Critical materials supply and risk

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Abstract
Rare earth Elements (REEs) are a subset of Critical materials (CMs) and are found in numerous modern electronic products and advanced technologies where, due to their unique physical and chemical properties, they cannot be substituted. Disruption in their supply chain has the potential to cause devastating impacts on production and consumers. To help manage such disruptions, this research focusses on the areas of critical materials, supply chain resilience, and supply chain risk. Research has established the challenges that can occur from disruptions caused by up-stream suppliers, necessitating supply-side resilience strategies. Supply-side risk factors associated with CMSs differ from conventional material supply chain risk, and it is advocated that they cannot be effectively managed through traditional material supply risk management practices. This study investigates the research on CMs that appears around the periphery of the OM (operations management) field by adopting a systematic literature review. Findings show a dearth of research work directly focused on REEs and CMs from within the OM field. Importantly, a call is made for OM researchers to investigate REEs and CMs based on the imperative that geopolitics, resource scarcity and environmental issues present.

Keywords: Critical materials, Natural resource scarcity, supply risk, resilience

Introduction

CMSs have unique physical and chemical properties that make them essential in the manufacture of a wide range of modern technologies and often cannot be substituted without loss of performance or functionality. A CM refers to a material where "*the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials*" (Hennebel *et al.*, 2015, p. 121).

Many CMSs can now be found in a variety of modern electronic products and advanced technologies due to their unique physical and chemical properties. They deliver significant performance improvements over alternative materials and in many applications are essential. This means they cannot be readily substituted without compromising functionality of a product (Graedel *et al.*, 2015). The global demand for CMSs is high and expected to continue to rise as new technological products using CMs are introduced to the marketplace (Dutta *et al.*, 2016; Eggert, 2017). Many countries that require CMSs for manufacturing have limited or no economically extractable domestic supply of most CMs. These countries are, therefore, dependent upon imports of CMS, raw materials, and CMs containing components for their manufacturing industries, and by extension, their economies.

Supply is not limited solely by the total global abundance of CMs but by a range of different factors including economic and political. For example, Rare Earth Elements (REE), a key sub-set of CMs, are assessed by nations and institutions as being highly critical and ranked as the most critical materials for the EU (European Commission *et al.*, 2017). Rare Earth Elements are actually relatively abundant globally, however, they are found in only a few locations worldwide in concentrations high enough to make them economically viable for extraction (King, 2022). The primary supply of CMs, therefore, are limited to just a few countries, thus the geopolitical factors surrounding international supply of CMs may be magnified as there may be few or no viable alternative origins of supply when supply issues arise. Geopolitical actions such as export quotas and tariffs have been seen to further compound supply issues and distort free market conditions of supply and demand.

Although there has been important work in consideration of supply risk and strategies related to CMs, also called materials of natural resource scarcity (NRS materials), (Lapko *et al.*, 2016; Kalaitzi *et al.*, 2019), there is an apparent gap in work more focused upon REE risk within the operations and SCM context. In this paper we follow-up on the call to further investigate critical materials scarcity and their potential impact upon manufacturing (Kalaitzi *et al.*, 2018) by identifying research trends in within operations and supply chain management studies and beyond. By looking at trends we can identify where further work needs to be undertaken to strengthen the knowledge base around managing the supply risk of CMs.

Background

Materials are an essential input for all manufacturing operations and maintaining a reliable and consistent supply is fundamental to its success (Zsidisin *et al.*, 2005; Tiess, 2010). Graedel *et al.* (2015, p. 1) defined "criticality" as "*the quality, state, or degree of being the highest importance*" whilst Frenzel *et al.* (2017, p.2) defined the criticality of a raw material as simply "*a measure of the (economic) risk arising from its utilisation (incl. production, use, and end-of-life) for a specific consumer over a certain period*". Further, "risk" is not exclusively economic and could also refer to environmental or societal risk (Frenzel *et al.*, 2015). It is important to note that virtually all criticality assessments are limited to non-fuel raw materials (Frenzel *et al.*, 2015; Blengini *et al.*, 2017). The word "critical" as a connotative expression in the context of material supply appears to have been first coined around the interwar period between the two world wars with "Strategic and critical materials" being defined by the US Munitions Board in 1944 (Haglund, 1984).

The EU and the USA consider Rare Earth Elements (REEs) as 'critical' due to their economic importance, scarcity of supply and the type of products that they are used in e.g., mobile phones, computers, wind turbines, and electrical vehicles. The increased global competition for REE has huge implications for manufacturing especially in high technology and high value-added industries. Fig.1 shows the importance of REEs to components in modern products.

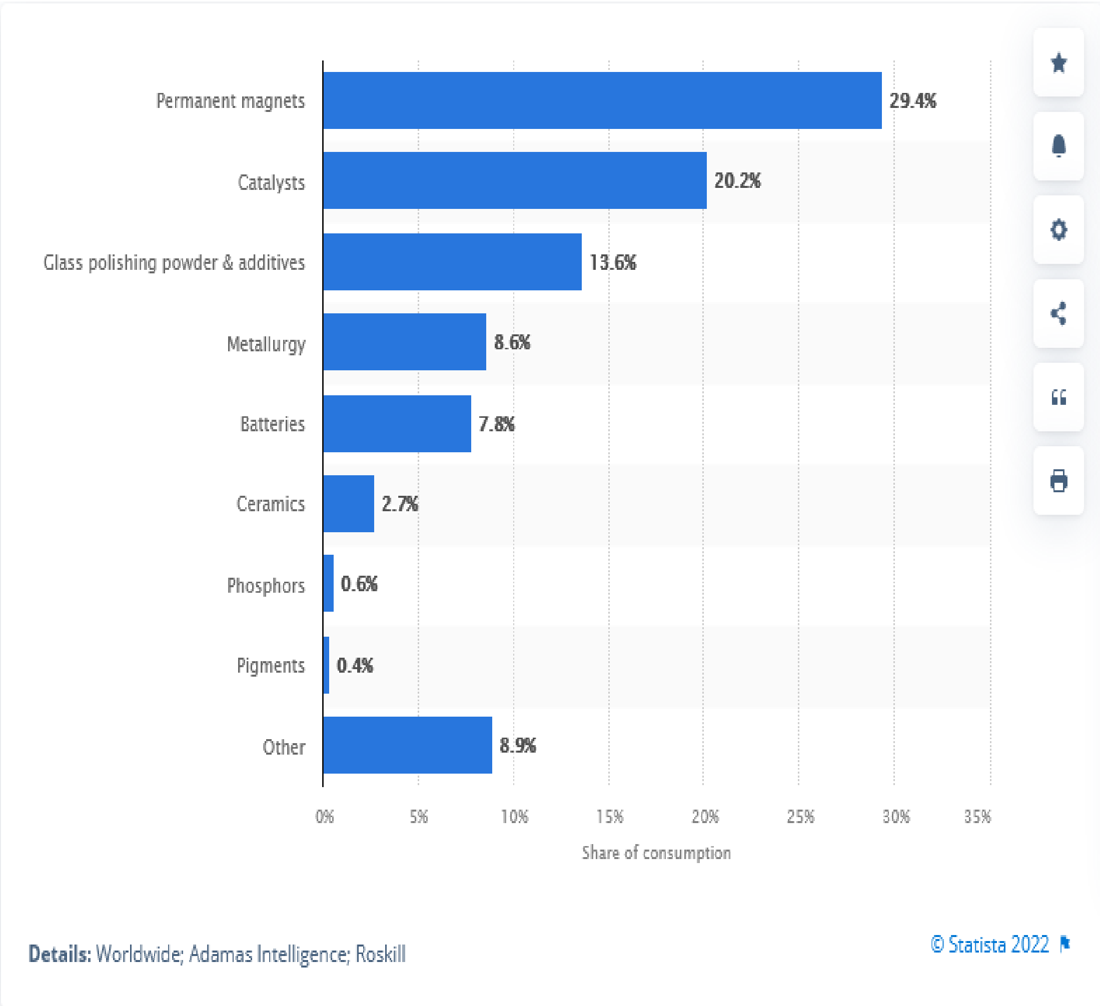

Figure 1 – Distribution of rare earth element consumption worldwide in 2020 (NRCan., 2022)

Two key aspects are clearly defined as crucial for the definition of critical raw materials: the economic importance of the material and a high risk of supply disruption (European Commission *et al.*, 2017). It follows, therefore, that material criticality will vary according to the economic priorities and circumstances of a particular region or country in which the company operates (Glöser *et al.*, 2015; Habib and Wenzel, 2016). Table 1 below shows the domination of China as the prime possessor and producer of REEs.

Table 1 – World production of REEs (Natural Resourcres Canada, 2022)

Ranking	Country	Thousand tonnes	Percentage of total
1	China	140.0	57.5%
2	United States	38.0	15.6%
3	Burma (Myanmar)	30.0	12.3%
4	Australia	17.0	7.0%
5	Madagascar	8.0	3.3%
-	Other countries	10.3	4.2%
-	**Total**	**243.3**	**100.0%**

It is, therefore, argued that criticality is not an inherent property of a material but a dynamic classification dependant on the time-period and circumstances surrounding the user (Graedel *et al.*, 2015). The aim of this work is to evaluate and bring together the current state of research in the areas of critical materials (CMS), natural resource scarcity (NRS) and supply risk from the operations and supply chain domain, in order to understand what knowledge currently exists, and where the future research direction needs to go in order to manage risk and ensure the supply of critical materials.

Methodology

A systematic literature review was adopted to provide an organised approach to synthesise the literature (Roy *et al.*, 2018). The systematic literature review followed the guidelines set out by Tranfield *et al.* (2003, p. 214) and Durach *et al.* (2017, p. 70). The first stage was defining the research question (identifying, preparing and developing the review); the second stage was defining inclusion/exclusion criteria (identification of research and study selection); the third stage was retrieving a sample of literature (undertaking the quality assessment); the fourth stage was selecting relevant literature (extracting data); the fifth stage was synthesising the literature; and the sixth stage was reporting the results (demonstrating evidence of practice). Similar to Durach *et al.* (2017), we reduced our data set down to articles published in the area of operations and supply chain management.

Data Collection and analysis

The databases used to conduct our review were Scopus, Emerald, Taylor & Francis, and Business Source Premier (EBSCO). Our search criteria used the keywords ‘critical materials’, ‘natural resource scarcity’, and ‘supply risk’. These search terms were applied to the title, keywords and abstract of potential publications. The search was done for all years available from the databases searched. In the first instance our review included peer-reviewed journal articles, books, conference papers. This resulted in 981 articles being identified. The references including abstracts and keywords were imported into EndNote. Due to page the limit constraint for this conference paper, we decided to select papers for study that appear in the ‘operations and technology’ section of the Academic Journal Guide (2021) (informally known as ABS list https://charteredabs.org/academic-journal-guide-2021/#how-to-use), covering operations and supply chain management subjects. In order to capture additional relevant articles, and although not strictly operations and SCM journals, we include relevant papers that appear in the ABS journal guide but cross-over and have implications for the field, specifically, Resources Policy and the Journal of Cleaner Production. A second filtering stage to capture only those articles occurring in journals listed in the ABS list reduced articles to 228 in number.

Results and Discussion

Table 2 below presents elementary findings that show the number of articles on the topics found in each journal and the number of articles whose principal focus is either operations management or REEs. The immediately noticeable fact being the very low number of articles on CMs. Due to this shortage of articles related directly to REEs found within ABS list journals, we continued to search for articles beyond the list in order to capture a wider and inclusive review of REE materials publications and their implication for operations and SCM. The following sections firstly discuss the spareness of articles related to REEs/CMs discovered from within OM journals. The subsequent four sub-sections reveal the relevant work outside the conventional OM publications field where the significant issues of materials availability, geopolitics, environment and 'the balance problem' are discussed.

Table 2 – Articles from key Operations and SCM journals listed in the Academic Journal Guide (2021)

Journal	No. of articles	Principal Relevance	
		Operations & Supply Chain Management	Rare Earth Elements/Critical Materials/Natural Resource Scarce materials
International Journal of Operations and Production Management	8	6	2
International Journal of Production Economics	15	14	1
International Journal of Production Research	96	95	1
International Journal of Supply Chain Management	3	3	-
Supply Chain Management: An International Journal	7	7	-
Supply Chain Management	17	17	-
Journal of Business Logistics	4	3	1
Journal of Purchasing and Supply Management	6	5	1
Production Planning & Control	17	17	-
International Journal of Physical Distribution & Logistics Management	7	6	1
IEEE Transactions on Engineering Management	2	2	-
Resources Policy	28	10	18
Journal of Cleaner Production	18	11	7
Total	**228**	**196**	**32**

Sparce mention of REEs in operations and SCM research

The data show from Table 2 that from 228 seemingly relevant articles only 32 directly deal with the issues of CMs, REEs and NRS, and where only 7 of these articles were published in operations and SCM journals. This confirms the dearth of research conducted from within the field and is potentially also an insight into research interests and drivers. What is more likely however is our belief that researchers may often follow popular topics as journals have a pattern of behaviour in publishing them – therefore the growth of topics like for instance, 'decision making in SCM', although important, has become a self-fulfilling prophesy and attracts a plethora of researchers' application.

Further, Operations and SCM researchers' natural concerns are with efficiency and effectiveness of manufacturing operations, and this is unambiguously reflected in articles published within this field. The study unsurprisingly finds that the following themes were most researched: risk and decision making for supply chains (He, 2013; Kumar *et al.*, 2018; Vanalle *et al.*, 2020; Vanpoucke and Ellis, 2020); supply chain disruption mitigation (Kaufmann *et al.*, 2016; Kamalahmadi and Parast, 2017); supply chain resilience (Thun *et al.*, 2011; Vanpoucke and Ellis, 2020; Taghizadeh *et al.*, 2021); and for supply chain strategies for NRS materials, only a few were found (Bell *et al.*, 2012; Kalaitzi *et al.*, 2018; 2019).

Rare earth materials availability

Mineral deposits are distributed unevenly across national boundaries due to the extremely heterogeneous geology of the Earth. The concentration of these minerals combined with their value and associated demand are usually the main determining factors in whether they can be extracted commercially. Although absolute geological scarcity is not the main issue with regards to REE, the minable deposits are less common than for most other ores (Massari and Ruberti, 2013; Van Gosen *et al.*, 2014).

Geopolitics

Geopolitics play a key factor in the availability of materials as not only do geopolitical boundaries define which national governments have sovereign rights for extraction, but they also define the legal framework regulating extraction. The attractiveness for economic activity for a nation will determine the production of its naturally occurring materials. However national and international policies can hugely affect the availability of certain material on the international market (European Commission, 2017). Many economies, especially emerging ones are adopting certain policies in an attempt to reserve their indigenous resource base for their own exclusive utilisation (Tiess, 2010; Alonso *et al.*, 2012; Massari and Ruberti, 2013; Wrighton *et al.*, 2014). Different nations are using various industrial development strategies that include instruments of investment, trade and taxation formulated to ensure export quotas, taxes and subsidies can secure domestic supply often at the expense of foreign exports, a not uncommon and recent example being China's control of REEs (Wübbeke, 2013; Sprecher *et al.*, 2015). This has meant that certain materials are not exported to other economies in the quantities that otherwise would occur under conventional free-market conditions. Many of these measures in use today are currently being challenged by global stakeholders through channels utilising trade agreements and trade alliances such as the World Trade Organisation (WTO). These geopolitical factors affecting global supply are magnified and become especially significant where production of a material is highly concentrated in just a single or few countries such as in the case of REE (Kanazawa and Kamitani, 2006; Tiess, 2010; Alonso *et al.*, 2012; Baldi *et al.*, 2014).

Environmental issues

There are significant environmental impacts associated with the extraction and primary processing of REE. These include high levels of water consumption; energy inputs and chemicals use (Edahbi *et al.*, 2019). Many REE mineral deposits are also associated with high concentrations of radioactive elements including uranium and thorium which require specialist treatment and disposal to ensure they do not contaminate soils or aquifers (Hong, 2006; Yang *et al.*, 2013; McLellan *et al.*, 2014). There have been many documented incidents resulting from REE processing including radioactive pollution in Malaysia (Halog *et al.*, 2001) and severe contamination of both the soil and surface and groundwater in China with heavy metals, toxic chemicals and radioactive elements (Li *et al.*, 2013). The allocation of land for mining and processing REE is another issue that has caused problems in producing countries particularly when most REE extraction sites active today are developed using opencast techniques (Edahbi *et al.*, 2019). This means that to access the ore the existing ecosystems are either removed or covered over by waste rock, tailings dams and processing plants. Any areas of ecosystem left undisturbed by these practices are still often fragmented by service infrastructure which can have a detrimental effect on the healthy functioning on the remaining ecosystem. There is therefore a real need to reduce the incursion of REE mining into balanced ecosystems to ensure their long-term survival (Li *et al.*, 2013; Rim *et al.*, 2013; Yang *et al.*, 2013; Adibi *et al.*, 2014; McLellan *et al.*, 2014).

Material coupling and balance problem

Many NRS materials are produced as by-products of the extraction and production processes of other materials. This means that the supply of one required raw material is coupled with, and often completely dependent upon, the extraction of a completely separate material regardless of the difference in actual demand for the separate materials (Klyucharev *et al.*, 2013; Bustamante and Gaustad, 2014). Often there is a large-volume resource that is the primary target for extraction, 'carrier material' such as industrial metals like copper, aluminium or zinc that is extracted along with a much smaller volume resource such as Tantalum. The smaller volume secondary material is often present as an impurity within the larger volume primary mineral and usually is simply a by-product of extraction rather than a targeted resource. This 'material-coupling' causes what is known as the Balance Problem (Bustamante and Gaustad, 2014). Neodymium for example is a key REE for many critical applications including permanent magnets used in wind turbines and electric vehicles. Primary mining of ores for neodymium generates an excess of the more abundant elements lanthanum and cerium. Therefore, in this example an effective reuse and recycling strategy for neodymium that reduces the requirement for neodymium extraction would have an even greater effect on reducing the total amount of REE required to be extracted as the linked reductions in non-target REE extraction would be proportionally greater (Falconnet, 1985; Binnemans and Jones, 2014).

The extraction processes (mining) of industrial minerals involves relatively long timescales comprising identification, planning and the facilitation of extraction and processing, can typically take 8-10 years in Europe. This means temporal factors of supply may be extremely inelastic compared with the relatively dynamic nature of increased material demand. The availability of the primary target material therefore largely determines the availability of the secondary material. Likewise the demand for, and thus the amount of, extraction of the large-volume target mineral indirectly dictates the supply of the secondary material with a complete disconnect to the variance of demand (Bustamante and Gaustad, 2014). The disconnect between material supply and material demand of the secondary material can have enormous implications on the availability and price of a material in the global market and lead to the occurrence of market crises. The price of REEs have significantly increased in recent years due to geopolitical and sustainability drivers. This has resulted in volatility on the stock market performance of some clean energy indices (Dutta *et al.*, 2020) and this effect should be relevant to policy makers with regards to actions supporting the development of the clean energy industry (Massari and Ruberti, 2013; Baldi *et al.*, 2014; Bustamante and Gaustad, 2014).

Conclusions

It was found that there is a dearth in publications that deal with NRS materials and particularly REEs, within the field of operations and SCM. If the manufacturing industry is to be resilient to this known CMs supply risk, there is a need for the issue of CMs availability to be addressed right across the board at international, national, company and product level. CMs resilience is particularly important as materials deemed CMs are critical for the viability and sustainability of many manufacturing operations and high technology products in key industries. This scarcity of articles on critical materials and their potential impact on production operations, supply chains, products and ultimately the consumer, presents a real opportunity for future work in this important but apparently overlooked niche. In the light of geopolitical economics, security and sustainability imperatives, the findings assert the position that this topic must be more actively pursued from within the field of operations and SCM.

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