ARTICLE IN PRESS

Resources Policy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

Assessing supply risks for non-fossil mineral resources via multi-criteria decision analysis

Dominik Jasiński[a,*,1], Marco Cinelli[a,b,2], Luis C. Dias[c], James Meredith[d], Kerry Kirwan[a]

[a] Warwick Manufacturing Group, University of Warwick, Coventry CV4 7AL, UK
[b] Institute of Advanced Study, Millburn House, University of Warwick Science Park, Coventry CV4 7HS, UK
[c] INESC Coimbra, CeBER and Faculty of Economics, University of Coimbra, Av. Dias da Silva 165, 3004-512 Coimbra, Portugal
[d] Department of Mechanical Engineering, University of Sheffield, S1 3JD, UK

ARTICLE INFO

Keywords:
Raw materials criticality
Supply risk
Non-fossil resources
Automotive Industry
Classification system
Multi-criteria decision analysis (MCDA)
Robustness analysis

ABSTRACT

Criticality assessments of raw materials are inherently based on multiple criteria, which justifies the use of multi-criteria decision analysis (MCDA) to aid the interpretation of the data by providing a comprehensive evaluation. A structured and transparent selection procedure is firstly introduced in this paper to choose eight supply risk assessment criteria to evaluate the security of supply for thirty-one raw materials used in automotive manufacturing. A synergic combination of MCDA methods is then proposed for the classification of raw materials in risk classes according to the supply risk criteria. Risk classes are recommended following from a robustness analysis based on stochastic and optimisation MCDA methods where risk levels assigned to the raw materials are firstly visualised on a relative frequency basis. The sorting of the raw materials is also refined by narrowing down the best and worst plausible classes when justifiable constraints on criteria weights are accounted for in the modeling. For example, the robustness analysis suggests that rare earth elements and tellurium have a high eventuality of supply chain disruption, closely followed by indium, germanium and boron. Conversely, the results suggest that the risk of supply disruption for iron, copper, zinc and aluminium is mostly medium-low or low. The proposed step-wise decision support approach can be used as a complementary tool to the existing life cycle assessment methods for a more comprehensive assessment of the short-term availability of natural resources.

1. Introduction

An uninterrupted supply of raw materials, free from disturbances and bottlenecks that may lead to volatility in commodity pricing and markets, is a requirement for sustainable economic development. Erdmann and Graedel (2011) Sectors that rely heavily on raw materials (e.g. construction, manufacturing, and transport) are extremely vulnerable to any physical shortage or increasing prices of these materials. Schneider et al. (2014) As such, the need for a systematic quantification and assessment of the risks and impacts related to the increasing depletion of natural resources is currently more important than ever (Rørbech et al., 2014).

The methods applied to assessment of the potential consequences associated with resource use frequently come from life cycle assessment (LCA) literature (Rørbech et al., 2014; Klinglmair et al., 2014). However, existing LCA models focus exclusively on the mid- to long-term geologic and economic finiteness of resources. They ignore other technological, geopolitical, regulatory and social risk factors (e.g. wars, market imbalances, governmental interventions or restrictions to mining due to environmental degradation) that may lead to supply disruptions and increasing commodity prices in the short term (Erdmann and Graedel, 2011; Schneider et al., 2014; Drielsma et al., 2016). Consideration of these additional risk factors in the evaluation of resource depletion impacts has recently emerged as a new research field

Abbreviations: MCDA, multi-criteria decision analysis; ELECTRE, ELimination and Choice Expressing Reality; SMAA-TRI, Stochastic Multicriteria Acceptability Analysis for ELECTRE TRI; IRIS, Interactive Robustness analysis and parameters' Inference for multicriteria Sorting problems; CAI, Class Acceptability Indices; C_i, Risk class *i*; g_j, Criterion *i*; w_i, Weight of criterion *i*; Pr_h, Class profile *h*; a_i, Alternative i; c a_i, Pr_h, Concordance index for considering alternative i at least as good as class profile h; λ, Lambda = minimum cumulative weight of the criteria to grant a classification; ‡, Cases where the coalition of six criteria is sufficient to grant the classification IRIS; *, Cases where fewer than six criteria trigger the classification with IRIS

* Corresponding author.
E-mail address: d.jasinski@warwick.ac.uk (D. Jasiński).
[1] Current address: Exergy Ltd, Design Hub, Coventry Technology Park, CV1 2TT, UK.
[2] Current address: Future Resilient Systems (FRS), Swiss Federal Institute of Technology (ETH) Zurich, Singapore-ETH Centre (SEC), Singapore.

https://doi.org/10.1016/j.resourpol.2018.04.011
Received 7 September 2017; Received in revised form 2 February 2018; Accepted 19 April 2018

Please cite this article as: Jasinski, D., Resources Policy (2018), https://doi.org/10.1016/j.resourpol.2018.04.011

and is known as 'minerals criticality assessment' (Drielsma et al., 2016; Helbig et al., 2016). The European Commission (EC) classes a raw material as critical when it faces high risks with regard to access to it, e.g. high supply risk or high environmental risks, and it is of high economic importance. EC (2010) Material criticality is determined by plotting the likelihood of supply disruption (the supply risk) against the vulnerability due to supply disruption, which can be interpreted as a measure of the economic importance of a raw material with consideration of potential direct substitution (Glöser et al., 2015).

Despite relevant contributions from, for example, the US National Research Council (Eggert et al., 2008), Yale University (Graedel et al., 2012; Nassar et al., 2012) and EC (EC, 2010, 2014, 2017; Chapman et al., 2013), minerals criticality assessment remains a new area of research with no widely agreed methodology developed to date (Glöser et al., 2015; Achzet and Helbig, 2013). The observed criticality studies differ with respect to (1) system under study (e.g. economy, country, company or technology), (2) criticality dimensions, (3) the choice of assessment criteria and indicators, (4) indicators weightings and aggregation method, (5) criticality assessment method (e.g. criticality index, criticality matrix or 3-dimensional vectors), (6) the reliance on quantitative data from third parties or expert judgement; and, (7) the degree to which the assessments are forward looking (or not) (Erdmann and Graedel, 2011; Achzet and Helbig, 2013).

While the choice of criticality dimensions, assessment criteria and weightings is subjective and associated with individual judgement, a consistent aggregation of criticality indicators into meaningful indices requires clear-cut methodological requirements (Böhringer and Jochem, 2007; Merad et al., 2004).

Criticality assessments are inherently based on multiple criteria, which calls for the use of multi-criteria decision analysis (MCDA) to provide a comprehensive evaluation. This evaluation can be provided in the form of a ranking, scoring or classification of raw materials by accounting for the evaluation criteria in an integrated manner.

MCDA is a process whose scope is to support decision makers (DMs) in structuring, understanding and solving a problem so that an informed decision can be recommended (Roy, 1996). It is emerging as a valuable strategy to carry out complex assessments due to its ability to effectively handle different types of information, include stakeholders' values and provide a transparent interpretation of the results (Cinelli et al., 2014; Balteiro-Dias et al., 2017). It has been widely used to support sustainability-related decision making (Diaz-Balteiro et al., 2017; Dias et al., 2015) and case studies have also emerged to evaluate criticality of raw materials (Schneider et al., 2014; Nassar et al., 2012; Bauer et al., 2011). The most used MCDA method in this area is the weighted sum approach (Erdmann and Graedel, 2011; Achzet and Helbig, 2013).

To date, the effect of uncertainties in data sets and variations in criteria weights have not been adequately addressed and the literature suggests that more research should be conducted to fill these research gaps and provide examples of robust assessments (Erdmann and Graedel, 2011; Glöser et al., 2015; Achzet and Helbig, 2013). This article is a response to this call by presenting the use of ELimination and Choice Expressing Reality (ELECTRE)-based methods to provide a classification system for the supply risk of raw materials, one of dimensions that determine a material's criticality (together with environmental implications and vulnerability to supply restriction) (Graedel et al., 2012). ELECTRE methods exhibit appealing advantages in comparison with other methods, such as weighted sum (Figueira et al., 2016): the weights of the criteria represent their "voting power" and are independent of their measurement scales, they are non-compensatory (they do not require trade-off rates), they allow performing sophisticated modeling through indifference, preference and veto thresholds and can accommodate any criteria without the need for any transformation.

In this paper we propose two novel contributions:

1. The development of an approach to assess the supply risk of raw materials;
2. The proposal of a synergistic use of MCDA methods to assign a risk class to each material by means of the integrated use of methods for ELECTRE-TRI based on algorithms for stochastic analysis (i.e. SMAA-TRI, Stochastic Multicriteria Acceptability Analysis for ELECTRE TRI) (Tervonen and Lahdelma, 2007) and optimisation (i.e. IRIS, Interactive Robustness analysis and parameters' Inference for multicriteria Sorting problems) (Dias et al., 2002).

To the best of the authors' knowledge, this is the first study of its kind to propose a classification system for raw materials criticality based on a synergistic use of classification methods, or based on driving robust conclusions from a set of weighting vectors.

The methodology adopted to select the evaluation criteria and indicators is presented in Section 2 together with the identification strategy of relevant MCDA methods. Section 3 presents the supply risk matrix and the robust classifications of the materials in risk levels. The results are presented in Section 4 demonstrating how the approach proposed in this paper can enhance the decision support potential of individual supply risk criteria and transparently inform DMs.

2. Materials and methods

2.1. Sample minerals and evaluation criteria

Sample minerals selected for this study are metals and metalloids used in automotive manufacturing. The automotive context in this paper derives from the fact that this research received support from a major British car manufacturer. Thirty-one minerals were selected based on the analysis of materials used to manufacture a diesel-hybrid vehicle, the most complex car in the company's range. The evaluation criteria selected in this study focus exclusively on supply risks (likelihood of supply disruption) associated with increased depletion of raw materials.

General guidelines to aid the assessment criteria selection process were proposed in the literature (Akadiri and Olomolaiye, 2012) and practically applied in the context of sustainable development. Akadiri et al. (2013); Cinelli et al., 2016; Jasiński et al., 2016 These guidelines are largely in line with the recommendations of the Organisation for Economic Co-operation and Development (OECD) and the European Commission Joint Research Centre (EC-JRC) for the construction and use of composite indicators. OECD (2008) The assessment criteria selected should be transparent (the selection process should be clear and understandable), comprehensive (i.e. they should measure each element of a multidimensional concept), applicable across a range of alternative options to ensure comparability and practical in the sense of the tools, time and resources available for analysis (Akadiri and Olomolaiye, 2012; Akadiri et al., 2013; Cinelli et al., 2016; Jasiński et al., 2016)

Following this set of guidelines, the supply risk assessment criteria were first identified based on the review of existing raw materials criticality studies (see Table S1 in Supplementary information for a summary). These criteria were then organised into six main areas of concern (geological, technological, economic, geopolitical, regulatory and social) (Graedel et al., 2012) to form a theoretical framework for the comprehensive supply risk assessment. Finally, all criteria were assessed against four attributes to evaluate whether a specific criterion is suitable to be used in the overall supply risk evaluation (OECD, 2008). These attributes were:

- **applicability** (the degree to which an indicator allows comparability of alternative options);
- **relevance** (the degree to which an indicator covers and contributes to the required topic and concept);
- **accessibility of the data** (the degree to which the data can be