



UNIVERSITY OF LEEDS

This is a repository copy of *Towards a dynamic assessment of raw materials criticality: linking agent-based demand--with material flow supply modelling approaches.*

White Rose Research Online URL for this paper:
<http://eprints.whiterose.ac.uk/80022/>

Version: Accepted Version

Article:

Knoeri, C, Wäger, PA, Stamp, A et al. (2 more authors) (2013) Towards a dynamic assessment of raw materials criticality: linking agent-based demand--with material flow supply modelling approaches. *Science of the Total Environment*, 461-46. 808 - 812. ISSN 0048-9697

<https://doi.org/10.1016/j.scitotenv.2013.02.001>

Reuse

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

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

Christof Knoeri¹, Patrick A. Wäger², Anna Stamp², Hans-Joerg Althaus², Marcel Weil^{3,4}

¹Sustainability Research Institute / School of Earth & Environment, University of Leeds, LS5 9JT Leeds, UK

²Technology and Society Laboratory / Empa, Swiss Federal Laboratories for Materials Science and Technology, CH-8600 Duebendorf, Switzerland

³Institute for Technology Assessment and Systems Analysis, Karlsruhe Institute of Technology (KIT), D-76021 Karlsruhe, Germany

⁴Helmholtz-Institute Ulm for Electrochemical Energy Storage, Albert-Einstein-Allee 11, 89081 Ulm, Germany

Corresponding Author: Christof Knoeri, c.knoeri@leeds.ac.uk

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 metals¹ significantly in the near future (Angerer et al., 2009; Wäger et al., 2012; Wäger et al., 2010; Weil et al., 2009). Recently, concern over disruptions to raw materials supplies have 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 "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,

¹ A metal is considered as "geochemically scarce" when it occurs at an average concentration in the earth's crust below 0.01 weight percent (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).

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 included⁴;
- 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

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).

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 - 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.

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 (Figure 1). This allows us to simulate the (economic and ecological) consequences of materials 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.

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; Hagelüken and Meskers, 2010). Such interdependencies are evident for REEs and PGMs 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 PGMs are considered and modelled depending on ore grade and on the materials 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 PGMs. 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).

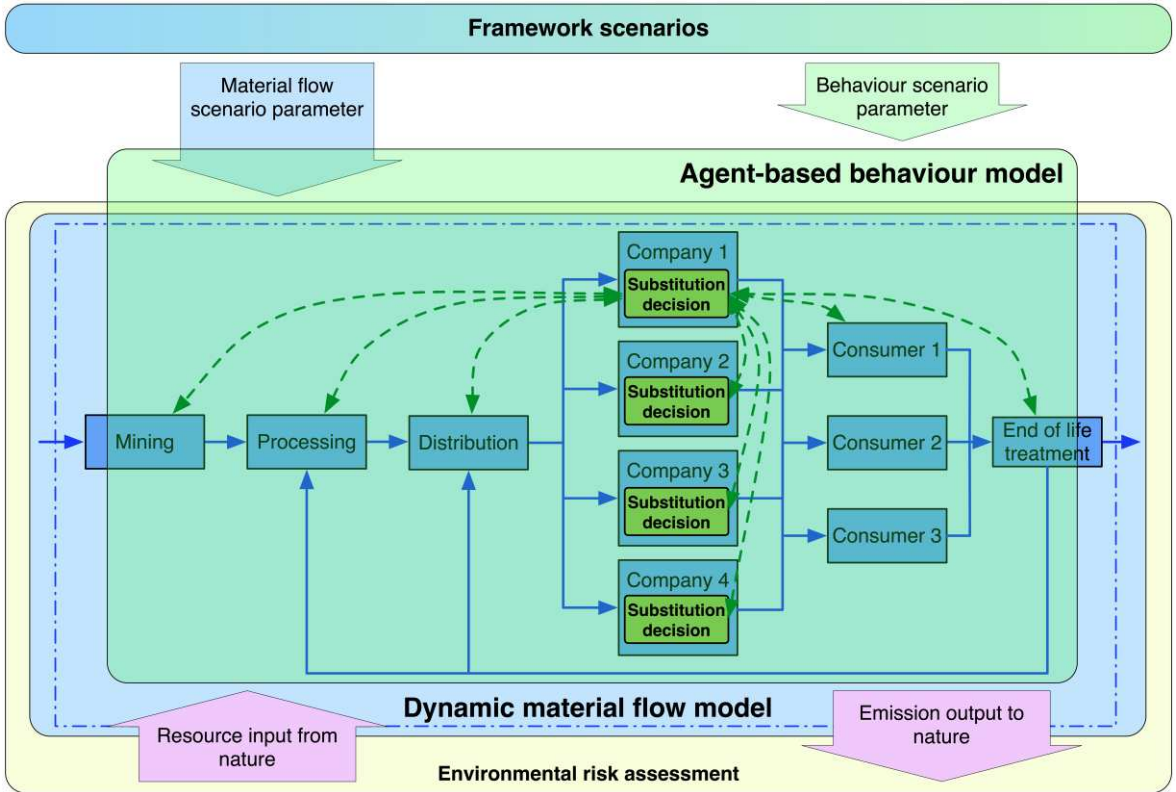


Figure 1: Conceptual framework for the dynamic material flow and agent-based behaviour model (blue boxes stand for processes, solid blue arrows for the flows in the material flow model; green boxes indicate the substitution decision taken by the individual companies/industrial sectors, green-dotted arrows indicate the interrelation of these decisions among themselves and with their environment in the agent-based behaviour model; the light brown box defines the scope of the environmental risk assessment assessing the resource inputs from and emissions to nature, both indicated by purple arrows)

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; Kempener 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; Kempener et al., 2009). Just recently metal flows were explicitly addressed as Bollinger et al. (2011) 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 societal

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 decisions of different companies in different sectors, and by their interaction driven by the demand for the end product from the consumers. Agents, their behaviour and their environment are the three basic components of an agent-based model, with agents being the representatives of real world actors (e.g. companies) within the model. Hence, implementing 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 substitution decisions, as illustrated in Figure 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).

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 parameters 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., 2009; Wiek, 2002) and cross-impact analysis (Weimer-Jehle, 2006) are possible approaches to assess such interrelations and to identify a consistent set of scenarios.

Environmental risk assessment

The framework concludes with an *environmental risk assessment*. In general, 'risk' refers to the uncertainty about and the severity of the consequences (or outcomes) of an activity with respect to something that humans value (Aven and Renn, 2009). In the context of materials' substitution, risk can be seen as the probabilities and extent of environmental consequences when substituting one material with another. Environmental consequences are the environmental impacts related to the life cycle of the products with different material substitutes. The probabilities 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; Frischknecht et al., 2007b; Frischknecht et al., 2007c).

3. Potential and limitations of the approach

The approach proposed aims to go beyond current criticality assessment based on static indicators by explicitly including the dynamic interrelation 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.

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 knowledge available at the time of modelling. As a consequence, uncertainty about future technologies and in particular industrial decisions might limit the accuracy.

Explicit behaviour modelling: In contrast to current approaches, which implicitly anticipate actors' 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 understanding of how substitution decisions are made and how they affect 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.

Environmental risk assessment: The explicit modelling of the socio-technical system will result in a distribution of outputs (e.g. material requirements) under certain scenarios. In combination with environmental impacts across the life cycle of metals, those distributions allow for an evaluation of environmental 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.

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

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 criticality 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 criticality discussion in the future.

As such, the approach will allow simulation of dynamic market responses 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 proposed and enable a more systematic analysis of complex market responses. 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.

Acknowledgements

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

References

- Alonso E, Field FR, Kirchain RE. The dynamics of the availability of platinum group metals for electronics manufacturers, 2008.
- Alonso E, Sherman AM, Wallington TJ, Everson MP, Field FR, Roth R, et al. Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies. *Environmental Science & Technology* 2012; 46: 3406-3414.
- Althaus HJ, Classen M. Life cycle inventories of metals and methodological aspects of inventorying material resources inecoinvent. *International Journal of Life Cycle Assessment* 2005; 10: 43-49.
- Andrews CJ, Yi D, Krogmann U, Senick JA, Wener RE. Designing Buildings for Real Occupants: An Agent-Based Approach. *IEEE Transactions on Systems Man and Cybernetics Part a-Systems and Humans* 2011; 41: 1077-1091.
- Angerer G, Marscheider-Weidemann F, Erdmann L, Scharp M, Handke V, Marwede M. Rohstoffe für Zukunftstechnologien (Raw Materials For Emerging Technologies). Stuttgart: Fraunhofer IBB Verlag, 2009.
- Aven T, Renn O. On risk defined as an event where the outcome is uncertain. *Journal of Risk Research* 2009; 12: 1-11.
- Axelrod R. The complexity of cooperation: Agent-based models of competition and collaboration. Princeton: Princeton University Press, 1997.
- Axtell RL, Andrews CJ, Small MJ. Agent-Based Modeling and Industrial Ecology. *Journal of Industrial Ecology* 2001; 5: 10-13.
- Baccini P, Brunner PH. *Metabolism of the Anthroposphere: Analysis, Evaluation, Design*: MIT Press, 2012.
- Beck J, Kempener R, Cohen B, Petrie J. A complex systems approach to planning, optimization and decision making for energy networks. *Energy Policy* 2008; 36: 2795-2805.
- Bergman N, Haxeltine A, Whitmarsh L, Kohler J, Schilperoord M, Rotmans J. Modelling socio-technical transition patterns and pathways. *Journal of Artificial Societies and Social Simulation* 2008; 11: 1460-7425.
- Bollinger LA, Davis C, Nikolić I, Dijkema GPJ. Modeling Metal Flow Systems. *Journal of Industrial Ecology* 2011.
- Chappin E JL, Dijkema GPJ. Agent-based modelling of energy infrastructure transitions. *International Journal of Critical Infrastructures* 2010; 6: 106-130.
- Classen M, Althaus H-J, Blaser S, Doka G, Jungbluth N, Tuchschnid M. Life Cycle Inventories of Metals. Final report ecoinvent data v2.1. 10. Swiss Centre for Life Cycle Inventories, Dübendorf, CH., 2009.
- Corfield R. Rare on Earth? *Chemistry & Industry* 2010: 16-18.
- Daigo I, Hashimoto S, Matsuno Y, Adachi Y. Material stocks and flows accounting for copper and copper-based alloys in Japan. *Resources Conservation and Recycling* 2009; 53: 208-217.
- Danlu T. China vows stricter rare earth regulation, Accessed July 7, 2012 from http://news.xinhuanet.com/english/china/2012-06/20/c_131666265.htm, 2012.
- Davis C, Nikolic I, Dijkema GPJ. Infrastructure modelling 2.0. *International Journal of Critical Infrastructures* 2010; 6: 168-186.
- DOE. *Critical Materials Strategy*. U.S. Department of Energy (DOE), 2010.
- Du X, Graedel TE. Global In-Use Stocks of the Rare Earth Elements: A First Estimate. *Environmental Science & Technology* 2011.
- EC. *Critical raw materials for the EU; Report of the Ad-hoc Working Group on defining critical raw materials*. European Commission (EC), 2010.

- Erdmann L, Graedel TE. Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses. *Environmental Science & Technology* 2011; 45: 7620-7630.
- Frischknecht R, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, et al. Overview and Methodology. Final report ecoinvent v2.0 No. 1. Swiss Centre for Life Cycle Inventories, Duebendorf, CH, 2007a.
- Frischknecht R, Althaus H-J, Doka G, Dones R, Hellweg S, Hirschier R, et al. Code of Practice. Final report ecoinvent v2.0 No. 2. Swiss Centre for Life Cycle Inventories, Duebendorf, CH, 2007b.
- Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Hellweg S, et al. Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent v2.0 No. 3. Swiss Centre for Life Cycle Inventories, Duebendorf, CH, 2007c.
- Graedel TE. On the Future Availability of the Energy Metals. In: Clarke DR, Fratzl P, editors. *Annual Review of Materials Research*, Vol 41. 41. Annual Reviews, Palo Alto, 2011, pp. 323-335.
- Graedel TE, Barr R, Chandler C, Chase T, Choi J, Christoffersen L, et al. Methodology of Metal Criticality Determination. *Environmental Science & Technology* 2012; 46: 1063-1070.
- Hagelüken C, Meskers CEM. Complex life cycles of precious and special metals. In: Graedel TE, Van Der Voet E, editors. *Linkages of Sustainability*. MIT Press, Cambridge, MA, 2010, pp. 163–97.
- Hatayama H, Daigo I, Matsuno Y, Adachi Y. Outlook of the World Steel Cycle Based on the Stock and Flow Dynamics. *Environmental Science & Technology* 2010; 44: 6457-6463.
- Haxeltine A, Withmarsh L, Bergman N, Rotmans J, Schilperoord M, Kohler J. A Conceptual Framework for transition modelling. *International Journal for Innovation and Sustainable Development* 2008; 3.
- Hirschier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R, et al. Implementation of Life Cycle Impact Assessment Methods: ecoinvent Report No. 3, version 2.2. Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2010.
- Janssen MA. Complexity and ecosystem management: the theory and practice of multi-agent systems. Cheltenham: Elgar, 2002.
- Kempener R, Beck J, Petrie J. Design and Analysis of Bioenergy Networks. *Journal of Industrial Ecology* 2009; 13: 284-305.
- Knoeri C, Binder CR, Althaus HJ. An agent operationalization approach for context specific agent-based modeling. *JASSS The Journal of Artificial Societies and Social Simulation* 2011; 14.
- Kooroshy J, Meindersma C, Podkolinski R, Rademaker M, Sweijts T, Dieteren A. Scarcity of Minerals. A strategic security issue! The Hague Centre for Strategic Studies, Den Haag, 2010.
- Krishnan V, Ulrich KT. Product development decisions: A review of the literature. *Management Science* 2001; 47: 1-21.
- Muller DB. Stock dynamics for forecasting material flows - Case study for housing in The Netherlands. *Ecological Economics* 2006; 59: 142-156.
- NRC USNRC. Minerals, Critical Minerals, and the U.S. Economy. Washington, D.C: National Academies Press, 2008.
- Scholz RW, Tietje O. Embedded case study methods; Integrating quantitative and qualitative knowledge. Thousand Oaks: Sage Publications, 2002.
- Skinner BJ. EARTH RESOURCES. *Proceedings of the National Academy of Sciences of the United States of America* 1979; 76: 4212-4217.
- Spoerri A, Lang DJ, Binder CR, Scholz RW. Expert-based scenarios for strategic waste and resource management planning - C&D waste recycling in the Canton of Zurich, Switzerland. *Resources, Conservation and Recycling* 2009; 53: 592-600.
- Tesfatsion L, Judd KL. *Handbook of computational economics: agent-based computational economics*. Vol 2. Amsterdam: Elsevier, 2006.
- Tietje O. Identification of a small reliable and efficient set of consistent scenarios. *European Journal of Operational Research* 2005; 162: 418-432.
- USGS. Rare Earth Elements—Critical Resources for High Technology. USGS Fact Sheet. U.S. Geological Service (USGS), 2002.
- Wäger PA, Lang D, Widmer D, Bleischwitz R, Hagelüken C. Towards a more sustainable use of scarce metals. A review of intervention options along the metals life cycle. *GAIA* 2012; 21: 300-309.

- Wäger PA, Lang DJ, Bleischwitz R, Hagelüken C, Meissner S, Reller A, et al. Seltene Metalle - Rohstoffe für Zukunftstechnologien [Scarce Metals – Raw Materials for emerging technologies]. Swiss Academy for Engineering Sciences (SATW), 2010.
- Weil M, Ziemann S, Schebek L. How to assess the availability of resources for new technologies? Case study: Lithium a strategic metal for emerging technologies. *Revue De Metallurgie-Cahiers D Informations Techniques* 2009; 106: 554-558.
- Weimer-Jehle W. Cross-impact balances: A system-theoretical approach to cross-impact analysis. *Technological Forecast and Social Change* 2006; 73: 334-61.
- Wiek A. Formative Szenarienanalyse zu den Entwicklungsmöglichkeiten des Ländlichen Gebiets Centovalli-Verbano-Locarnese: Leitfaden und Ergebnisse [Formative scenario analysis for development opportunities in the rural area of Centovalli-Verbano-Locarnese; Guideline and Results]. ETH Zürich, Professur für Umweltnaturwissenschaften, Zürich, 2002.
- Yang F. Situation and Policies of China's Rare Earth Industry, Accessed July 7, 2012 from http://news.xinhuanet.com/english/bilingual/2012-06/20/c_131665890.htm, 2012.
- Yu X. China Cuts Rare Earth Export Quota, May Cause Dispute. *Bloomberg Businessweek*, 2010.