

A Dynamic and Endogenous Coupling of Environment and Economy as a Future Approach to Assessing Raw Material Criticality



Fenintsoa Andriamasinoro*, Antoine Boubault, Antoine Beylot and Stéphanie Muller

Bureau de Recherches Géologiques et Minières (BRGM), France

Submission: February 22, 2021; Published: March 03, 2021

*Corresponding author: Fenintsoa Andriamasinoro, Bureau de Recherches Géologiques et Minières (BRGM), 3 avenue Claude Guillemin - BP 36009, 45060 Orléans Cedex 2, France

Abstract

This article presents our views on some of the approaches used in the state of the art to estimate mineral raw material criticality and how the complexity, required in such a study, is taken into account. Next, it argues for a complementary view that could be an emerging way of understanding this complexity: an endogenous generated dynamic from the coupling of environmental and economic variables, conducted from a sustainable development perspective (technically implemented here via a prospective simulation of the system over approximately 20 years - 1 generation). This coupling consists technically

of representing, for time t and along the processing chain of the substance studied, dynamic decision-making rules via an approach called ACE (Agent-based Computational Economics),

of addressing their economic impacts in a MFA (Material Flow Analysis) and environmental in a LCA (Life-Cycle Analysis) and

of returning the results (from this time step t) to the input of the ACE as constraints/levers for the next decision (at time step $t + 1$), producing a loop on the time scale.

This coupling is in a spirit of seeking the relative balance between the need for openness toward new approaches (ACE) and the promotion of the existing one (MFA and LCA) already well-known and accepted by experts (broadly) in the field of geosciences and the environment. Likelihood of ACE acceptance by these experts is also briefly discussed.

Keywords: Mineral raw material; Criticality assessment; Environment; Economy; Agent-based model; Life-cycle analysis; Material flow analysis

Abbreviations: ACE: Agent-based Computational Economics; AI: Artificial Intelligence; EI: Environmental Impact; IO: Input-Output; LCA: Life-Cycle Analysis; MFA: Material Flow Analysis; SD: Sustainable Development; SFC: Stock-Flow Consistent; SR: Supply Risk; VSR: Vulnerability to Supply Risk

Introduction

Sustainable development (SD), which aims to ensure that economic growth does not come at the expense of environmental quality for present and future generations [1], also concerns the criticality of mineral commodities. Criticality is understood here to mean the current and future level of availability of a mineral material whose economic importance is proven but whose production sometimes generates significant environmental impacts [2]. This means that time considerations and a prospective approach are key to analysing criticality, especially since one of the characteristics of the minerals market is asynchronous supply and demand. So, for instance consumption could change every

10 days while a mining project at the exploration stage today might only be operational in 10 years, yet the impact of this future mining operation in the current market should nevertheless be anticipated in decisions [3].

Regarding this prospective analysis of criticality, one of the questions (Q) would be: *in an attempt to simultaneously reduce the economic and environmental costs along a given substance's processing chain, what are the levers (Pricing? Market share? Process?) that move the stakeholders involved at each stage? What decisions must also be taken (that can account for future events), knowing that these levers and decisions will change over time*

because the market is subject to permanent unknowns (for instance, changes in environmental regulation)? Since the production/processing chain of the substance studied is distributed in different territories (countries or groups of countries), 'stakeholders' is understood here to mean (a) the administrations and operators involved in each of these territories (operators aggregated to the scale of a chain node for data reasons), (b) local communities in the territory where the mining project will open up and (c) experts (broadly) in the field of geosciences and the environment (now abbreviated in this article as 'experts') who support the other categories of stakeholders. This question (Q) implies that it is not enough to represent the flows concerned (mass, energy, financial, etc.). The original decision rules should also be represented [4] to show how decision/impact balance is generated endogenously. In particular, this endogenisation would enable every stakeholder to learn, over time, how to adapt constantly to an event (e.g., a producer: "The mining project I have just proposed has been rejected because it is considered to be too polluting, so I am reviewing the extraction processes I had envisaged and making a new proposal") while trying to maintain their objectives (e.g., make a profit). All of this shows that the criticality analysis is complex, as the Graedel team [2] reminds us. We therefore believe that it should be conducted at a multi-stakeholder and multi-scale [5] level, whether these scales are spatial or temporal.

The remaining of this article presents our views on some of the approaches used in the state of the art to estimate criticality and how this complexity is taken into account. Next, it argues for a complementary perspective that could be an emerging way of understanding this complexity: an endogenous generated dynamic from the coupling of environmental and economic variables, conducted from a SD perspective (technically implemented here via a prospective simulation over approximately 20 years - 1 generation). This new idea would enable stakeholders, as they estimate the future criticality of a given substance, to have much richer information about the question (Q), but next an interpretation that remains subject to the subjectivity of the respective stakeholders. The article also highlights the barriers related to this new view.

To estimate criticality, a reference work often cited, for example in [6], is that described in [2]. This work determines criticality in three dimensions (axes): (a) the supply risk (SR) axis which represents the geological, technological, socio-economic and geopolitical risks related to supply, (b) the vulnerability to supply risk (VSR) axis, which represents how vulnerable demand is to SR and is based on the substance's economic importance and the ability to innovate so as not to rely too much on it, and (c) the environmental impact (EI) axis, which represents environmental involvements related to the production of substances from a life-cycle perspective. Relative to SD, SR and VSR cover the economy, and EI the environment. The SR axis also covers social issues, particularly local communities [7]. To understand the SR and VSR axes at the same time, the material flow analysis (MFA) approach,

which follows some variables (stock and flow of materials and energy), is often used as has been done in [8] in the cobalt sector and [9] in rare earths. MFA enriches the thinking on criticality by identifying the nodes in the chain that are out of balance from a technical, environmental, or geopolitical point of view. On the environmental impacts of a sector's activity, a commonly adopted approach is life-cycle analysis, LCA, to make choices, for example for how to process substances, based on these impacts, as has been done in the gold [10] and platinum [11] sectors. As for the time factor, Graedel's team [2] admits that no unique approach exists to assess it. For MFA, the state of the art often consists in looking at the incremental changes in the parameters studied year after year, giving them either a lifetime (e.g., for a product, see how long the substance will remain used in the product in this way), or a consideration of the substance's residence time in the Technosphere, once it has been extracted, as has been studied in [12] on 18 metals. In this scenario, MFA also exchanges data with LCA, as has been seen in the aluminium sector [13].

Our point of view on this state of the art is that if we refer to the three paradigms to represent the complexity of a system [14], namely paradigm 1, analytical (classical expertise approach using global mathematical models), paradigm 2, limited complexity (collective intelligence approach using multi-stakeholder models), and paradigm 3, general complexity (discussion among multiple stakeholders), economic and/or environmental analysis of mineral pathways is part of the first paradigm where MFA and LCA are widely used (and thus accepted) by experts. However, the complexity of the criticality analysis is not fully covered by these two approaches. For example, these approaches do not consider the geopolitical parameters of criticality (in the SR axis), the decision-making rules that explain flows and impacts, or the entire endogenous dimension of the economic-environmental link as explained in the introduction. Finally, they do not include the multi-scale aspect of criticality (in the VSR axis), whereas, for example, the criticality of lithium, cobalt and tungsten in Europe is not the same as that in France [15], even though France is one of Europe's member countries.

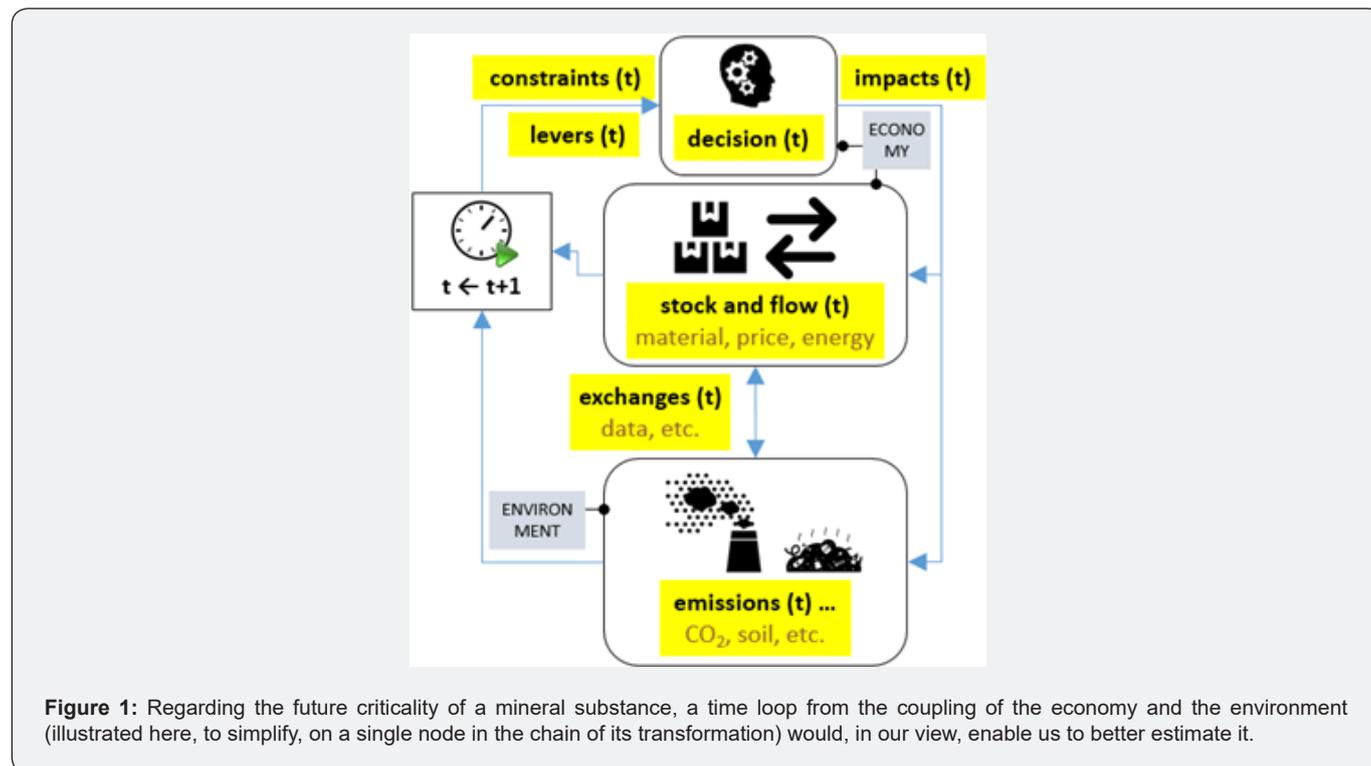
To better integrate the prospective estimation of criticality and thus take the representation (deemed necessary) of complexity further, we believe that the paradigm of representation of the sector studied should evolve: to couple paradigm 1 and paradigm 2, with SD always in mind. Technically, SD is implemented here via a prospective simulation of the economy ↔ environment interaction over about 20 years - 1 generation. For Paradigm 2, we specifically suggest introducing agent-based computational economics or ACE, a sub-domain of artificial intelligence (AI), which corresponds to the study of an economic process modelled and simulated in the form of agents that interact dynamically [16]. The agent-based approach is, according to [5], the best way to model complex decision-making (also considering events yet to come), up to those of human individuals in all cases for land use [17]. Despite this capacity, agent-based models have, until

now, tended to disregard physical resource flows and energy [18], hence the interest of coupling with MFA. The reasoning applies to LCA in the same way. This coupling of the paradigms consists technically (See Figure 1):

(i) of representing, for time, t and along the processing chain of the substance studied, dynamic decision-making rules (via ACE),

(ii) of addressing their economic impacts (variation in stock and flow of materials and energy) in the MFA and environmental (variation of air pollution, soil, water) in the LCA and

(iii) of returning the results (from this time step t) to the input of the ACE as constraints/levers for the next decision (at time step $t + 1$), producing a loop on the time scale.



A fourth approach that would complement ACE to close the financial flow loop at the macroeconomic level would be the stock-flow consistent or SFC approach [19] supported by an input-output (IO) table. SFC focuses on financial flow, just as MFA focuses on material and energy flows. LCA itself can be coupled with the IO table [20] or ACE [21]. In sum, our coupling viewpoint agrees with [18], which stated that studying the flows and stocks of physical resources (here via MFA) and money between agents (via ACE) within the framework of SFC accounting buttressed by IO data could form the basis of a fruitful research program for ecological macroeconomics and ecological econophysics. Here we resume this statement by additionally making the LCA approach explicit and applying it as a whole to the mineral raw material criticality assessment.

One of the main disadvantages attributed to ACE is often their low acceptance in the mining field [22], unlike the MFA and LCA approaches, which are more widely known and used by experts. However, in the past seven years, there is growing interest in the implementation of ACE for criticality: [23] on lithium, [24] on minerals in general, [3] on rare earths, and [11] on platinum. These few ACE projects have allowed us to begin to grasp some

of the limitations pointed out by the state of art. For example, the Yuan team [11] implemented a dynamic and endogenous ACE model of platinum criticality which also incorporates the 3 criticality axes. But it also has limitations: for example, it ignores the representation of negotiations between agents. Conversely, the ACE model in [3] elucidates negotiations in the rare earths market but does not take into account the parameters of the axes of criticality. On the other hand, neither project uses methodologies that are already known and validated by experts (like LCA and MFA), which could complicate their acceptance by those same experts.

Conclusion

For the future, and in particular with a view to obtaining much richer information in the prospective analysis of the criticality of mineral raw materials (See the question (Q) in the introduction), we believe that a shift from the current estimate method of commodity criticality toward greater recognition of its complexity will require a more emergent approach: establishing an endogenously generated dynamic between the coupling of environmental and economic variables. This coupling is always

carried out from a perspective of SD (technically implemented here via a prospective simulation over about 20 years – 1 generation) and also in a spirit of seeking the relative balance between the need for openness toward new approaches (ACE) and the promotion of the existing one (MFA and LCA) already well-known and accepted by sector analysis experts. In this era of growing AI and its potential applications, dynamic endogenisation would, in particular, enable every stakeholder to learn, over time, how it constantly adapts to an event caused or experienced while trying, for example, to respect economic and environmental constraints.

Regarding the acceptance of the new ACE approach by the experts, we believe that this will change positively over time for at least the following reasons: (a) the increasing amount of ACE work on criticality in the past seven years, (b) the coupling of ACE with other approaches that these experts already know, thus highlighting its added value from the expert perspective, (c) the progressive acceptance of AI by today's society (of which the experts are part) [25], aided by the growing computing power of computers, AI of which ACE is a sub-domain, and (c) the successful extension of a protocol called Overview, Design Concepts, Details or ODD [26], which is now becoming an increasingly standard protocol for describing, communicating and reproducing agent-based models. Designed by ecological modellers, ODD seems to have the growing support of a number of communities in the field of the environment [27-29]. Nothing prevents that from being used to write a criticality assessment ACE model. For this likelihood of ACE acceptance to increase in the LCA/MFA/ACE coupling we are interested in, it must be supported by at least two actions. The first is to clearly explain the validation protocol for the criticality model being developed. Indeed, the lack of a clear validation protocol is now one of the reasons for an agent model not to be accepted [30], knowing that even if the model reaches the statistical goodness of fit, it is valid only if it has been validated/accepted subjectively by the stakeholder [31], here experts, for example. The second action is to instil into an expert or a decision-maker the existence of the decorrelation between the scale of calculation (the most complex) and the scale of return (the simplest) of the results to users in a flexible manner, as requested by, for example, the decision-maker Lynn Hamill [32]. This decorrelation will appeal to the understanding of the theory of simplicity that Schumacher [33] describes in his theory of elegance: the creation of a tool and method whose complexity is not eliminated but whose visual reproduction is simple and elegant so that its appropriation is subsequently facilitated.

The point of view we raise in this article contains barriers other than ACE being accepted: like different sub-domains of AI (here ACE), coupling will require a huge amount of data at the finest possible scale, for example, weeks, as Riddle's rare-earth team used [3]. However, enterprise data on a small scale is often confidential. Nonetheless, in this era of big data, it is clear that enterprises that own small data as well and can measure its short-term effects (via AI and thus ACE) are ahead of their competitors. Perhaps this could encourage companies to open up their data

better? Therefore, for our proposed coupling, discussions on how to mobilise data would be prioritised in the future plans.

Conflict of Interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript..

References

1. Cheever F, Campbell Mohn CI (Eds.), Sustainable development.
2. Graedel TE, Chandler C, Barr R, Chase T, Choi J, et al. (2012) Methodology of Metal Criticality Determination. *Environmental Science & Technology* 46(2): 1063-1070.
3. Riddle ME, Tataru E, Olson C, Smith BJ, Irion AB, et al. (2021) Agent-based modeling of supply disruptions in the global rare earths market. *Resources, Conservation & Recycling* 164: 105193.
4. Ponte S, Sturgeon T (2014) Explaining governance in global value chains: A modular theory-building effort. *Review of International Political Economy* 21(1): 195-223.
5. Fromm J (2004) *The Emergence of Complexity*. Kassel university press, Kassel, p. 200.
6. BRGM (2017) Fiches de criticité sur Minéralinfo : parution des fiches chrome et indium & mise à jour de la fiche tungstène.
7. Nassar NT, Brainard J, Gulley A, Manley R, Matos G, et al. (2020) Evaluating the mineral commodity supply risk of the U.S. manufacturing sector. *Sciences advances* 6(8).
8. Danino Perraud R (2019) A Material Flow Analysis of cobalt: Observation of the evolutions of cobalt flows in Europe from 2008 to 2017.
9. Guyonnet D, Planchon M, Rollat A, Escalon V, Tuduri J, et al. (2015) Material flow analysis applied to rare earth elements in Europe. *Journal of Cleaner Production* 107: 215-228.
10. Elomaa H, Sinisalo P, Rintala L, Aromaa J, Lundström M (2020) Process simulation and gate-to-gate life cycle assessment of hydrometallurgical refractory gold concentrate processing. *International Journal of Life Cycle Assessment* 25: 456-477.
11. Yuan Y, Yellishetty M, Muñoz MA, Northey SA (2019) Toward a dynamic evaluation of mineral criticality: Introducing the framework of criticality systems. *Industrial Ecology* 23(5): 1264-1277.
12. Helbig C, Thorenz A, Tuma A (2020) Quantitative assessment of dissipative losses of 18 metals. *Resources, Conservation & Recycling* 153: 104537.
13. Ciacci L (2013) Integration of MFA and LCA methodologies: the anthropogenic aluminium cycle in Italy. PhD Thesis, Bologna.
14. Rossignol JY (2018) Complexité: Fondamentaux à l'usage des étudiants et des professionnels. (1st edn), p. 262.
15. Andriamasinoro F, Danino Perraud R (2019) Use of artificial intelligence to assess mineral substance criticality in the French market: the example of cobalt. *Mineral Economics*, pp. 1-19.
16. Nardone C (2019) Agent-Based Computational Economics and Industrial Organization Theory. Ch. 1. In: Cecconi F, Campenni M (Eds.), *Information and Communication Technologies (ICT) in Economic Modeling*. Springer, Cham, pp. 3-14.
17. Groeneveld J, Müller B, Buchmann CM, Dressler G, Guo C, et al. (2017) Theoretical foundations of human decision-making in agent-based land use models – A review. *Environmental Modelling & Software* 87: 39-48.

18. Berg M, Hartley B, Richters O (2015) A stock-flow consistent input-output model with applications to energy price shocks, interest rates, and heat emissions. *New Journal of Physics* 17: 015011.
19. Caiani A, Godin A, Caverzasi E, Gallegati M, Kinsella S, et al. (2016) Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *Economic Dynamics and Control* 69: 375-408.
20. Nakamura S, Nansai K (2016) Input-Output and Hybrid LCA. Ch. 5. In: M Finkbeiner (Ed.), *Special Types of Life Cycle Assessment. LCA Compendium – The Complete World of Life Cycle Assessment*. Springer, Dordrecht, pp. 219-291.
21. Walzberg J, Dandres T, Merveille N, Cheriet M, Samson R (2019) Assessing behavioural change with agent-based life cycle assessment: Application to smart homes. *Renewable and Sustainable Energy Reviews* 111: 365-376.
22. Lefebvre G, Andriamasinoro F (2016) Mining economist opinions on using multi-agent methodology to simulate metal markets. *International Journal of Trade and Global Markets* 9(1): 83-102.
23. Andriamasinoro F, Ahne H (2013) Prospective analysis of the world lithium market: contribution to the evaluation of supply shortage periods. *International Business & Economics Research Journal* 12(3): 359-372.
24. Knoeri C, Wäger PA, Stamp A, Althaus HJ, Weil M (2013) Towards a dynamic assessment of raw materials criticality: Linking agent-based demand with material flow supply modelling approaches. *Science of the Total Environment* 461-462: 808-812.
25. Bradley R (2018) 16 Examples of Artificial Intelligence (AI) in Your Everyday Life.
26. Grimm V, Berger U, DeAngelis DL, Polhill JG, Giske J, et al. (2010) The ODD protocol: A review and first update. *Ecological Modelling* 221(23): 2760-2768.
27. Polhill G (2010) ODD Updated. *Journal of Artificial Societies and Social Simulation* 13(4).
28. Kremmydas D, Athanasiadis IN, Rozakis S (2018) A review of Agent Based Modeling for agricultural policy evaluation. *Agricultural Systems* 164: 95-106.
29. Guerrin F (2020) Agent-Based Modelling of a Simple Synthetic Rangeland Ecosystem. Ch. 10. In: W Mirschel, V Terleeve, KO Wenkel (Eds.), *Landscape Modelling and Decision Support. Innovations in Landscape Research*. Springer, Cham, pp. 179-215.
30. An L, Grimm V, Turner II BL (2019) Editorial: Meeting Grand Challenges in Agent-Based Models. *Journal of Artificial Societies and Social Simulation* 23(1).
31. Augusiak J, Van den Brink PJ, Grimm V (2014) Merging validation and evaluation of ecological models to 'evaluation': A review of terminology and a practical approach. *Ecological Modelling* 280: 117-128.
32. Hamill L (2010) Agent-based modelling: the next 15 years. *Journal of Artificial Societies and Social Simulation* 13(4).
33. Schumacher P (2007) Arguing for Elegance. In: H Castle, A Rahim, H Jamelle (Eds.), *Architectural Design* 77(1): 28-37.



This work is licensed under Creative Commons Attribution 4.0 License
DOI: [10.19080/IJESNR.2021.27.556212](https://doi.org/10.19080/IJESNR.2021.27.556212)

Your next submission with Juniper Publishers will reach you the below assets

- Quality Editorial service
- Swift Peer Review
- Reprints availability
- E-prints Service
- Manuscript Podcast for convenient understanding
- Global attainment for your research
- Manuscript accessibility in different formats
(Pdf, E-pub, Full Text, Audio)
- Unceasing customer service

Track the below URL for one-step submission
<https://juniperpublishers.com/online-submission.php>