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# Criticality of material resources in industrial enterprises – structural basics of an operational model

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**Abstract**

Resource use in industries is attended by various risks for companies. Sustainable decision making thus requires a valid information basis. Most companies, however, neglect major information concerning the application of resources. While many analysis in this area have been published on a national level, few focus on operations in companies. In this paper we present structural basics of an operational model to quantify resource criticality on the business level based on the diffusion curve of environmental problems. Therefore, we describe methodological procedures, identify various causes that may lead to possible effects within upstream and downstream system and present tailored indicators.


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*Keywords:* Resource criticality, risk assessment, efficiency

## 1. Introduction

The manufacturing of products is based on the transformation of resources, generally referred to as the process of value adding [1–3]. Hereby, especially the supply and use of natural resources depict several risks to companies. Due to the wasteful consumption of the past centuries since the first industrial revolution many natural resources have simply become scarce, e.g. silver, antimony [4]. Price increases or stoppage of supply of these resources considerably hinder a company’s performance requisitions. Other resources lead to significant damage to humans, societies and the environment during extraction, refinement, combination, use and/or end-of-life, e.g. fossil fuels, tantalum, gold, mercury and cadmium. Governments and NGOs have thus introduced various programs, regulations and standards in order to antagonize their lavish extraction and little reasoned application. According to Compliance and Risk, the global amount of environmental legislations companies have to comply with has thus roughly increased sixtyfold between 2003 and 2014 [5]. Miehe et al. indicate that this trend may presumably continue as many environmental and humanitarian problems have not yet been targeted globally [6]. 40 percent of middle class companies in Germany estimate a future downstroke of economic performance due to resource shortages [7]. Simultaneously, the quantity of applied resources in industries rises dramatically. The CAS registry currently contains over 100 million substances out of which approximately 75% were added over the past 10 years. According to the Chemical Abstract Service during the past 50 years one substance has been registered every 2.5 minutes [8]. Likewise, the quantity of substances that are classified as potentially harmful to humans and the environment increases constantly. Since its introduction in October 2008 the REACH SVHC list has thus more than decoupled its entries [9]. In the same period, the SIN (substitute it now) list that serves as an indicator for potentially regulated substances under article 57 of the REACH regulation increased its entries by over 300% [10].

Depending on the specifics of the supply chain, various risks of application of each resource may occur. For instance the rare earth neodymium that in fact deposits more often in


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earth's crust than lead may be subject to concentration risk as China dominates the production with over 90 % of market share [11,12]. A reduction or stoppage of exports will eventually cause difficulties for manufacturers of magnets and batteries worldwide. Another example is the light alloy Lithium whose demand is supposed to increase dramatically with the expansion of e-mobility concepts [13], while over 80 % of its reserves are limited to just two countries (Chile and China) [14]. Due to its main application in batteries, various studies estimate that its demand will exceed its supply around the year 2020 [13,15,16]. In this case manufacturers of lithium-ion batteries should strongly focus their research on potential substitutes.

Each substance has certain applications in industrial products. While products become more and more complex, so do its components. In case of the semiconductor industry, this trend can be demonstrated by the quantity of elements required for an average product. While in the early years around the 1960s 11 elements sufficed for the entire industry, todays average semiconductors consist of over 60 elements [17]. With higher complexity of products comes higher complexity of supply chains. The complex resource market leads to increased difficulties for companies to assess their current situation [7].

In this paper we discuss the question, how companies can adapt to the increased complexity of resource utilization and abate the risk of significant economic damage and/or gain competitive advantages.

## 2. State-of-the-art

Recently, the term resource criticality has evolved in literature. Early analyses in this area have been conducted in the first half of the 20th century in the context of both world wars. According to Haglund the criticality of resources was determined by their strategic importance to warfare [18]. While these studies mostly focused on minerals, later analyses have extended the scope. According to Graedel et al. the term resource criticality has subsequently evolved to the standard designation for raw materials that exhibit great supply risks [19]. Today, resource criticality is commonly understood as the product of vulnerability and supply risk . While its general definition is beyond controversy, the composition of its ingredients (vulnerability and supply risk) heavily depends on the level of observation and considered parameters.

To date, numerous studies have been published on a global and national level [20–23]. Although it seems apparent that companies would apply different criteria and parameter for the calculation of vulnerability and supply risk, little research has been done on the business level.

The term criticality describes a potentially dangerous development. In the context of resource use, it characterizes a certain risk for the user. In accordance to the ISO 31000, risk is defined as the product of probability of occurrence and extent of damage. The first study that provided an aggregation of both aspects was published by the US National Research Council of the National Academies (US NRC) [23]. The hereby presented analysis of supply risk and economic importance to the US economy was based on qualitative expert knowledge. As a tool for visualization the US NRC used a Cartesian coordinate system, referred to as the criticality matrix. Table 1 illustrates the approach according to the US NRC [23].

Table 1. Criticality matrix according to US NRC [23].

| | | **Supply risk** | | |
|---|---|---|---|---|
| | | *Low* | *Medium* | *High* |
| **Vulnerability** | *Low* | | | |
| | *Medium* | | | |
| | *High* | | | |

Subsequently, this approach was applied to various studies globally with only minor adjustments [20–22,24]. While applying a similar approach, each study considers different criteria in order to quantify economic importance and supply risk. The US NRC especially investigates environmental and social aspects of resource application [23], whereas the EC neglects these issues [20,21]. Hereby, economic importance is derived from raw material applications and value to previously defined EU megasectors. Supply risk, in contrast, is based on substitutability, recycling rate, country concentration and governance. In order to include environmental aspects, Graedel et al. add a third dimension to the traditional approach [25]. Thereby, supply risk is derived from geologically economic, geopolitical, social and regulatory aspects. In contrast, Tuma et al. divide the criticality analysis in economic, ecologic and social aspects ab initio [26]. Environmental aspects may be derived from impacts of resource use and/or damage to environmental conversation subjects, social aspects may include human rights, forced and child labor, corruption, discrimination, etc.

While numerous studies have been published on the global, national and sector level, little research has been done on the business level. Globally oriented studies generally focus on the determination of an overall scarcity of resources and its impact to humanity and the world economy. National level analysis, in contrast, aim at identifying certain resources of great importance to the local economy and its population. These studies set the basis for legislations and programs that lead to higher recycling rates, efficiency, and substitution of certain resources. The criticality to an entire economy, however, does not reflect the criticality a certain resource has to a single company. Company requirements may significantly differ from national level studies. While the latter set the basis for sustainability oriented policies, the former focus on business performance. For instance, a range of 100 years of a certain resource will not affect a company that acts in strategic planning intervals of 10 years. Then, a general technological substitutability of a substance in a certain sector (e.g. automotive) does not provide evidence if a replacement is precluded for a certain application within a company. National level studies either calculate or estimate material flows. The degree of information regarding material/substance flows and transparency, however, declines considerably on the business level. Table 2 illustrates a comparison of national level studies and business requirements in order to identify intersections and gaps.

On the business level Rosenau-Tornow et al. present a model to calculate the long-term supply risks for mineral raw materials considering past and future trends [27]. An analysis of raw material market developments over the past 50 years sets the basis for an evaluation in five categories: current supply and demand, production costs, geostrategic risks, market power, supply and demand trends. The following calculation of risk is based on certain standard indicator for each category, e.g. Herfindahl–Hirschman Index (HHI), Worldwide Governance Indicator (WGI). While this study provides a sound basis for the calculation of supply risk, essential aspects are neglected, e.g. ecologic and social risks and vulnerability aspects.

Table 2. Comparison of national level studies and business requirements

| | **National level** | **Business level** |
|---|---|---|
| **Gaps** | General scarcity of a resource depending on occurrence in earth's crust, technological capacity and degradation rate | Scarcity of a resource regarding strategy, product life span, time of stock-keeping, etc. |
| | General calculation and/or estimation of resource flows within a certain system (e.g. nation, sector) | Concrete resource transparency regarding certain products and processes |
| | General technological substitutability within a certain system (e.g. nation, sector) | Concrete substitutability regarding a certain technological application |
| | General market situation and development of a certain resource | Concrete supplier and customer market situation and development of a certain resource |
| **Inter-sections** | Adverse economic and/or social effects during life cycle of a certain resource | |
| | Concentration of reserves | |
| | Mine capacity | |

In summary, current resource criticality assessments in particular are conducted on the national level. Information about material flows, however, is rare and even declines within a company. Statements on resource criticality of nations are thus conditionally possible, although not on the business level. Selective analysis on this level neglect major information [27]. Generally, supply risks of certain resources are not calculated. At present, companies attempt to absorb price increases via adaption of purchase. Common strategies are price negotiations, quantity adjustment and/or supplier replacement. Additional approaches aim at transferring price increases to the customer and/or increasing resource efficiency. These actions, however, do not reflect a differentiated assessment. Instead, companies currently base decision making regarding the utilization of resources on simplification. Especially efforts of SMEs do not suffice to properly react on insecurity of supply [7]. A differentiated assessment of resource criticality is, however, crucial as perceived price increases may not reflect real price increases due to the availability of alternative technologies. Non-existence of such alternatives will eventually lead to significant damage in case of resource supply stoppage.

We thus conclude that companies currently lack to establish the required transparency regarding their utilized resources and thus underestimate the risk of supply shortages.

## 3. Operational approach

We define the term resource criticality from a business perspective as the risk of damage to a certain unit of analysis due to the utilization of certain resources. Organizational damage hereby is expressed by a negative variation of factual and/or formal goals. The unit of analysis may either be a product, process, division or organization. The term resource is understood as a synonym for substance / chemical component. The term criticality describes a violation of a certain limit of breach of one or more particular targets company is willing to accept. Conversely: if a certain limit is violated, a resource becomes critical, e.g. a deviation of 5 % of profit objective due to the price increase of a certain resource.

In dependence on the ISO 14040 and 14044, we differ between five steps a company has to execute in order to implement a criticality assessment. Fig. 1 illustrates the approach. The following subsections discuss each step in detail.

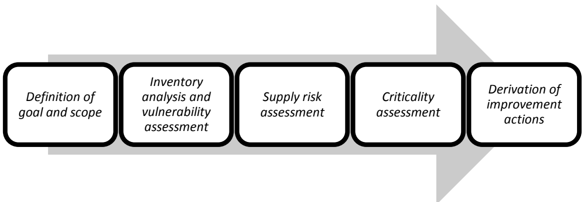


Fig. 1. Five step approach for organizational criticality assessment.

### *3.1. Definition of goal and scope*

The first step sets the basis for an operational analysis. As every company disposes greatly different preconditions (e.g. products, applied resources, customers, strategy), a target analysis has to be conducted. From a theoretical perspective a differentiation has to be made between factual and formal goals. The factual goal of an organization is the satisfaction of internal and external needs [28]. It depicts the premier goal of a company. Formal targets, in contrast, reflect the success of a company in its current systemic environment. Corsten and Reis differ between four characteristics of formal goals: technical (e.g. flexibility, degree of capacity utilization, product quality), economic (e.g. cost effectiveness, liquidity, productivity, growth), ecologic (e.g. resource consumption, environmental impact) and social (e.g. humanity of working conditions, employee development, social responsibility) [28]. A clear prioritization of formal goals is, however, not possible. It rather depicts a situational decision related to a company's current status and its characteristic parameter.

In order to simplify the analysis, we reduce the quantity of possible organizational targets to certain performance requisitions a company is obliged to fulfill. These may be summarized as follows: *To provide a customer with the desired product in the required quality and time*.

Thereupon, the unit of analysis has to be chosen. This might be a single product, process or the entire company. Also, the time horizon of the analysis should be defined. Hereby, a reasonable approach is to use existing timeframes a company has applied related to the unit of analysis, e.g. strategic horizon, planned product life span.

In this paper, we furthermore differ between three premier parameter of analysis that set the basis for a deployment of tailored indicators: price, time and technology. The price represents the realized value of a product. As such it is the value a customer is willing to pay. It should cover all previous value adding process steps as well as additional requirements (e.g. supporting processes, compliance with legislations and standards). Possible environmental and/or social problems that occur during upstream processes and are regulated by law thus will be imparted to the customer. Time, however, depicts a different parameter of the criticality assessment. Here, we assume that the position within the supply chain partly determines the short term dependence on a certain resource. If a company for instance takes a spot at the end of a supply chain, it will thereinafter notice the effect of a potential change of supply. Technology, not least, depicts another source of criticality on a business level. This aspect essentially covers functionality and substitutability. Non-supply of a certain resource might lead to impossibility of fulfilling certain technical functions.

For a company it is necessary to develop a consistent weighting system of these three parameters in regard to its previously defined unit of analysis. For instance, the removal of direct access to a certain resource may initially lead to a higher price as well as a delay in delivery. The degree of criticality, however, increases significantly with substitutability. If a substitution is not possible, the fulfilment of a company's performance requisitions is hampered for long.

### *3.2. Inventory analysis and vulnerability assessment*

The second step combines two aspects. First, an inventory analysis has to be conducted regarding the unit of analysis. Inventory, in this context, refers to the utilized materials and devices. The basis for this step is a classification of materials depending on the scope of analysis. Appendix A presents a classification system according to the IEC 62321 and 62474. A further analysis requires a high level of transparency regarding substances / chemical components of each material and device. In a best possible scenario, the chemical composition for all used materials and devices should be identified. Realistically, information on chemical compound of devices is scarce. In this case the degree of information as well as empirical value may serve as alternatives. Therefore, sources of information gathering have to be determined. Possible sources are standards, bill of materials, ERP-data, screenings (e.g. XRF, IR), expert knowledge, experience values, etc. The result of this step is an inventory table with the chemical composition of each relevant material and device.

Hereupon, the vulnerability of the analysed unit can be determined. Based on the inventory table an overall quantity and price of a certain resource can be calculated. In addition, an analysis of substitutability of the applied resources determines another source of vulnerability.

### *3.3. Supply risk assessment*

The term supply risk describes the probability of supply shortfalls. In this context, we divide the field of observation into upstream and downstream system.

#### *3.3.1. Upstream system*

The price of a resource depicts a snap-shot. Potential future developments, however, may not easily be derived from a simple price analysis. The upstream perspective thus solely focuses on the correlation of supply and demand, which determines the fulfillment of a company's performance requisitions. Hereby, two modes may be classified as critical to an organization. Either the offered resource on the market does not suffice to meet a company's demand regarding quantity and/or quality. In this mode, the manufacturing of a good is not possible. Then again, the quantity and/or quality of a resource, a company has direct access to, is subject to volatility. In this mode the manufacturing of a good is still possible although under inferior conditions. Ecological and/or social factors are not observed within the upstream system. It is assumed that possible changes will either lead to price adaptions within the supply chain or will be approached to the company from the downstream system via customer refusal or law.

*Mode 1 (no supply)* has to focus on both primary and secondary sources of supply. The former is determined by the existence of sources in earth's crust and the existing technology. Possible indicators are static and dynamic range of feedstock as well as mine capacity. This again affects the type of manufacturing (e.g. coupled production) and the concentration of either sources or tiers within the upstream system. Here, especially uncertain events may cause a temporary stop of supply. As an indicator the Herfindahl-Hirschman-Index (HHI) may be adducted. As an indicator for a secondary source of supply, the recycling rate of a resource is appropriate.

*Mode 2 (limited supply)* requires a market analysis of supply and demand of each material. Hereby, an investigation of both supply and demand regarding its composition and development is necessary. Market composition of both may be differed in monopolistic (single supplier/consumer market), oligopolistic (few supplier/consumer market) and polypolistic (multi-supplier/-consumer market). The comparison of both determines the actual market type, as illustrated in table 3 according to Stackelberg [29].

Table 3. Market composition according to Stackelberg [29].

| | | Supply | | |
|---|---|---|---|---|
| | | *Polypolistic* | *Oligopolistic* | *Monopolistic* |
| **Demand** | *Polypolistic* | Perfect competition | Supply oligopoly | Supply monopoly |
| | *Oligopolistic* | Demand oligopoly | Bilateral oligopoly | Limited supply monopoly |
| | *Monopolistic* | Demand monopoly | Limited demand monopoly | Bilateral monopoly |

Supply and demand development may be classified qualitatively as increasing, constant or decreasing. A comparison of both may be adducted as an indicator of critical market conditions. Table 4 illustrates the lineup of supply and demand development. Hereby, little (L), medium (M) and highly (H) critical market situations are differed.

Table 4. Market development criticality.

| | | Supply | | |
|---|---|---|---|---|
| | | *Increase* | *Constant* | *Decrease* |
| **Demand** | *Increase* | M | M | H |
| | *Constant* | L | L | M |
| | *Decrease* | L | L | M |

Concerning a potential harmful development of supply and demand for a single company, the entire supply chain has to be analyzed regarding market type and development. In this context, a critical business situation occurs if a company's demand cannot be met by the supplied quantity and/or quality. The probability of occurrence of that condition increases with the degree of imbalance between supply and demand. Supply monopoly and oligopoly depict the highest form of criticality. Here, suppliers may easily establish an overly high prize or refuse access. A medium stage of criticality occurs in cases of perfect competition, bilateral oligopoly and bilateral monopoly, while demand monopoly and oligopoly may be classified as comparatively low risk.

### *3.3.2. Downstream system*

A supply stoppage of a certain resource may not only occur due to depletion, concentration, natural disaster, etc. Social perception depicts another source of possible supply stoppage. This especially applies to ecological and/or social problems during the process of value adding, product usage and end-of-life. Hereby, two modes are possible. Either customers refuse purchase of a certain product or governments regulate the usage of a certain resource. An evaluation of the downstream system requires a high level of transparency regarding the applied substances / chemical components (see 3.2). As an indication for this perspective an observation of medial reporting of potential harmful developments regarding the applied resources is necessary. We therefore propose the diffusion curve of environmental and/or social problems, as displayed in Fig. 2. Various authors indicate that every environmental and/or social problem follows this trend [30,31]. For companies the level of medial presence represents a possibility to derive future risks based on the utilization of certain resources. Therefore, the diffusion curve has to be grouped in different levels of criticality. The closer the medial presence approaches the end of the curve, the higher the criticality of a certain resource is.

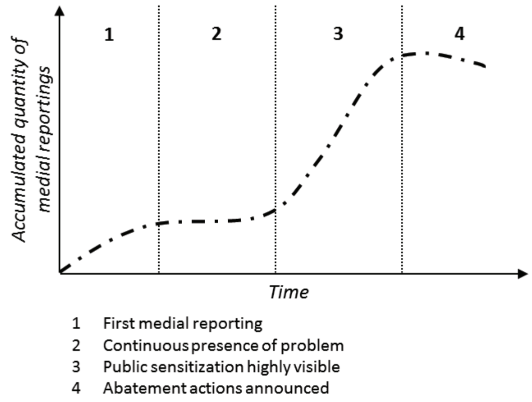


Fig. 2. Diffusion curve according to Steger [31].

## *3.4. Criticality assessment*

The criticality assessment, subsequently, follows the common definition of the US NRC [23]. The criticality of a single resource (i) results from the product of its supply risk (s) and its vulnerability (v), i.e.

$$c_i = s_i * v_i \qquad (1)$$

The total criticality (C) of the unit of analysis hereupon may be calculated as the sum of all single resource criticality values, i.e.

$$C = \sum_{i=1}^{n} c_i \qquad (2)$$

## *3.5. Derivation of improvement actions*

We understand the term criticality as a violation of a certain limit of breach of one or more particular targets related to the unit of analysis. If the previously executed assessment depicts certain fields of violation, improvement actions have to be conducted. As various aspects of criticality evaluation are based on estimations or assumptions, we propose a sensitivity analysis in order to identify appropriate operating levers. Thereupon, a variety of actions exist in order to enhance the long term resource criticality of socio-technical systems. To mention only a few, we suggest investments in R&D, changes of suppliers, insurance protection, installation of backup capacity, review of stock-keeping, etc.

Appendix B illustrates the above described approach in form of a detailed process map.

## 4. Discussion and conclusion

With increasing scarcity of resources, companies are forced to adjust business procedures. While in this context numerous studies have been published on the global and national level, little research has been done on the business level. For the future wellbeing of companies, tailored systems are required to identify possible risks that attend resource use. In this paper we thus discussed the question, how companies can adapt to the increased complexity of resource utilization and abate the risk of significant economic damage and/or gain competitive advantages. We presented a five step approach for organizational criticality assessment based on ISO 14040 and 14044. In addition we provided a classification system for material and device assessment and reconsidered the applicability of different indicators related to the upstream and downstream system of a certain unit of analysis. We argue that upstream resource criticality is essentially described by supply and demand trends. Hereby, two modes of scarcity have to be differed on the business level: no supply and reduction of supply. Economic and/or social problems that may also lead to resource scarcity for a company are allocated to the downstream system, irrespective of their occurrence in the supply chain. This type of scarcity is either based on regulative measures or on customer refusal.

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## Appendix A. Material classification system according to IEC 62321-3 and IEC 62474

| Material classes according to IEC 62474 / 62321-3 | | | |
|---|---|---|---|
| | | *Name* | *Description* |
| | M/0 | *0. Drawing part* | |
| IEC 62474 | M/1 | *1. Material* | |
| IEC 62474 | *M-001* | *Stainless steel* | A group of corrosion resisting ferrous alloys containing minimum 10% chromium content be present. |
| IEC 62474 | *M-002* | *Other Ferrous alloys, non-stainless steels* | Iron and any alloy whose defining component is iron and is not stainless steel. |
| IEC 62474 | *M-003* | *Aluminum and its alloys* | Aluminum and any alloy whose defining component is aluminum. |
| IEC 62474 | *M-004* | *Copper and its alloys* | Copper and any alloy whose defining component is copper. |
| IEC 62474 | *M-005* | *Magnesium and its alloys* | Magnesium and any alloy whose defining component is magnesium. |
| IEC 62474 | *M-006* | *Nickel and its alloys* | Nickel and any alloy whose defining component is nickel. |
| IEC 62474 | *M-007* | *Zinc and its alloys* | Zinc and any alloy whose defining component is zinc. |
| IEC 62474 | *M-008* | *Precious metals* | Any metal or alloy whose defining component is Ruthenium, rhodium, palladium, silver, osmium, iridium, platinum and/or gold. |
| IEC 62474 | *M-009* | *Other non-ferrous metals and alloys* | Other non-ferrous metals and alloys that are not included in M-003 through M-008 |
| IEC 62474 | *M-010* | *Ceramics / Glass* | An inorganic, non-metallic solid prepared by the action of heat and subsequent cooling. Materials in this category may have a crystalline or partly crystalline structure (e.g. ceramics), or may be amorphous (e.g. glass). |
| IEC 62474 | *M-011* | *Other inorganic materials* | Other inorganic materials which are not included in M-001 through M-010 |
| IEC 62474 | *M-012* | *PolyVinylChloride (PVC)* | A thermoplastic material composed of polymers of vinyl chloride. |
| IEC 62474 | *M-013* | *Other Thermoplastics* | Resin or plastic compounds that has the potential to be remelted and remolded. Poly Vinyl Chloride (PVC) is excluded from this category. |
| IEC 62474 | *M-014* | *Other Plastics and Rubber* | All polymers and rubbers whose main matrix is other than thermoplastic are included in this Material Class. Note that even if the filler content is high, material will be grouped into this class if main matrix considered "Other Plastics & Rubber". |
| IEC 62474 | *M-015* | *Other Organic Materials* | Other organic materials which are not included under M-012 through M-014. |
| IEC 62321-2 | | *3. Components* | |
| IEC 62321-2 | B/2 | *3.1 Coatings* | *Components/Materials* |
| IEC 62321-2 | Z/3 | *3.2 HBC materials* | *Components/Materials* |
| IEC 62321-2 | E/4 | *3.3 PWB electronic parts* | *Components/Materials* |
| IEC 62321-2 | O/5 | *3.4 Optical components* | *Components/Materials* |
| IEC 62321-2 | F/6 | *3.5 Formed components* | *Components/Materials* |
| IEC 62321-2 | M/7 | *3.6 Mechanical components* | *Components/Materials* |
| IEC 62321-2 | G/8 | *3.7 Body parts* | *Components/Materials* |
| IEC 62321-2 | N/9 | *3.8 Standard components* | *Components/Materials* |
| IEC 62321-2 | K/10 | *3.9 Catalogue components* | *Components/Materials* |
| IEC 62321-2 | S/11 | *3.10 Other purchased parts* | *Components/Materials* |
| IEC 62321-2 | O/12 | *3.11 OEM products* | *Components/Materials* |

## Appendix B. Resource criticality assessment