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 overcome 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.

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.

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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 (Angleser 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

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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).
2 The Rare Earth Elements (REEs) family includes 17 chemical elements: scandium (Sc), yttrium (Y) and the 15 lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu).
3 The Platinum Group Metals (PGMs) family consist of 6 elements: iridium (Ir), osmium (Os), palladium (Pd), platinum (Pt), ruthenium (Ru) and rhodium (Rh).
to as “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
two most evident examples – although the insights are generally transfer-
able 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 wide-
spread REEs (USGS, 2002), for example, would not belong to the
critical 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 mul-
tifactorial 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 discus-
sion by proposing the “criticality matrix” which condenses the var-
ious 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, produc-
tion 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 availabil-
ity, technical and economic feasibility). A qualitative evaluation of

This criticality matrix approach was adopted by the EU study
and extended with quantitative measurements. The economic im-
portance is measured by a breakdown of the value added attributed
to a raw material, and the supply risk by the concentration and

Criticality. Some important aspects that have not been fully accounted
for so far include:

- changes in products or activities over time – by using static indica-
tors, only a ‘snapshot’ of the criticality of a certain material at one
point in time is provided – are not included4;
- feedback between possible demand and supply chain develop-
ments, 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” ap-
proaches implicitly assume that substitution decisions on the
demand side only marginally affect the supply chain.

Previous studies recognize the potential dynamics affecting the crit-
icality 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
these 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 deci-
sions of large international companies might induce changes in the sup-
ply chain (e.g. the installation of new mining facilities) and therefore
affect the raw materials’ criticality. To take such decisions based on a

4 This is why the ad hoc working group of the EC recommends updating the list of

2. Conceptual framework

Our approach aims to advance existing criticality assessments by modelling the interrelated factors affecting criticality dynamically outlined in part above, and by assessing the related environmental risks from a life cycle perspective. It is designed to investigate how far criticality will be affected by industrial substitution decisions if dynamic interrelations are considered and thus might directly support such decisions.

The framework couples an agent-based behaviour model (describing the material substitution decisions of industries) with a dynamic material flow model (Fig. 1). This allows us to simulate the (economic and ecological) consequences of material substitution decisions under constraints (i.e. different framework scenarios). Simulation experiments will result in material availability distributions at a certain point in time, to a certain price and environmental impact. The coupled dynamic model therefore provides the basis for assessing the environmental risks (i.e. probability of certain outcomes) related to material substitution decisions. In the subsequent paragraphs the two models, framework scenarios, and the environmental risk assessment are addressed in more detail.

2.1. Agent-based model and dynamic material flow model

The **dynamic material flow model** aims to simulate the material flows across their life cycle. For this purpose, all relevant processes along a materials life cycle such as mining, processing, distribution, manufacturing within companies as well as usage and end of life treatment have to be analysed and modelled. Dynamic material flow analysis (MFA) has become a standard tool for forecasting material flows, assessing recycling schemes and related environmental impacts (e.g. Baccini and Brunner, 2012; Daigo et al., 2009; Hatayama et al., 2010; Muller, 2006).

Many scarce metals are not mined on their own but as by-products of other material mining, and therefore tied to the demand for the main metal (Graedel, 2011; Hagellüken and Meskers, 2010). Such interdependencies are evident for REEs and PCMs and define to a large extent which processes to include in the life cycle (i.e. system boundary definition). In addition, the environmental impacts along the production chain of REEs and PCMs are considered and modelled depending on ore grade and on the material technical performance and durability. This allows us to understand the interdependencies between environmental impacts and – inter alia – demand and product/by-product ratios. Furthermore, it reveals whether recycling is environmentally beneficial and how relevant its contribution can be for supply security. The material flow model builds the frame (i.e. the technical environment) for the agent-based behavioural model.

The **agent-based behaviour model** aims to understand and simulate the dynamic interrelation between the substitution decisions and the underlying material flow system. For this purpose, it focuses on how substitution decisions affect each other and how they are interrelated with the material flows down-stream and upstream in the consumption chain. Today, such substitution decisions are taken to achieve marketing and engineering design goals which in turn are mainly based on consumer preferences and material properties with little account for the criticality of single elements (e.g. Krishnan and Ulrich, 2001). Once the product is established on the market, increased demand from other applications might restrict the availability of marginal elements such as REEs and PCMs. Such potential supply restriction can be seen as an emergent property of interacting agents across the supply–demand network, which can be captured with agent-based modelling (ABM) (Axelrod, 1997; Janssen, 2002; Tesfatsion and Judd, 2006).

ABM as a bottom-up approach is commonly used for analysing transition dynamics in socio-technical systems (Bergman et al., 2008; Chappin and Dijkema, 2010; Haxeltine et al., 2008). Its combination with top-down approaches such as global dynamic optimization or dynamic MFA allows for additional insights into e.g. what can be achieved with particular measures and what could create barriers to an implementation of such plans (Beck et al., 2008; Kempen et al., 2009). Until now, such a combination has mostly been applied to energy systems (Andrews et al., 2011; Axtell et al., 2001; Davis et al., 2010; Kempen et al., 2009). Just recently metal flows were explicitly addressed as Bollinger et al. (2012) contrasted MFA with an agent-based model including material entities (resulting in flows) for analysing different recycling schemes. They concluded that on the upside such an
agent-based model allows for a more native representation of the societ-
tal material flow system, while on the downside the approach was more
computationally intensive than top-down equation-based techniques.

The demand for REEs and PGMs is determined by the substitution de-
cisions of different companies in different sectors, and by their interac-
tion driven by the demand for the end product from the consumers.
Agents, their behaviour and their environment are the three basic com-
ponents of an agent-based model, with agents being the representatives
of real world actors (e.g. companies) within the model. Hence, im-
plementing such a model requires the identification of those agents
that demand REEs and PGMs, as well as an analysis of the interactions
among agents and the agent specific decision-making (intention) and
behaviour (Knoeri et al., 2011). Depending on the focus of the study
the main level of decision analysis might shift from industrial substitu-
tion decisions, as illustrated in Fig. 1, to consumer technology adoption.
A combination of such an agent-based model with a material-flow
model, which represents the agents’ technical environment, allows for
understanding how the interacting agents affect the material flows
under which conditions (i.e. framework scenarios).

2.2. Framework scenarios

A small set of consistent framework scenarios is the key for assessing
future development and case study research (Scholz and Tietje, 2002;
Tietje, 2005). From the conceptual model the important scenario pa-
rameters required for the material flow, and the behaviour model, are
derived. Some of these parameters might be consistent with criticality
indicators and partly interrelated. Formative scenario analysis (Spoerri
et al., 2005; Wiek, 2002) and cross-impact analysis (Weimer-Jehle,
2006) are possible approaches to assess such interrelations and to iden-
tify a consistent set of scenarios.

2.3. Environmental risk assessment

The framework concludes with an environmental risk assessment. In
general, ‘risk’ refers to the uncertainty about and the severity of the con-
sequences (or outcomes) of an activity with respect to something that
humans value (Aven and Renn, 2009). In the context of materials’ sub-
stitution, risk can be seen as the probabilities and extent of environmental
consequences when substituting one material with another. Environ-
mental consequences are the environmental impacts related to the life
cycle of the products with different material substitutes. The probabil-
ities of the consequences of a substitution decision are calculated from
the coupled model. The severities of the environmental consequences
can be assessed with life cycle assessment (LCA) (Frischknecht et al.,
2007a,b,c).

3. Potential and limitations of the approach

The approach proposed aims to go beyond current criticality assess-
ment based on static indicators by explicitly including the dynamic in-
terrelation between industrial substitution decisions and the criticality
of metals considered. By doing so, we expect to resolve some of the
known shortcomings of existing approaches; however, this might result
in other drawbacks. In the following we elaborate on the potential and
limitations related to specific characteristics of the approach.

3.1. Dynamic vs. static

The proposed approach aims to assess the availability of scarce
metals over time by explicitly modelling industrial decisions and their
interaction and consequences on the materials’ stock and flows. Such
a dynamic assessment depends on the technology and decision knowl-
edge available at the time of modelling. As a consequence, uncertainty
about future technologies and in particular industrial decisions might
limit the accuracy.

3.2. Explicit behaviour modelling

In contrast to current approaches, which implicitly anticipate ac-
tors’ behaviour in their indicators, we propose to explicitly model
actor behaviour. While this might be beneficial for the transparency
of assumptions about industrial decisions it requires a thorough un-
derstanding of how substitution decisions are made and how they af-
fect each other and the related supply stream actors. In turn it might
greatly enhance the understanding of interrelated industrial decisions
in the context of critical metals.

3.3. Environmental risk assessment

The explicit modelling of the socio-technical system will result in a
distribution of outputs (e.g. material requirements) under certain sce-
narios. In combination with environmental impacts across the life
cycle of metals, those distributions allow for an evaluation of environ-
mental risks related to industrial substitution decisions. Compared to
previous approaches this is again a more explicit evaluation of potential
environmental implications, however it bares the risk of undermining
accepted life cycle assessment insights with modelling uncertainties.

3.4. Addressee

With the exception of Graedel et al. (2012), current approaches
assessed the criticality of metals for whole industrial sectors or coun-
tries. The approach proposed here focuses on single industries or even
companies. This allows a customized criticality assessment for industri-
al stakeholders on the one hand, but limits the transferability of results
on the other hand.

3.5. Scope

The explicit dynamic modelling of industrial actors’ behaviour and
its consequences on the material flows and criticality of metals at
stake clearly limits possible scopes of the approach. While the coupled
model would allow highly context specific criticality assessment,
cross-insights to other industries and/or elements are limited.

4. Conclusion and outlook

In this paper we proposed an approach to evaluate the criticality
of raw materials that goes beyond the current state of the art in the
sense that it explicitly includes the dynamic interrelations between
industrial substitution decisions and their implication on the critical-
ity of metals considered. Our motivation for doing so was to stimulate
research about dynamic criticality assessment tailored for industrial
stakeholders, which we envision as an important addition to the crit-
icality discussion in the future.

As such, the approach will allow simulation of dynamic market re-
sponses to substitution decisions as part of risk management strategy
of industrial stakeholders. This will advance the understanding of supply
risk significantly beyond the static indicator approaches currently pro-
posed and enable a more systematic analysis of complex market re-
sponses. Although the prospective approach addresses rather specific
industrial substitution decisions and their consequences, we encourage
further research to start with a generic “proof of concept” aiming at an
in-depth analysis of the additional insights gained through the approach.

Conflict of interest statement

None.
Acknowledgements

The authors thank Katy Roelich and Ruairi Revel for their helpful comments on earlier versions of the manuscript.

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