$: Supplying amount of $\mathrm{M_i}$
AoP: Target producing or purchasing amount of product P
$\mathrm{R_{(M_i)}}$: Ratio of material $\mathrm{M_i}$ in the product
LoP: Production loss of product P
$\mathrm{ASA_{(M_i-S_j)}}$: Available supplying amount of $\mathrm{M_i}$ from $\mathrm{S_j}$

As shown in Eq. (1), the demand amount for the ith material can be calculated from the planned production amount of the product, as well as the percentage of the contained material, taking into account production loss.

$$D_{(M_i)} = AoP * (1 + LoP) * R_{(M_i)} \qquad \text{Eq.(1)}$$

The supply amount of each material can be calculated by summing up the available supply amounts that the company's suppliers can offer (see Eq. (2)).

$$ASA_{(M_i)} = \sum_1^X ASA_{(M_i-S_j)} \qquad \text{Eq. (2)}$$

The imbalance between demand and supply of M_i can be calculated as below in Eq. (3).

$$\frac{D_{(M_i)}}{S_{(M_i)}} = \frac{AoP*(1+LoP)*R_{(M_i)}}{\sum_{j=1}^{j=X} ASA_{(M_i-S_j)}} \quad \text{Eq. (3)}$$

On the other hand, if the company already has data on demand or supply, it can directly use its ratio rather than applying Equation 3.

2.3.2 Criterion 2: Value (functional and economic) of this material to the target product

This criterion is a combination of functional value and economic value. In terms of functional value, we need to 1) establish a functionality table for each material offered to the product, such as table 1, and 2) conduct a survey using experts for weighting.

Table 1. Functionality contribution of each material to the product

GF1	***General Functionality 1 (i = 1 to l)***
F1	The 1st functionality
F2	The 2nd functionality
Fl	The lth functionality
GFL	***General Functionality L (i = l to …)***
F(l+1)	The (l+1)th functionality
…n	The nth functionality

In this table, we establish a functionality profile for each material to be analysed for the product. After determining general functionalities (e.g., physical properties, thermal properties, magnetic properties, etc.), we can determine all functionalities offered by each material (e.g., hardness, density, physical carrier, etc. for physical properties).

After establishing the functionality profile, we can conduct a survey using technical experts, designers, or clients in order to determine functionality, including GF and F, for each material. We recommend the Analytic Hierarchy Process or Delphi method for weighting.

In the survey, experts provide the percentage that each material contributes to each functionality. The functional value of the ith material to the product is shown as follows:

$$FV_{(M_i)} = \sum_1^H Con_{(M_i-F_l)} * W_{(F_l)} \quad \text{Eq. (4)}$$

With:

$FV_{(M_i)}$: Functional value of the ith material to the product
$Con_{(M_i-F_l)}$: Contribution of M_i to the functionality F_l in the product
$W_{(F_l)}$: Weighting (Importance) of the functionality F_l to GF_L in the product

In terms of economic value, we use the money needed to purchase this material for producing the total product. The reason is explained in 2.1.

Economic influence of the ith material is as shown in Eq. (5):

$$EI_{(M_i)} = \sum_{j=1}^{X} \left[SA_{(M_i-S_j)} * Price_{(M_i-S_j)}\right] \quad \text{Eq. (5)}$$

With:

$EI_{(M_i)}$: Economic influence of the ith material
$SA_{(M_i-S_j)}$: Supplying amount (purchasing amount) of M_i from S_j
$Price_{(M_i-S_j)}$: Price of M_i offered by S_j

In the end, the "Value" is represented by the association between functional value and economic influence (without money unit), as shown in the following formula:

$$V_{(M_i)} = FV_{(M_i)} * (EI_{(M_i)}/\$) \quad \text{Eq. (6)}$$

2.3.3 Criterion 3: Substitutability of the material to the product

Poulizac [4] used cost and performance (material properties) to evaluate substitutes, addressing both functional and economic aspects. While a material might meet these requirements in laboratory settings, it may fail as a viable replacement if it cannot be industrialized quickly or if the company lacks the necessary equipment or workforce to adapt to the new process. This underscores the importance of considering technological maturity, as substitutes often require additional time or research before becoming feasible. Even after achieving technical and economic viability, supply restrictions may arise, potentially necessitating further criticality assessments. To streamline the evaluation, we recommend focusing solely on the substitute's resource depletion rather than conducting a full reassessment. Eligibility is determined by comparing substitutes to the reference material in terms of functionality (weighted and threshold-tested per technical specifications), technological maturity (assessed via expert surveys such as the Delphi method), price (as an economic proxy), and resource depletion (sourced from Ecoinvent). Substitutability hinges on the number of eligible substitutes available and their satisfaction level—how closely each meets minimum requirements. For example, when assessing a given material, we first identify functionally eligible substitutes by verifying whether their performance measurements fall within required thresholds. Candidates failing this check are excluded, while qualifying substitutes undergo further substitutability satisfaction analysis, comparing their experimental measurements against weighted functionality criteria.

$$FSW_{(F_l - Stt_k)} = \left| \frac{MV_{(F_l - Stt_k)} - Thh_{F_l}}{Thh_{F_l}} \right| \times W_{F_l} \quad \text{Eq. (7)}$$

With

$FSW_{(F_l - Stt_k)}$: Functionality satisfaction with weighting of functionality F_l of materials Stt_k
$MV_{(F_l - Stt_k)}$: Measurement value (MV) of F_l of substitute Stt_k
Thh_{F_l}: Threshold settled for the functionality F_l

We calculate the general functionality satisfaction of the eligible substitute $FSW_{(Stt_k)}$ by averaging all related functionalities.

$$FSW_{(Stt_k)} = \left\{ \overline{\sum_{l=1}^{H} FSW_{(F_l - Stt_k)}} \right\} \quad \text{Eq. (8)}$$

Similarly, we obtained the general functionality satisfaction FSW_{M_i} of the reference material.

$$FSW_{(M_i)} = \left\{ \overline{\sum_{l=1}^{H} FSW_{(F_l - M_i)}} \right\} \quad \text{Eq. (9)}$$

Then, we compare $FSW_{(Stt_k)}$ to $FSW_{(M_i)}$ in order to obtain the relative functionality satisfaction (RFS) of the substitute.

$$RFS_{Stt_k} = \frac{FSW_{Stt_k}}{FSW_{M_i}} \quad \text{Eq. (10)}$$

Technological maturity can be marked by experts as a percentage. A value of 100% means that the technology is totally mature. Then, we compare the technology maturity (TM) of the substitute to that of the reference material.

In terms of economics, we first benchmark the cost for using the substitutes C_{Stt_k} and reference material C_{M_i}.

$$C_{Stt_k} = M2R_{Stt_k} * PoM_{Stt_k} \quad \text{Eq. (11)}$$

With

C_{Stt_k}: Cost of substitute with equivalent of 1 kg of reference material M_i
$M2R_{Stt_k}$: Mass of kth substitute needed compared to 1 kg of reference material
PoM_{Stt_k}: Price of material Stt_k per kg.

After determining the cost of substitute, we calculate the cost difference CD_{Stt_k} between using the substitute and reference material. When CD_{Stt_k} is positive, a higher absolute value means that the substitute has improved economics. When CD_{Stt_k} is negative, a lower absolute value means better economics.

$$CD_{Stt_k} = \frac{C_{M_i} - C_{Stt_k}}{C_{M_i}} \quad \text{Eq. (12)}$$

With

CD: Cost difference between substitute $Stt_k$and reference material M_i

Then, we use the exponential function to solve the negative or positive problem while calculating the economic accessibility (EA) of the substitute according to the following formula.

$$EA_{Stt_k} = e^{CD_{Stt_k}} \quad \text{Eq. (13)}$$

In terms of resource depletion, we calculate the relative RDR of the substitute to its reference material. Similar to economic accessibility, a positive $RDRBR_{Stt_k}$ means a higher absolute value and improved contribution to substitutability. When $RDRBR_{Stt_k}$ is negative, its lower absolute value means improved contribution to substitutability.

$$RDRBR_{Stt_k} = \frac{RDR_{M_i} - RDR_{Stt_k}}{RDR_{M_i}} \quad \text{Eq. (14)}$$

With

$RDRBR$: Resource depletion ratio benchmarking with the reference material

Then, we use the exponential function to solve the negative or positive problem according to the following formula.

$$Exp\left(RDRBR_{Stt_k}\right) = e^{\frac{RDR_{M_i} - RDR_{Stt_k}}{RDR_{M_i}}} \quad \text{Eq. (15)}$$

$Exp(RDRBR)$: $RDRBR$'s exponential function value

By combining the above four terms, we can obtain the general evaluation of the performance of the substitute material $Stt_k(GESP_{Stt_k})$ as follows:

$$GESP_{Stt_k} = \overline{\left(RDB_{Stt_k} + EA_{Stt_k} + TM_{Stt_k} + RFS_{Stt_k}\right)} \quad \text{Eq. (16)}$$

With

$RDBSttk$: Resource Depletion Benchmarking. It is equal to $Exp(RDRBRSttk)/\ Exp(RDRBRMi)$
$TMSttk$: Technology Maturity of substitute k

Therefore, the substitutability of M_i after considering all substitutes can be integrated as in equation (17).

$$Substitutability = \sum_{k=1}^{Y}\left(GESP_{Stt_k}\right) \quad \text{Eq. (17)}$$

2.3.4 Criterion 4: Environmentally friendly level

A low environmental-friendliness level means the material causes greater environmental harm based on selected indicators such as human toxicity, ecotoxicity, or global warming potential (GWP). At the same time, the public is becoming increasingly environmentally conscious. This growing sensitivity pressures industries to consider the environmental impact of their products. Materials with lower environmental damage (higher environmental-friendliness levels) will likely face fewer challenges in the future, such as social pressure, environmental regulations, eco-taxes, or other restrictions. This criterion assesses the likelihood of encountering such issues. We use human toxicity, ecotoxicity, and GWP as the three indicators for this criterion. Companies can select one of these indicators or use their average to represent the criterion's outcome. The values for these indicators can be sourced from databases like Eco-invent.

2.3.5 Criterion 5: Legislation ban or hinder level

Table 2. Legislation ban or hinder level marking standards

Source: Inventory of legislation in the sector of the product	
Note	**Description**
1	There is a legislative (laws, directives etc.) ban on the usage of this material in the corresponding sector in the geographic area related to the product for a short time.
0.75	There is a legislative (laws, directive, etc.) ban on the usage of this material is hindered in the corresponding sector in the geographic area related to the product activities for a medium-long time.

0.50	There is a high possibility that the material will be banned or hindered by legislation in the corresponding sector in the geographic area related to the product activities for a known time.
0.25	There is a low possibility that the material will be banned or hindered by legislation in the corresponding sector in the geographic area related to the product activities for a known time.
0	There is no legislative (laws, directives etc.) ban or the usage of this material is not hindered in the corresponding sector in the geographic area related to the product activities for a known time.

For this criterion, we need to establish a legislative inventory (or legislative intelligence) for each material based on the standards above by collecting legislative information in the product sector. This criterion is inspired by the mercury limitation in the lighting system based on EU RoHS Directive (2011/65/EU). A similar case can occur in other materials for other products. In this case, the material might become critical if it is inaccessible. The solution is similar to other critical materials: looking for substitutes, decreasing or eliminating demand for this material, or even changing the product design. However, we do not need to increase the supply amount, find better suppliers, or find stable supplying countries. Based on the above standards, we can become aware of the legislative risk, which can stimulate similar problems of criticality.

2.3.6 Criterion 6: Quality of relationship with suppliers including diversity of suppliers (concentration of suppliers)

The important role played by suppliers is sometimes underestimated by companies. Suppliers can influence companies in the following aspects: quality, timeliness, competitiveness, innovation, and finances [19]. After considering these aspects, we extracted the following key points to evaluate the quality of the relationship with suppliers.

a. Quality of supplying product (QoM_{S_j}): quality of supplied materials from supplier S_j directly affects quality of products the company will produce.
b. Timeliness (TIM_{S_j}): delivery time of S_j.
c. Innovation (Inn_{S_j}): effort that suppliers S_j make for innovation. Companies can take advantage of innovative materials offered by suppliers by becoming more competitive.
d. Exchange (Xch_{S_j}): an exchange between the company and its supplier S_j in terms of company strategies, newsletters, and perspectives.
e. Human (HF_{S_j}): humans are a vital factor in purchasing or business dealings. A reliable and royal partner (human) assures the quality of the relationship between two companies.

Table 3. Standards for marking the relationship with suppliers

Source: Interview with department of purchase					
Note	**Quality of supplying materials**	**Timeliness**	**Innovation**	**Exchange**	**Human**
0	Excellent quality	Always in time	Strong innovations strategy, innovated end product (materials)	Deep and comprehensive exchange	Reliable, royal, responsible
1	Bad quality	Always late	No innovations at all, no plan to stimulate innovation neither	No exchange at all	Shady, personal conflicts

This table shows the standards for giving scores of the six factors mentioned previously. Firstly, we establish a relationship profile of each supplier by asking the purchase department to make the above standards. Secondly, we combined the quality of relationship with supplier (QRS_{S_j}) with its supplying share for material $(SR_{(S_j-M_i)})$. Finally, this criterion - quality of relationship with suppliers of M_i material (QRS_{M_i}) is obtained by averaging all suppliers' relationships for each material.

$$QRS_{S_j} = \overline{\left(QoM_{S_j} + TIM_{S_j} + Inn_{S_j} + Xch_{S_j} + HF_{S_j}\right)} \quad \text{Eq. (18)}$$

$$QRS_{M_i} = \sum_{j=1}^{X} SR_{(S_j-M_i)}{}^2 * QRS_{S_j}, \quad \text{Eq. (19)}$$

2.3.7 Criterion 7: Depletion of reserves

This value can be obtained from databases such as Eco-invent. We can also calculate the value based on the ratio of production and reserve amount of each mineral or raw material. If the material is synthetic, we can use the ratio relating production amount and capacity.

$$Depletion\ \ of\ \ reserve = DoR = \frac{Global\ \ production\ \ amount\ \ of\ \ material\ \ (or\ \ related\ \ minerals)}{Global\ \ reserve\ \ amount\ \ of\ \ material\ \ (or\ \ related\ \ minerals)} = \frac{GProd_{M_i}}{GRsv_{M_i}}$$, Eq. (20)

2.3.8 Criterion 8: Geo-relation (political and bilateral economic exchange) between supplying and buying countries

This geo-relation involves how two countries (the countries of supplier and buyer) get along with each other both politically and economically. More economic exchange reduces the risk of conflicts between two countries. On the contrary, if there is some territorial dispute or historical conflict, the policies of the two countries may influence the commercial relationship between companies. Sometimes, import or export is ongoing even during tense bilateral political relations, which is why bilateral economic exchange must also be considered. To determine the geo-political relationship between two countries, geopolitical or international diplomatic experts must be interviewed based on the above standards (table 4). We can also apply the Delphi method to approach a consensus. For economic bilateral exchanges, we considered a) export, b) import, c) tourist revenue, d) stock investment of the buying country in supplying countries, e) stock investment of supplying countries in the buying country, and f) turnover of the buying country's companies in supplying countries. The money amount can be obtained from government documents for France-related bilateral economic exchange.

Table 4. Standards for geo-political relation scores are inspired by China's diplomatic ranking system

Source: Interview with geopolitical or international diplomatic experts and designers	
Note	**Description**
1	War
0.75	Relation
0.5	Partnership
0.2	Traditional good partnership
0	Ally / Union

Since higher diplomatic scores contribute more to bad bilateral political relations and higher money exchanges contribute more to good bilateral economic relations, we can use Eq. (17) for the geo-relation calculation.

$$Geo - relation = \frac{Diplomatic\ \ score}{Economic\ \ bilateral\ \ exchange\ \ (M\ \ \$)} \qquad \text{Eq. (21)}$$

2.3.9 Criterion 9: Global demand to supply ratio

This criterion is calculated based on the ratio of global demand to supply. The global supply amount is the sum of global production and the stock amount of a material (see Eq.(18)).

$$\text{Global demand and supply ratio} = \frac{\text{Global Demand Amount}_{M_i}}{\text{Global Supply Amount}_{M_i}} \qquad \text{Eq. (22)}$$

Alonso et al. [7] developed an evaluation methodology for the demand and supply ratio of REE. They also reported methods and different scenarios to forecast demand and supply. Their method can be used in this criticality evaluation methodology.

2.3.10 Criterion 10: Stability of the supplying country

To evaluate supplier country stability, we incorporated four indicators: the Ease of Doing Business index [20, 21], Fragile States Index [22], Estimated Political Stability by Country [23] and Worldwide Governance Indicator [21]. The Ease of Doing Business index annually ranks 189 countries across nine business condition factors - including business startup procedures, construction permits, property registration, credit access, investor protections, taxation, cross-border trade, contract enforcement, and insolvency resolution - where lower scores indicate more favorable business environments. The Fragile States Index annually assesses 178 nations' vulnerability, with higher rankings reflecting greater fragility. Estimated Political Stability by Country measures 188 regions' stability through Quandl data, with higher values denoting greater political stability. The Worldwide Governance Indicator, referenced in EU critical materials studies, annually evaluates over 200 countries across six governance dimensions (voice/accountability, political stability, government effectiveness, regulatory quality, rule of law, and corruption control) on a 0-100 scale (higher scores indicating better governance). To ensure comparability, all indicators were standardized to a 0-100 scale with consistent directional meaning (lower values representing better conditions for all metrics except Worldwide Governance, where higher values are preferable).

2.3.11 Criterion 11: Recycling rate

The recycling rate here represents the percentage of materials that can be recycled. It is frequently stated as a measure to mitigate the criticality issue [4] as a higher recycling rate and more urban mines lead to a more available supply. This indicator has also been considered by some criticality evaluation studies [5], [24]. It can be obtained from existing studies, e.g., the USGS [25] mineral reports, United Nations environment programme's recycling rates report [26], and other academic studies [27].

3. Results and Discussion

3.1 Presentation form for evaluation results

The 11th criteria listed above have different physical meanings and units. We need three steps to make them comparable. Firstly, we need to put them in the same order. This means that when the value of each criterion increases, it contributes more to criticality. Secondly, we take the relative value of each criterion. It is obtained by Eq. (23).

$$\text{Relative value of each criterion} = (value\ \ of\ \ criterion - threshold)/\ threshold \quad \text{Eq. (23)}$$

After processing the initial data, which contains both positive and negative values from previous calculations, the third step normalizes these values to either positive-only or within a specified range using one of two proposed methods: (1) an arctangent function that constrains values within a π range (adjustable from -2π to 2π or modified to 0 to π for positive-only results) while standardizing all criteria thresholds to identical values, or (2) an exponential function that produces exclusively positive values and simplifies radar chart visualization (Poulizac, 2013) with all thresholds set to "1", followed by weighting adjustments based on criteria importance. Beyond visualization via radar charts, each material receives a general score representing its relative criticality compared to other studied materials, though these scores remain meaningful only within the study's specific context including product specifications, supplier details, supply shares, and material functionalities. For mitigation recommendations (the third output), we first establish a database of existing mitigation measures from literature, then map these to corresponding criteria and impact parameters to identify relevant strategies only for threshold-exceeding criteria.

3.2 Completeness and sensitivity

The evaluation methodology contains numerous impact parameters. However, not all can be covered in each study due to a lack of data, human resources, budget, etc. The coverage of the impact parameter of each principal parameter can be used to show the uncertainty of the study.

Taking the coverage of the dimension "imbalance between and supply" as an example. According to the diagnosis (Figure 8), this dimension was divided into "demand" and "supply" in which "demand" has three impact parameters and "supply" has two impact parameters. If only one impact parameter is covered under "demand" in a case study, then its coverage is 33%. Similarly, if one impact parameter is covered under "supply", then its coverage is 50%. Thus, we can obtain the coverage of "imbalance between and supply" by combing "supply" and "demand" as: 33%×0.5+50%×0.5=42%. Same for the two other principal parameters: importance and accessibility to supply.

In terms of sensitivity, the same proportion change of the same input of all materials will not influence the relative criticality of materials when the change doesn't surpass the interval of inputs and the inputs are non-zero. We suggest analysing the sensitivity by changing one input of one material individually.

3.3 Discussion of weighting

In applying the evaluation model, determining weightings and thresholds without subjectivity is difficult. In terms of model development, a space can be left to adjust the weighting. It is challenging to provide weightings during the calculation for certain criteria. Moreover, the final result presentation is a radar chart containing 11 criteria in the basic scenario. Different weightings of criteria might completely change the final result. In the methodology, there are two places where weighting is needed: functionality and the four aspects of substitutability. We can use the Delphi Method [28] to provide weighting in which marks are given by a group of distinguished experts in limited rounds anonymously. Analytic Hierarchy Process (AHP) [29] is also an option for weighting.

Two places were needed to give thresholds: substitutability evaluation and criteria normalisation. The thresholds in the substitutability evaluation are related to the requirements of products from clients or the corresponding sectors' legislation. It can be obtained from the product's technical specifications or from technical experts in the industry. The threshold of the criterion for the final results presentation is the limit value of each criterion before arriving at the critical area. We propose two ways to determine the thresholds for criteria. The first way is to use a certain ratio such as 20:80 or 30:70. For example, if the values of all materials for one criterion are from 0 to 100, then 80 will be this criterion's threshold. The second way is to settle each threshold by experts. This is similar to the Delphi method. A problem such as "how much should we settle the threshold of this criterion?" can be given to a panel of experts. After a determined number of rounds, we use the median value in the final round as the threshold.

3.4 Possibility to adapt to the general sector level

It is possible to apply the framework of the methodology for adaptation to a general sector level by modifying the scope of the study and certain impact parameters. For example, we can alter the demand for a product by a company into global demand for the product. The suppliers will be the general suppliers worldwide or for a country. The relation to the suppliers will be difficult to quantify and can be replaced by geo-relation with the supplying countries. The stability of the supplying countries can be calculated using the indicator such as "Ease of doing business" or "Stability" with those countries' supplying share. Some other criteria's calculations might need to be adjusted as well.

Another potential use of this methodology is to determine the criticality of components instead of one raw material. As showed in the LED application, certain materials contain more than one metal and the criticality of these materials can also be determined. The ways used in LED application to treat these materials can be used for components as well.

4. Conclusion

The market and technologies will react to criticality issues, which will eventually be resolved. Although it is possible to identify substitutes for critical materials, implementing substitutes takes time, the substitutes themselves may be critical materials, and emergency substitution could increase costs while decreasing production efficiency (Congressional Budget Office, 1983). Therefore, before prices drop, new supply sources are established, or substitutes are found, material criticality can damage industries or countries where materials are inaccessible. A criticality evaluation methodology can determine which materials are critical to procure in order to avoid or mitigate disruption and promote healthier development.

Once critical materials are identified, countries or companies can implement preventive measures. A radar chart can reveal which criteria contribute most to criticality, enabling targeted mitigation measures. For example, if the "substitution" criterion contributes significantly to material criticality, a company could increase funding for substitute research or reduce material usage through design changes. For sudden, short-term criticality, maintaining high stock levels remains the safest measure [30].

The criticality evaluation model supports decision-making in several ways: establishing general strategy guidelines, informing material selection in product design, enabling risk management, optimizing purchasing strategies, and ensuring industry stability. Also, it can be integrated 7with IT convergence technologies. The model can be integrated into a product life cycle [31] through: a) Eco-design during the pre-market "introduction" phase b) Ongoing R&D throughout the product lifecyclec) Purchasing strategy and risk management after market launch [32].

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