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Towards a dynamic assessment of raw materials criticality: Linking agent-based demand — With material flow supply modelling approaches

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HIGHLIGHTS

- ► Current criticality assessment methods provide a ‘snapshot’ at one point in time.
- ► They do not account for dynamic interactions between demand and supply.
- ► We propose a conceptual framework to overcomes these limitations.
- ► The framework integrates an agent-based behaviour model with a dynamic material flow model.
- ► The approach proposed makes a first step towards a dynamic criticality assessment.

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ABSTRACT

Emerging technologies such as information and communication-, photovoltaic- or battery technologies are expected to increase significantly the demand for scarce metals in the near future. The recently developed methods to evaluate the criticality of mineral raw materials typically provide a ‘snapshot’ of the criticality of a certain material at one point in time by using static indicators both for supply risk and for the impacts of supply restrictions. While allowing for insights into the mechanisms behind the criticality of raw materials, these methods cannot account for dynamic changes in products and/or activities over time. In this paper we propose a conceptual framework intended to overcome these limitations by including the dynamic interactions between different possible demand and supply configurations. The framework integrates an agent-based behaviour model, where demand emerges from individual agent decisions and interaction, into a dynamic material flow model, representing the materials' stocks and flows. Within the framework, the environmental implications of substitution decisions are evaluated by applying life-cycle assessment methodology. The approach makes a first step towards a dynamic criticality assessment and will enhance the understanding of industrial substitution decisions and environmental implications related to critical metals. We discuss the potential and limitation of such an approach in contrast to state-of-the-art methods and how it might lead to criticality assessments tailored to the specific circumstances of single industrial sectors or individual companies.

1. Introduction

Emerging technologies such as information and communication-, renewable energy generation-, and energy storage-technologies are expected to increase the demand for geochemically scarce metals[1] significantly in the near future (Angerer et al., 2009; Wäger et al., 2010, 2012; Weil et al., 2009). Recently, concern over disruptions to raw materials supplies has risen in the light of China's export restrictions – that controls 95% of the global supply of rare earth elements (REEs)[2] (Corfield, 2010; Du and Graedel, 2011) – causing the availability of these commodities to drop by 40% between 2009 and 2010 (from 50,149 to 30,258 metric tons) (Danlu, 2012; Yang, 2012; Yu, 2010). This demonstrates the vulnerability of high-tech industries in the EU economy in times of acute supply disruption (Kooroshy et al., 2010). For the ICT-, aerospace-, automotive- and electronics industries, there is a risk that supply disruptions will constrain technological progress in the near future. For this reason REEs and other geochemically scarce metals, such as platinum group metals (PGMs)[3] are often referred to as

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[1] A metal is considered as “geochemically scarce” when it occurs at an average concentration in the earth's crust below 0.01 wt.% (Skinner, 1979).

[3] The Platinum Group Metals (PGMs) family consist of 6 elements: iridium (Ir), osmium (Os), palladium (Pd), platinum (Pt), ruthenium (Ru) and rhodium (Rh).

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"critical" raw materials (DOE, 2010; EC, 2010; NRC, 2008). In the following the issues related to critical raw materials are mainly illustrated with REEs and PGMs since they provide some of the most evident examples although the insights are generally transferable to most geochemically scarce metals.

Measuring raw materials' criticality only by the relative abundance of chemical elements in the Earth's upper continental crust can be considered as insufficient. In this regard, the relatively widespread REEs (USGS, 2002), for example, would not belong to the metals with the highest supply risk, as stated by the European Commission (EC) (2010). Rather, as shown by e.g. China's supply dominance of the last years (Du and Graedel, 2011) and its ability to control the exports (Yu, 2010), raw materials' criticality is a multifactorial issue depending on geological, geopolitical, technological, economic, ecological and social issues (see e.g. NRC, 2008; Wäger et al., 2010).

Recently, several static indicator-based criticality assessment methodologies have been developed, pioneered by the US National Research Council (NRC) (2008) and the European Union (EC, 2010). The US study laid the basis for the on-going criticality discussion by proposing the "criticality matrix" which condenses the various criticality aspects into two dimensions, the *supply risk or risk of a supply restriction* on one axis and the *impact of supply restriction or economic importance* on the other one. The *supply risk* is evaluated (i) on the short term by the fragility of the existing market, production concentration, reliance on by-product sources of supply, opportunities of developing alternative sources; and (ii) on the long term, by considering geological, technical, environmental and social, political, and economic availability. The *impact of a supply restriction* is evaluated by considering the difficulty of substituting a restricted material, where the consequences (i.e. economic costs) depend on the particular form of restriction (e.g. physical availability, technical and economic feasibility). A qualitative evaluation of criticality was accomplished by an expert committee, as in this pioneering study emphasis was given to evaluating the feasibility of the approach to measure criticality, concentrating on eleven elements or element groups, respectively, relevant for the US economy (NRC, 2008).

This criticality matrix approach was adopted by the EU study and extended with quantitative measurements. The *economic importance* is measured by a breakdown of the value added attributed to a raw material, and the *supply risk* by the concentration and stability of production of raw materials (i.e. the distribution of the worldwide production linked with the political and economic stability of the producing countries), the substitution potential (i.e. substitutability index) and the recyclability (i.e. measured with the recycled content). The study analysed the criticality of 41 raw materials across all industrial sectors. A material was labelled as "critical" when the risks of supply shortage and their impacts on the economy are higher than for most of the other raw materials (EC, 2010).

The application of these methodologies resulted in fourteen raw materials that were considered as critical in a European context, and five considered critical in a United States context. According to a recent survey, the following elements or element families have most frequently been evaluated as critical in a selection of seven selected studies including amongst others the two above mentioned and a study of the US Department of Energy specifically focusing on emerging clean energy technologies (DOE, 2010) indium, niobium, platinum, REEs, rhodium, ruthenium and tungsten (Erdmann and Graedel, 2011).

Current static criticality assessment methods set the stage for the on-going criticality discussion across a wide range of elements. However, they exclude several interrelations relevant for criticality issues, partly as a consequence of their wide scope, but also because of limited data availability and the conceptual novelty of measuring criticality. Some important aspects that have not been fully accounted for so far include:

- changes in products or activities over time by using static indicators, only a 'snapshot' of the criticality of a certain material at one point in time is provided are not included[4];
- feedback between possible demand and supply chain developments, and their effects on the background systems on which these products and activities depend (e.g. the supply of electricity) are not explicitly considered. The presently applied "static" approaches implicitly assume that substitution decisions on the demand side only marginally affect the supply chain.

Previous studies recognize the potential dynamics affecting the criticality of elements but, owing to the complexity of these dynamics, limit their assessment to static analysis of a fixed time period. However, industrial stakeholders may still base their long-term decisions on those assessments and implicitly assume that criticality stays constant.

Thus dynamic criticality issues are often caused by interdependencies not included in previous assessments such as: Material substitution decisions of large international companies might induce changes in the supply chain (e.g. the installation of new mining facilities) and therefore affect the raw materials' criticality. To take such decisions based on a static criticality assessment might be misleading. In addition, the induced production capacities will occur with a certain time delay and therefore will be accompanied by a short-term supply restriction. Furthermore, even if the companies' substitution decisions in specific sectors do not significantly affect the supply chain, raw materials criticality might dramatically change due to an increasing demand from other sectors (e.g. an increased Indium price for thin-film photovoltaic driven by the demand for flat screens) or geopolitical constraints (e.g. China's REEs export limitation or production dominance Yu, 2010). First approaches to consider criticality with dynamic models have been reported for PGMs (Alonso et al., 2008) and REEs (Alonso et al., 2012). Recently, Du and Graedel (2011) quantified the stocks and flows of REEs from 1995 to 2007. However, none of the approaches included the interrelation of individual industrial decisions and supply-chain development and are therefore ill suited for industrial decision support.

In addition, environmental issues related to metals criticality have only been marginally considered in criticality studies so far, although metals' mining and manufacturing is known as having considerable environmental implications (Althaus and Classen, 2005; Classen et al., 2009). Graedel et al. (2012) have developed a methodology which extends the criticality matrix applied in the NRC study (NRC, 2008) by an environmental dimension based on available cradle to gate life cycle inventory data for the evaluated metals from the ecoinvent database (Hischier et al., 2010). Doing so, they separate supply restrictions due to regulatory measures, which is covered in the supply risk, from the environmental implications of utilizing particular metals, allowing for an independent assessment of environmental issues from other criticality aspect. As mentioned by Graedel et al. (2012) such accounting of environmental implications provides a snapshot in time, and environmental impacts might change with increasing demand that leads to the exploitation of lower ore grades and additional pressure on ecosystems. Furthermore, environmental impacts might appear with different probabilities and therefore have varying risk implications.

Hence, new approaches are needed not only to include the interactions of demand and supply parameters of critical raw materials, but also to address their dynamic changes over time and related environmental impacts along the materials life cycle. In this paper we present a conceptual framework that could be used to model the interrelated criticality aspects dynamically, elaborate on the potential and limitation of the approach, and discuss potential future research requirements.

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[4] This is why the ad hoc working group of the EC recommends updating the list of critical raw materials every 5 years (EC, 2010).

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