



A framework for firm-level critical material supply management and mitigation

Gillian Griffin^a, Gabrielle Gaustad^{a,*}, Kedar Badami^b

^a Golisano Institute for Sustainability, Rochester Institute of Technology, 111 Lomb Memorial Drive, Rochester, NY 14623, United States

^b Lean Manufacturing, Mettler-Toledo International, Inc., 5 Barr Rd, Ithaca, NY 14850, United States

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ABSTRACT

Organizations of all sizes are vulnerable to critical material supply disruptions. Although there is a significant body of literature that examines how large entities such as nations and governments can assess and mitigate criticality, there is very little work that addresses firm-level criticality in a way that is actionable for businesses. This work uses literature review and case study analysis to understand the impact of critical material supply risk at the firm level, and to determine salient internal indicators. A total of 42 criticality studies were reviewed and the findings were used to develop a matrix to assess and monitor criticality risk using internal firm-specific data. The matrix incorporates three categories of risk including product concept viability, production, and profitability. It also contains four key business functions including finance, procurement, marketing, and production. These aspects were chosen because they are relevant to all businesses that produce and sell manufactured goods, and because they represent dynamics that are within the control of an individual firm. Unlike the global and national level indicators emphasized in most current research, the indicators proposed in this research are derived from data that firms can compile with reasonable ease. Finally, this work considers the role of the organization in criticality risk assessment and mitigation through an examination of the data needed to complete the aforementioned matrix and the likely sources of that information. The findings of this analysis elucidate the gap between internal and external and micro- and macro- criticality assessment, as well as provide a framework for firm-level criticality mitigation.

1. Introduction

The extraction and use of raw metals for the production of goods and technologies has increased by 19 times over the past 100 years. The use of some individual metals, such as aluminum, has increased by a factor as high as 1000 (Graedel, Barr et al., 2012). Because these raw materials are used by a rapidly growing global population for a wide range of products, demand is expected to increase further. The rapid consumption of some of these finite resources—such as cobalt, rhenium, platinum group metals, and rare earth elements—is noteworthy because these materials are strategically important for renewable and clean energy technologies as well as national defense. Referred to as critical materials, the minerals and metals needed for these sectors must be monitored and managed to mitigate risk and promote the sustainable development of the technologies that depend upon them. There is a large body of literature that examines how nations and governments can assess and mitigate criticality (Graedel and Reck, 2016). However, most firms lack a standard way to track and measure the risk of critical

material supply disruptions that is adaptable to their specific business operations and strategies. In addition, firms have little control or leverage on the external factors emphasized in many current criticality assessment methodologies. This research quantifies impacts to firms from supply chain disruption and proposes a method to address risk monitoring using metrics and organizational structure inherent to most companies.

1.1. Why should firms care about critical materials?

The precise definition of a critical material varies but here we focus on two dimensions for firms: (a) supply disruptions and (b) high economic and/or strategic importance.

1.1.1. Supply disruption

Critical material supply disruptions are caused by many different and often interdependent dynamics. For example, scarcity concerns the physical availability of materials and can be measured by factors such

* Corresponding author.

E-mail address: gxgtcc@rit.edu (G. Gaustad).

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as crustal abundance, reserve levels, mine production, static depletion times, and national stockpiles (Alonso et al., 2007). Other factors that can cause supply disruption include natural disasters, politics, conflict, production bottlenecks, and lack of producer diversity (Alonso et al., 2007).

Some materials have codependence with primary production, for example cobalt and tellurium are commercially obtained as a byproduct of copper mining. This can cause supply issues as an increase in demand of the byproduct material may not have an economic impact on the production of the parent material (Bustamante and Gaustad, 2014). Import reliance and lack of producer diversity may exacerbate other supply issues (Bustamante and Gaustad, 2014; Buijs and Sievers, 2011; Gunn, 2014). Geopolitical risk is defined as political and governance activity across the globe that may restrict or limit critical material availability. Components of this category may include conflict, political instability, violence, government trade policies and interventions, corruption, and government effectiveness.

Volatility in demand may cause supply risk due to unbalanced markets, competing technology demand, and artificial inventory fluctuations across the supply chain (i.e. the bullwhip effect). Ecological damage that occurs as a result of raw material extraction and processing, such as soil degradation, air pollution, water contamination, and loss of biodiversity may cause supply risk issues if producing firms cannot keep up with regulatory compliance.

For each cause of supply disruptions there are multiple indicators used to identify supply risk. Achzet and Helbig (2013) found that the most frequently observed indicators are country risk, country production concentration, depletion time, and byproduct dependency. The next most frequently observed indicators are company concentration in mining corporations, demand growth projections followed by recycling and recyclability, substitutability, import dependence, and commodity prices (Achzet and Helbig, 2013). Less common indicators include things such as production costs in extraction, stock keeping, mine/refinery capacity, future market capacity, and investment in mining (Achzet and Helbig, 2013).

1.1.2. Economic and strategic importance

A key impact of critical material supply disruption is market vulnerability to sudden price spikes (Duclos, Otto et al., 2010; Graedel, Barr et al., 2012). Price spikes affect firm competitiveness by creating uncertainty in costs, product pricing, earnings, and credit availability, thus affecting short-term profitability and long-term survival (Agarwal et al., 2012). Surveys and reports published by leading business consulting firms highlight this as a growing concern among modern businesses and the academic literature supports these findings (Agarwal et al., 2012; Schoolderman and Mathlener, 2011). Additional studies (e.g. (Chapman et al., 2002; Helferich and Cook, 2002; Martha and Subbakrishna, 2002)), have also reported costly consequences of disruptions.

Recent emphasis on lean supply chain management principles in corporations makes firms more vulnerable to supply disruptions because they tend to have limited stockpiles. It also poses significant challenges for supply chain managers tasked with maintaining operational efficiencies while also increasing supply resilience (Hendricks and Singhal, 2005a). Material shortages can slow or halt production in manufacturing plants, increase costs, and quickly diminish a firm's competitive advantage and revenue. For example, in early 2000, a phone chip supply disruption caused by a fire in a manufacturing plant impacted two companies, Nokia and Ericsson. Nokia responded aggressively to the supply disruption by securing alternate suppliers, modifying product designs to accommodate different chips, and communicating regularly with the original manufacturer. Ericsson was slow to take action and therefore unable to expediently secure an alternate supplier. As a result, the company sustained an estimated revenue loss of \$400 million and soon after exited the consumer cell phone market (Sheffi and Rice Jr, 2005).

As demonstrated in the Ericsson case, negative consequences of critical material supply disruptions in sectors such as manufacturing, transportation, electric power, and telecommunications can be enduring and can impact multiple business sectors. In a study of supply chain disruptions in publicly traded firms, Hendricks and Singhal found that stock returns, share price volatility, and profitability are all negatively impacted by supply disruptions (Hendricks and Singhal, 2005a; Hendricks and Singhal, 2005b). Across nearly 800 disruptions analyzed, stock returns were found to drop, on average, 33–40% over a three year time period and, notably, Hendricks and Singhal assert that this underperformance can be observed in the year prior to the supply disruption (Hendricks and Singhal, 2005a). Share prices were found to have 13.5% higher volatility in the year following the supply disruption than in the year prior to the disruption (Hendricks and Singhal, 2005a). In terms of impact to firm profitability, Hendricks and Singhal reported that, on average, firms that experienced a supply disruption faced an operating income decrease of 107%, a drop in return on sales of 114%, a drop in return on assets of 93%, 7% lower sales growth, 11% growth in cost, and 14% growth in inventories (Hendricks and Singhal, 2005b).

In terms of recovery, Hendricks and Singhal found that it can take two or more years to return to the performance levels prior to a disruption (Hendricks and Singhal, 2005a). Some firms never return to the same performance levels that existed prior to the disruption (Sheffi and Rice Jr, 2005). Additionally, firms lack clear contingency plans and well-defined roles for managing disruptions. Mitroff and Alpaslan assessed the crisis readiness of Fortune 500 companies over two decades and found that 75–95% of companies analyzed were not prepared for any kind of disruptive event (Mitroff and Alpaslan, 2003). This was further corroborated by Hillman and Keltz (Hillman and Keltz, 2007).

1.2. Current approaches to criticality assessment

A criticality is something of extreme importance, and the process of criticality assessment involves identifying essential assets and determining the consequences of loss, disruption, and/or failure. In this case, the criticalities are various raw physical materials (i.e. critical materials), needed by various stakeholders (e.g. nation states, global humanitarian organizations, environmental organizations, research firms, corporations, etc.), for production of goods in a variety of sectors (renewable and clean energy technologies, industry, and national defense, etc.).

A review of 42 of the most relevant criticality studies to date was conducted in an effort to understand how criticality is currently being assessed. These studies include peer-reviewed journal articles, research project reports, and policy reports. We conducted our search using Google Scholar, ScienceDirect, Wiley Online Library, and Web of Science. Keywords queried include critical material supply risk, critical material framework, criticality assessment, criticality matrix, raw materials criticality, and raw material assessment. The overall set of literature identified included topics such as material recovery and recycling, demand forecasting, supply chain resilience, supply chain management, crisis readiness, and criticality assessment methodologies. We focused on studies that specifically addressed criticality assessment and that did so using a defined scope, explicit risk indicators, and a model, matrix, or framework. For broad studies that didn't address firm-level criticality assessment we relied on the more highly cited works. We did not use any criteria for firm-level studies. Our goal was to identify all literature that incorporated a firm-level scope.

The metrics used in each study can be organized into six broad categories as follows, with significant overlap among these categories.

- *Scarcity risk* concerns the physical availability of critical materials. Indicators may include crustal abundance, reserves, mine production, static depletion times, stockpiles, substitutability, and recycling.
- *Geopolitical risk* quantifies risk stemming from political and

governance activity across the globe that may restrict or limit material availability. Geopolitical dynamics impact the export, pricing, and regulations of materials supplied. The most commonly used indicator is the Herfindahl-Hirschman Index (HHI) which can show the presence of monopolies. The World Governance Indicators (WGI) are the primary geopolitical stability indicators used to weight the HHI. This category also includes regulatory and compliance indicators.

- *Demand risk* is a key determinant of material availability that considers the volatility of demand relative to a supplier's ability to scale up or down. It is most often assessed using demand projections derived from sources like consultancy and market analyst reports, expert opinion, and assumed annual growth rates relative to economic growth.
- *Environmental risk* considers environmental damage that may occur as a result of raw material extraction and processing. The primary tool used for this assessment is the Environmental Performance Index (EPI). Life cycle assessment (LCA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), are also used to assess environmental risk.
- *Supply chain risk* refers to factors that can influence material procurement due to suppliers, manufacturers, and distributors of critical materials. Examples include the number of suppliers of a given material as well as the physical concentration of a material in a particular geographic area (e.g. a country).
- *Market risk* is a determinant of the market viability of products that rely on critical materials. The primary factor of market risk in this context is material price. Indicators include price volatility, price spikes, cost competition, and ability to pass on increased costs to consumers. One example of market risk is a price spike due to rapid market adoption of products containing critical materials such as electric vehicles or solar panels. Another example is competing demand for critical materials due to emerging technologies in different industries and/or novel applications of critical materials.

Although the actual materials assessed and the specific metrics used vary from one study to the next, each study aims to assess criticality in terms of vulnerability to supply disruptions. The studies reviewed represent criticality metrics in addition to those proposed by the U.S. National Research Council (NRC) in 2008. The NRC was among the first research groups to suggest metrics that consisted of two key dimensions of criticality: supply risk and impact of supply disruption. All of the evaluated studies are listed in Table 1.2.1.

The major point of distinction among the studies reviewed is the scope of each criticality assessment, which varies from global to European to national to firm level. Of the 42 studies, 10 assess criticality at the global level exclusively (Buchert et al., 2009; Rosenau-Tornow et al., 2009; Bauer et al., 2010; Bauer et al., 2011; Brown et al., 2011; Achzet and Helbig, 2013; Helbig et al., 2017; Sustainability, Survey et al., 2017; Brown, 2018; Jasiński et al., 2018), four focus exclusively on Europe (EC, 2010; EC, 2014; Deloitte Sustainability et al., 2017; Blengini et al., 2017), nine focus exclusively at the national level (Council, 2008; Morley and Eatherley, 2008; Angerer et al., 2009; AEA Technology, 2010; AEA Technology, 2011; Hatayama and Tahara, 2015; Glöser-Chahoud et al., 2016; Bach et al., 2017; Daw, 2017), and 11 focus exclusively on the corporate or firm level (Duclos et al., 2010; Lloyd et al., 2012a; Lloyd et al., 2012b; Nieto et al., 2013; Bensch et al., 2015; Gardner and Colwill, 2016; Lapko et al., 2016; Miehe et al., 2016; Hallstedt and Isaksson, 2017; Gardner and Colwill, 2018; Kolotzek et al., 2018). An additional seven studies address the global, national, and firm levels (Graedel et al., 2012; Graedel et al., 2014; Graedel et al., 2015b; Graedel et al., 2015b; Nassar et al., 2015; Helbig et al., 2016; Knobloch et al., 2018). The final study in the group of 42 focuses on the global and national level (Nassar et al., 2015). There is a useful diversity of approaches within each scope as well. The British Geological Survey provides a supply risk assessment index that considers factors

that effect material availability for 42 elements at the global level (Brown et al., 2011). Conversely, the Öko Institute provides assessment methodology for just a select few materials required for renewable and energy efficient technologies at the global level (Buchert et al., 2009). The parameters of the studies conducted on a national level differ by country. Developed nations such as the U.S., the U.K., and Germany each focus on criticality assessment methods that affect their respective economies specifically.

As evidenced by the literature discussion above and in Appendix A of the supplemental information, the majority of the existing work on criticality assessment focuses on risk quantification derived from primarily external factors (e.g. geological and economic availability, policy and regulation, geopolitical risk, environmental, etc.). While fundamentally relevant to criticality, external factors can't be directly controlled by individual firms. For example, some of the most frequently used indicators concern supply from a geopolitical perspective. These include the Policy Potential Index, the Human Development Index, the World Governance Indicators, and the Fund for Peace's Failed State Index. Intended to capture risk in the countries that supply critical materials (due to things like taxation and regulation, vulnerability to political conflict or collapse, standard of living, government corruption, and likelihood of violence), these indicators are even further outside the sphere of influence of an individual firm. Nevertheless, 10 out of 11 firm-level studies incorporated one or more indicators in the geopolitical category (Rosenau-Tornow et al., 2009; Duclos et al., 2010; Lloyd et al., 2012a; Lloyd et al., 2012b; Nieto et al., 2013; Bensch et al., 2015; Lapko et al., 2016; Miehe et al., 2016; Hallstedt and Isaksson, 2017; Kolotzek et al., 2018).

While a majority of the studies incorporated demand indicators, only four of the 11 studies that consider the firm-level perspective incorporated such indicators in their assessment methodologies (Duclos et al., 2010; Bensch et al., 2015; Lapko et al., 2016; Kolotzek et al., 2018). Demand is relevant to any business and as such, most firms use forecasting tools to predict future product sales for themselves and competitors within their industry. However, forecasting for other industries that might compete for the same materials is often outside of a firm's scope.

Although many studies did include some criticality indicators that are environmental in scope, these were primarily regulatory in nature. From a business perspective, the implication here is that environmental indicators of criticality, such as material recovery potential, recyclability, and R&D funding committed to the development of substitute materials, aren't relevant to firms. Also absent from studies reviewed in this work are metrics related to lost profit correlated to environmental harm caused by a firm's use of critical materials, or lost profit due to negative media exposure related to that environmental harm. Furthermore, no studies could be found that consider specific environmental impacts such as air, land, and water pollution, carbon emissions, or hazardous waste, as they specifically relate to obtaining and using critical materials at the firm level. In their work on material supply chain resilience, Sprecher et al. report that environmental considerations were omitted from their framework altogether because their interviewees indicated little to no concern for them (Sprecher et al., 2015). A total of 13 regulatory and compliance indicators were found in the environmental, geopolitical, and supply chain categories; all of them were external and none of them directly considered environmental impact caused by firms or any downstream effect to firm profit. These indicators are listed in Table 1.2.2.

Existing literature disproportionately addresses criticality risk on an aggregate basis (e.g. industry, national, and global), with few studies considering the impacts of material criticality at the individual firm level. This is not surprising given the resources needed to collect data with such a massive scope. Measuring and assessing factors such as geological availability and geopolitical risk on a global scale is extremely challenging because the necessary data collection is complex, dynamic, expensive, and time consuming. It also requires someone to

Table 1.2.1
Criticality Assessment Literature Summary.

	Author(s)	Affiliated Institution(s)	Scope(s)	Title
1	AEA Technology (2010)	Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) Scottish Environment Protection Agency (SEPA) Northern Ireland Environment (NIEA)	Scotland	Raw Materials Critical to the Scottish Economy
2	Achzet and Helbig (2013)	University of Augsburg	Global	How to Evaluate Raw Material Supply Risks – An Overview
3	AEA Technology (2010)	Department for Environment, Food and Rural Affairs	UK	Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability
4	Angerer et al. (2009)	Fraunhofer ISI	Germany	Raw Materials for Emerging Technologies
5	Bach et al., (2017)	Technische Universität Berlin	National	Enhancing the assessment of critical resource use at the country level with the SCARCE method–Case study of Germany
6	Bauer et al. (2010)	U.S. Department of Energy	Global	Critical Materials Strategy
7	Bauer et al. (2011)	U.S. Department of Energy	Global	Critical Materials Strategy
8	Bensch et al. (2015)	University of Augsburg	Firm	Decision Support System for the Sustainability Assessment of Critical Raw Materials in SMEs
9	Blengini et al. (2017)	European Commission, DG Joint Research Centre, Ispra, Italy European Commission, DG Joint Research Center, Petten, Netherlands European Commission, DG GROW Brussels, Belgium Politecnico di Torino	EU	EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements
10	Brown (2018)	British Geological Survey	Global	Measurement of mineral supply diversity and its importance in assessing risk and criticality
11	Buchert, Schüler et al. (2009)	Öko-Institut e.V. United Nations Environment Programme	Global	Critical Metals for Future Sustainable Technologies and their Recycling Potential
12	British Geological Survey (2015)	British Geological Survey	Global	Risk List 2015: An update to the supply risk index for elements or element groups that are of economic value
13	Daw (2017)	Université Paris	National	Security of mineral resources: A new framework for quantitative assessment of criticality
14	Duclos et al. (2010)	GE	Firm	Design in an Era of Constrained Resources
15	European Commission (2010)	Fraunhofer ISI	EU	Critical Raw Materials for the EU
16	European Commission (2014)	Fraunhofer ISI Oakdene Hollins Roskill	EU	Report on Critical Materials for the EU
17	European Commission (2017)	Deloitte Sustainability British Geological Survey Bureau de Recherches Géologiques et Minières Netherlands Organisation for Applied Scientific Research	EU	Study on the Review of the List of Critical Raw Materials
18	Gardner et al. (2016)	Loughborough University	Firm	A Framework for the Resilient Use of Critical Materials in Sustainable Manufacturing Systems
19	Gardner et al., (2018)	Loughborough University	Firm	A framework and decision support tool for improving value chain resilience to critical materials in manufacturing
20	Glöser-Chahoud et al. (2016)	Fraunhofer ISI	National	Taking the Step towards a More Dynamic View on Raw Material Criticality: An Indicator Based Analysis for Germany and Japan
21	Graedel et al. (2012)	Yale University	Global National Firm	Methodology of Criticality Determination
22	Graedel et al., (2014)	Yale University	Global National Firm	Metal resources, use and criticality (in <i>Critical Materials Handbook</i>)
23	Graedel et al. (2015)	Yale University	Global National Firm	On the Materials Basis of Modern Society
24	Graedel et al., (2015)	Yale University	Global National Firm	Criticality of metals and metalloids
25	Hallstedt et al. (2017)	Blekinge Institute of Technology	Firm	Material Criticality Assessment in Early Phases of Sustainable Product Development
26	Hatayama and Tahara (2015)	National Institute of Advanced Industrial Science and Technology	National	Criticality assessment of metals for Japan's resource strategy

(continued on next page)

Table 1.2.1 (continued)

	Author(s)	Affiliated Institution(s)	Scope(s)	Title
27	Hatayama and Tahara (2018)	National Institute of Advanced Industrial Science and Technology	Global	Adopting an objective approach to criticality assessment: Learning from the past
28	Helbig et al. (2016)	University of Augsburg	Global National Firm	How to Evaluate Raw Material Vulnerability – An Overview
29	Helbig et al. (2017)	University of Augsburg	Global	Benefits of resource strategy for sustainable materials research and development
30	Jasiński et al. (2018)	University of Warwick University of Coimbra University of Sheffield	Global	Assessing supply risks for non-fossil mineral resources via multi-criteria decision analysis
31	Knobloch et al. (2018)	University of Bremen Ökopol – Institute for Environmental Studies	Global National Firm	From criticality to vulnerability of resource supply: The case of the automobile industry
32	Kolotzek et al. (2018)	University of Augsburg	Firm	A Company-Oriented Model for the Assessment of Raw Material Supply Risks, Environmental Impact and Social Implications
33	Lapko et al. (2016)	Politecnico di Milano KTH Royal Institute of Technology	Firm	The Business Perspective on Materials Criticality: Evidence from Manufacturers
34	Lloyd et al. (2011)	Rolls Royce	Firm	Ecodesign through Environmental Risk Management: A Focus on Critical Materials
35	Lloyd et al. (2012)	Rolls Royce	Firm	A Framework for Environmental Risk Management
36	Miehe et al. (2016)	Fraunhofer ISI	Firm	Criticality of material resources in industrial enterprises – Structural basics of an operational model
37	Morley and Eatherley (2008)	Resource Efficiency Knowledge Transfer Network Oakdene Hollins	UK	Material Security: Ensuring Resource Availability for the UK Economy
38	Nassar et al. (2015)	Yale University	Global National Firm	By-Product Metals are Technologically Essential but Have Problematic Supply
39	Nassar et al. (2015)	Yale University	Global National	Criticality of the rare earth elements
40	Nieto et al. (2013)	The Pennsylvania State University	Firm	Addressing Criticality for Rare Earth Elements in Petroleum Refining: The Key Supply Factors Approach
41	National Research Council (2008)	The National Academies	US	Minerals, Critical Minerals, and the U.S. Economy
42	Rosenau-Tornow et al. (2009)	Volkswagen AG Federal Institute for Geosciences and Natural Resources (BGR)	Global	Assessing the Long-Term Supply Risks for Mineral Raw Materials – a Combined Evaluation of Past and Future Trends

Table 1.2.2
Regulatory and Compliance Indicators.

Indicator	Category	Study
Impact of ecological implications on biodiversity (using ReCiPe)	Environment	Bensch et al. (2015)
Environmental regulation (e.g. policy decisions, legislation)	Environment	Gardner et al. 2018 ; Hallstedt et al. 2017 ; Nieto et al. (2013)
Socio- and ecological impact risk	Environment	Hallstedt et al. 2017
Anthropogenic vs. natural flows	Environment	Hallstedt et al. 2017
Impact of ecological implications on human health (using ReCiPe)	Environment	Bensch et al. (2015)
Likelihood of substance becoming unavailable due to the Registration, Evaluation, Authorization and Restriction of Chemicals regulation (REACH)	Environment	Lloyd et al. (2012a)
Electric vehicle (ELV) directive non-compliance	Environment	Lapko et al. (2016)
Registration, Evaluation, Authorization and Restriction of Chemicals regulation (REACH) non-compliance	Environment	Lapko et al. (2016)
Restriction of Hazardous Substances (RoHS) non-compliance	Environment	Lapko et al. (2016)
Waste Electrical and Electronic Equipment (WEEE) non-compliance	Environment	Lapko et al. (2016)
Emissions legislation non-compliance	Geopolitical	Lapko et al. (2016)
The California Transparency in Supply Chains Act (re: human trafficking and slavery)	Supply Chain	Lapko et al. (2016)
Conflict Elements	Supply Chain	Gardner et al. 2018 ; Hallstedt et al. 2017

acquire, manage, and assess data that is typically under the purview of national and global organizations, and often lacks timeliness. For example, the annual mineral reports produced by the United States Geological Survey (USGS) have a one year lag time (e.g. 2016 data is released in 2017), and were created as part of a \$70.8 billion budget in 2017 (Department of Defense, 2017).

The specific research gap that this work attempts to fill has three components. The first is to understand what individual firms are currently doing to monitor critical material supply risk. Governments, think tanks, and academics use national, global, and technology-based indicators (e.g. static depletion times, human development index, life cycle assessment, gross domestic product, etc.), to assess and monitor criticality. Do firms use the same or unique indicators? The second component concerns how individual firms can monitor their own supply risk using existing internal firm-level data. All corporations regularly create, monitor, and analyze myriad kinds of internal data (e.g. financial, operational, supply chain, marketing), but little is known about if and how that information can be translated into criticality assessment tools. The third and final component considers how individual firms can use internal data to predict and mitigate supply risk. For example, what might a company infer from revenue from a given product, or the availability of suppliers, or their inventory variance ratio for a given material?

2. Methods

Criticality assessment is a complex undertaking with internal and external variables as well as macro and micro level variables. There are also several levels of analysis (e.g. global, national, industry, material, country of origin), and many different analysis methodologies such as traditional risk assessment, supply chain management, and sustainability practice. As depicted in [Figure SI.1](#) in the supplemental information, a multi-factor approach was used to understand critical material supply risk. First, an exploratory case study of the use of rhenium in the aviation industry was used to evaluate the impact of critical material price volatility on firm performance. Second, 11 existing firm-level studies (Rosenau-Tornow et al., 2009; Duclos et al., 2010; Lloyd et al., 2012a; Miehe et al., 2016; Lloyd et al., 2012b; Nieto et al., 2013; Bensch et al., 2015; Gardner and Colwill, 2016; Lapko et al., 2016; Hallstedt and Isaksson, 2017; Kolotzek et al., 2018)—a subset of the 42 studies initially reviewed and noted in [Section 1.2](#)—were analyzed to identify data and indicators for criticality assessment. Third, a firm-level risk analysis was conducted to determine internal indicators relevant to firm-level supply disruption mitigation. Finally, a framework for firm-level criticality assessment was developed by combining the above analysis, firm organizational structures, and the role of inventory and demand management as characterized by an established economic phenomenon, the bullwhip effect.

The case study approach used in this paper was chosen because the research conducted here is preliminary and primarily conceptual. Very little work has been done on firm-level criticality assessment to date, and this approach allows criticality assessment to be explored from the perspective and scope of a firm rather than that of geography, politics, or the environment, all of which are extremely broad and have been studied extensively. By examining one metric (price volatility), for one material (rhenium), used in one application (jet turbine blades), in one industry (aviation), we can begin to establish parameters around firm-level criticality risk assessment. This case specifically examines the price volatility of rhenium and its impact on the cost of production of jet engines. Price volatility is the chosen metric because it is easily measurable and material costs have significant impacts on the financial well-being of firms.

The existing firm-level studies noted above contain a total of 96 indicators of criticality. Analysis of these indicators included sorting them into the six broad categories of risk outlined in [Section 1.2](#) (scarcity, geopolitical, demand, environmental, supply chain, and

market risk), and then breaking them down further into sub-categories based on the specific aim of each indicator. For example, within the category of scarcity, six sub-categories were identified: physical/geological abundance (e.g. abundance of a given material in the earth's crust); production capacity (e.g. utilization of mine/refinery capacity); recycling (e.g. recyclability of a given material); stock/reserves (e.g. known stockpiles); substitutability (e.g. firm's ability to substitute one material for another due to supply disruption); and supply (e.g. percent of world supply used). Next, each indicator was identified as having an internal or external scope. Out of the 96 indicators identified, 79 were classified as external and 17 were classified as internal. Examples of indicators classified as internal in scope include impact on revenue, non-forecasted upside demand, delivery capability, and potential cost increase. Examples of indicators in the external scope include future market capacity, concentration risk, co-production risk, and environmental regulation. A table of the indicators reflecting this analysis and identifying the study from which each indicator was found can be found in [Appendix A](#) in the [Supplemental material](#).

Informed by the analysis described above, a novel set of internal indicators intended to support the assessment of supply risk at the firm level was developed. Criteria used to select indicators included the availability of data needed for criticality assessment; the frequency with which that data is generated; the accessibility of the data in the regular course of business (i.e. whether or not the data is already being collected, analyzed, reported, etc.); the potential for a firm to influence the data being collected through its business strategies and objectives; the extent to which the indicators as a whole address the basic functions of any typical business; and the alignment of the indicators with existing key performance metrics such as revenue, profit, stock price, etc.

The framework for firm-level criticality assessment was designed with the goal of being relevant to most any business that produces and/or sells manufactured goods, and to incorporate all major operational aspects of such firms. To accomplish this, three categories of risk to manufacturing-related firms were defined: profitability, design and concept viability, and production. The first category is intended to capture threats to the fundamental integrity (i.e. a product's ability to meet performance requirements if an originally specified critical material experiences a supply disruption), and market potential of products that rely on a given critical material. The second category is intended to capture threats to the manufacturing and distribution of products that rely on a given critical material. The third category is intended to capture threats to the financial sustainability of firms that produce products that rely on a given critical material. The selection of indicators for each risk category was driven by four core business functions that incorporate all activities needed to produce and/or sell manufactured product—finance, procurement, marketing, and production—as well as their potential to generate actionable data.

Unlike the global and national level indicators emphasized in most current research, these indicators must be derived from primary (and often proprietary), data. In addition, because the aim of this research is to provide an accessible resource for many different kinds of firms, this data must generally be available in the normal course of business such that firms can compile it with reasonable ease. The ultimate goal of the proposed internal indicators is to facilitate a holistic and multifaceted analysis of critical material supply disruption risk at the firm level.

3. Results

3.1. Firm-level impacts

Current literature suggests that the impact of critical materials at the firm level is evident in supply disruptions, short-term profitability, and long-term financial sustainability. To assess this assertion, a case study of the impact of rhenium price volatility on the aviation industry was conducted. Price volatility was selected as the impact factor because material cost is highly relevant for manufacturing firms and

because firms have direct access to purchasing and pricing data for at least the first tier of their supply chains. Firms also have some ability to influence the prices they pay through procurement and inventory strategies like hedging. The aviation industry was selected because it is the largest consumer of rhenium.

Price volatility is a measure of the changes in the price of commodities over a short period of time, and can result in many negative impacts to firms. For example, an increase in the cost of goods sold (e.g. price of materials), a decrease in raw material and finished product supply (e.g. inventory on hand), a decrease in production efficiency (e.g. idle machine time), and a decrease in revenue due to lost sales. Other problems include uncertainty in costs, product pricing, earnings, and credit availability, thus affecting the short-term profitability and long-term survival of firms (Agarwal et al., 2012). Specifically, price volatility negatively impacts margin, working capital, and share prices, with earnings shown to rise and fall as much as 10–30% (Agarwal et al., 2012).

Each of these financial metrics can provide valuable insight to a firm's health and financial sustainability. A firm's margin represents the amount of money that it earns per sales dollar and is correlated to profit. When margins decrease, profit may decrease as well. At the product level, this may cause a firm to stop manufacturing a particular technology such as the more fuel efficient turbine blades used in GE's jet engines. A firm's working capital represents the amount of cash and other short term assets (e.g. accounts receivable) that it has available to pay for operating expenses at any point in time. Low working capital increases a firm's financial risk. If a firm like GE is faced with a price spike for a material (e.g. rhenium) that it relies on, the firm's ability to service its short-term debt may be compromised. If the impact persists, a decline in working capital could threaten the viability of a firm overall. A firm's share price is the amount of money that a person is willing to pay for the firm's stock. Changes in share price impact a firm's ability to raise capital and are an indicator of the financial health of the organization. A decrease in share price may cause a firm to cut costs in order to increase margins. A firm might cut costs by abandoning certain products or through more invasive measures such as cutting funding for research and development.

Rhenium is an expensive metal with historical price volatility that is used in the manufacture of superalloys, catalysts, and gas-to-liquid (GTL) refinery processes (Polyak, 2017).

It is a byproduct of copper ores with little to no direct mining, and approximately 80% of demand is met through primary production (MSP-REFRAM, 2017). Secondary rhenium provides the remaining supply and is produced mostly through foundry and mill scrap recycling and recycling of parts from jet engines that have reached end of life (Duclos et al., 2010). Estimated world reserves of rhenium are 11 kt of which 5 kt are found in the U.S. (John, 2015). Despite the considerable reserves of rhenium located in the U.S., a lack of production facilities drastically limits what can be supplied domestically (John, 2015). For example, in 2017, world production of rhenium was 52,000 kg. Of the 42,600 kg consumed by the U.S. in the same year, 8500 kg was mined in the U.S. which has a total of six mining operations: four in Arizona, one in Montana, and one in Utah (Polyak, 2018).

Most of the remaining 34,100 kg of rhenium consumed in the U.S. in 2017 was imported from Canada, Chile, Germany, Kazakhstan, and the Republic of Korea (Polyak, 2018). Additional sources included Estonia, France, Japan, Poland, and Russia (Polyak, 2018). Although the United States currently has positive diplomatic relations with the majority of these countries, political conditions and trade policy are subject to change at any time. Particularly in the context of sustainable technologies, should demand for materials like rhenium dramatically increase, tariffs could make imports unfeasible. Foreign countries may also elect to stop exporting certain materials altogether. China's trade policies are of particular concern. In 2017 China produced 80% of the supply and accounted for more than 66% of global demand for rare earth elements, many of which are considered critical (GlobalData Energy 2018).

Mancheri et al. argue that China's influence on the resilience of the rare earth element supply chain is strong enough that trade policies affect China differently than they do the rest of the world (Mancheri et al., 2019).

The predominant driver of the price of rhenium is demand created by the aviation industry which relies on this material to achieve high-temperature properties in blades and vanes for high pressure aero and industrial gas turbine engines. These turbines are in high demand because their ability to withstand extremely high temperatures enables increased performance and fuel efficiency in jet engines. The cost of rhenium is based on prices issued by the London-based Minor Metals Trade Association and long-term purchasing agreements between the consumer and producer (Lipmann, 2005). Because rhenium operates in an opaque market—most transactions are made through long-term contracts that aren't publicly recorded—it is susceptible to drastic and sudden price changes that are generally triggered by market speculation (Lipmann, 2005; Polyak, 2017). For example, in 2008, strong demand triggered by speculation and sudden large orders for new generation aircraft—built with blade turbines requiring rhenium—led to a price spike in which the cost of rhenium reached \$12,500/kg compared to a more typical cost in the range of \$1,800/kg to \$2,600/kg. By the middle of 2009, the market corrected to a cost of \$4,000/kg to \$4,500/kg (EC, 2014). Fig. 3.1.1.

Although rhenium can be recycled from decommissioned gas turbines and catalytic converters, this secondary source does not necessarily relieve price pressure in the broader market because recycled rhenium has lower purity than rhenium derived directly from ore and therefore produces different technological results. GE, for example, initially touted the use of recycled rhenium as a demand (and therefore cost), reduction strategy in the wake of the 2008 price spike (Duclos et al., 2010). Although possible from an engineering standpoint, the reduction and/or elimination of the use of rhenium in these engines was ultimately unviable because it resulted in decreased fuel efficiency (Duclos, 2016). GE is currently pursuing and finding success with the development and implementation of ceramic matrix composites (Kellner, 2017).

The economic and strategic importance of rhenium in the aviation industry is evident in the cost of production. The average amount of rhenium needed to manufacture engines for one commercial aircraft, such as Rolls-Royce's Trent XWB, is 50 kg (MSP-REFRAM). The cost for this amount of rhenium at the all-time high 2008 price of \$10,400 USD/kg would be \$520,000 USD per aircraft vs. \$76,500 USD per aircraft at the 2017 price of \$1,530 USD/kg, a decrease of 85.29%. Based on the 2017 list price of about \$35 M USD per engine, a gross margin of 14.9%, and the 2017 price of rhenium, the Trent XWB earns \$5,215,000 USD per engine on a revenue and cost basis (Rolls-Royce Holdings, plc, 2018). By comparison, the Trent XWB earns just \$1,753,500 USD per engine at 2008 rhenium prices. This is equal to a loss of -9.89% in gross

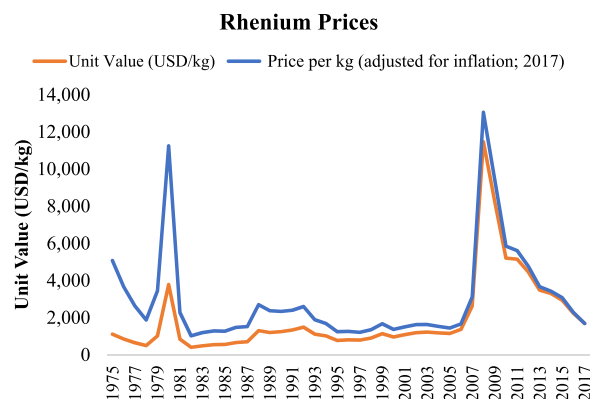


Fig. 3.1.1. Price Volatility of Rhenium, 1975 – 2017 (Kelly et al., 2005; Polyak, 2017; Polyak, 2018).

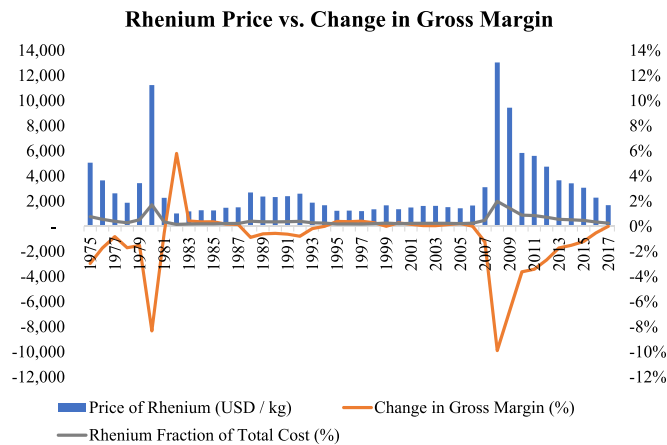


Fig. 3.1.2. Unit Cost of Rhenium per Trent XWB Engine vs. 2017 Gross Margin of Rolls-Royce.

margin, or \$3,461,500 USD per engine. Material fraction of total material cost, which provides an indication of the importance of a given material with regard to product functionality and value, also demonstrates the criticality of rhenium in aviation. In this case, the amount of rhenium needed to produce one Trent XWB engine accounts for just 0.69% of the total dry engine weight of 7277 kg (Agency, 2013). At 2008 rhenium prices, the material fraction cost is equal to 1.99% versus 0.26% at 2017 prices. This is illustrated in Fig. 3.1.2.

Despite the suggested role of speculation in the 2008 rhenium price spike, it is important to note that the broader macroeconomic climate was also extremely volatile at this time. The financial crisis of 2007–2008 resulted in a steep global recession in 2009 so, although the rhenium market did experience a market correction in 2009, real correlative relationships cannot be asserted between the cost of critical materials and firm profit based on this data alone. The circumstances surrounding a similar price spike that occurred in 1980 mimic those of the 2008 price spike. The single-crystal nickel-based superalloys that rely on rhenium for their high creep strength were emerging in the early 1980s when U.S. economy also experienced a significant recession (Mottura and Reed, 2014).

3.2. Firm response

It is unlikely that firms will be able to prevent critical material supply disruptions altogether so their response to them when they occur is important. Fig. 3.2.1. is an adaptation of a supply chain disruption profile developed by Sheffi and Rice (2005). It depicts changes to firm performance relative to a supply disruption and mitigation tactics over time, and includes several of the mitigation strategies such as hedging, substitution, and development of new materials and technologies. It

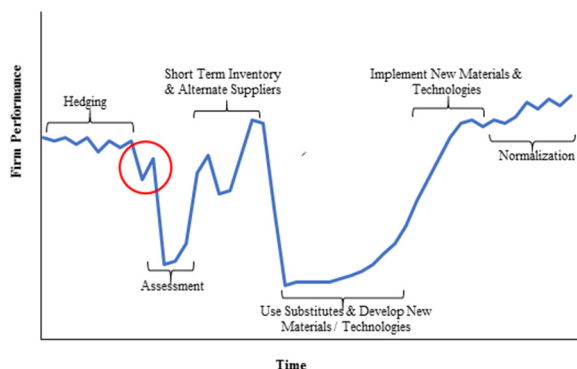


Fig. 3.2.1. Conceptual timeline of firm response to supply disruption.

may be surprising, but even firms that have long-term contracts in place for commodities can still experience delays in delivery of that commodity due to disruptions. Nokia had large losses due to a disruption in delivery of semiconductor devices that was caused by a supplier fire (a supplier that had long-term price contracts) (When the chain breaks, 2006). General Electric also had long-term contracts in place for rhenium; these agreements may not always ensure commodity delivery when actual physical disruptions occur (Duclos, 2016). Firms are then forced to get the commodity, part, or product from a different supplier that they do not have long-term contracts with and thus are forced to pay a much higher price.

Although the trajectory of the response shown assumes that the firm was engaged to some extent in hedging, we can clearly see that once the benefits of hedging have been depleted (i.e. short-term inventory and alternate suppliers), the time to recovery and normalization is about three times as long as the time between the disruption and the use of short term solutions. One way that the profile is instructive on the goal of firm-level criticality assessment (i.e. to mitigate and/or prevent a negative impact on firm performance due to supply disruption), is to apply the scenario in Fig. 3.1.2. For example, if Rolls-Royce had proactively identified substitutes or developed new materials and technologies in place of rhenium, these mitigation tactics could have been implemented directly following the assessment phase of the response, thereby substantially reducing the drop in firm performance and its duration.

A number of additional insights and conclusions can also be drawn from the disruption profile. First, firm performance relative to a supply disruption appears to be correlated to time. Second, the severity of the disruption's impact varies throughout the profile suggesting that interim firm actions are correlated to that firm's progression through the profile. Third, the time from the disruptive event to recovery, as well as the time between stages, is contingent on a firm's actions. In other words, although supply disruptions create predictable impacts across organizations, an individual firm's response determines the ultimate outcome. This means that firm-level risk monitoring and mitigation is not only possible, but necessary.

Some of the ways that individual manufacturing firms can moderate the risk of critical material supply disruption involve material usage, product development, product design, and inventory management. For example, a firm might use one alloy in place of another, develop an entirely new alloy, reduce waste through increased materialization, or decrease the amount of material needed by increasing material efficiency. Another strategy might be cross-functional collaboration during product development; at least some of the information needed to assess criticality from the development stage is often located outside of R&D, so involving engineering and procurement experts can make a determination of viability more efficient and prevent long-term risk. A third approach to risk mitigation is to design products that accommodate efficient extraction of critical materials at end-of-life and create mechanisms to maximize end-of-life material recovery. Inventory management strategies could include the use of long-term supply contracts, hedging, and supplier transparency. Large firms might also use vertical integration to acquire their suppliers or secure a primary source of material through mining rights and smelting plants (Cullbrand and Magnusson, 2012). Vertical integration is a supply chain strategy and business model that firms use to gain more control over the inputs of production. Instead of using third-party suppliers to secure materials, firms with an integrated supply chain own the companies that provide the materials needed.

The success of these strategies depends on two things: associated costs (in terms of product quality, product efficacy, and financial expense), and timeliness of implementation. In the former case, a firm may have a substitute material available that is feasible but results in a lower durability; an alternate material that meets minimum requirements but results in lower performance; or the technological ability to extract a critical material from a product that has reached end of life

that is not economical. In the latter case, a firm may complete a product redesign (which eliminates the need for critical material), only after it has lost most of its market share due to a supply disruption.

General Electric provides a real world example of firm-level risk mitigation that found success in terms of timely implementation but not cost. When confronted with a perceived shortage of rhenium (a material critical to the manufacture of turbine engines), GE's aviation segment used a multiple step internal strategy to address the impact of an externally driven supply disruption (Duclos et al., 2010). Below, we use GE's strategy and the disruption profile from Sheffi and Rice to demonstrate the firm-level impact and response (Sheffi and Rice Jr, 2005).

The first action taken by GE took place before the rhenium shortage occurred, corresponding with the preparation stage of the disruption profile. By examining each material that it deemed critical to its operations, GE was then able to evaluate each material based on four sub-risks: GE percentage of world supply, impact on GE revenue, ability to use substitute materials, and ability to pass through cost increases to consumers. Each of these sub-risks can be quantified and tracked using internal data. Once known, additional preventive action can be taken such as hedging, securing long-term supply agreements, material stockpiling, redesigning products to decrease material utilization, and developing new technology that requires no or fewer critical materials.

After the disruptive event occurred (i.e. the perceived rhenium shortage), GE conducted a material usage audit that was then used to determine sources and sinks of rhenium in the products being manufactured. This corresponds with the first response stage of the disruption profile and it enabled GE to fully assess its ability to internally mitigate the risk at hand. Next, although GE couldn't control the initial impact of the disruption, they could take steps to move toward the recovery stage of the disruption profile. Beginning with the initial impact stage and through the time of the full impact and preparation for recovery stages, GE took four actions based on its assessment in the third stage of the disruption profile. First, GE employed a common foundry practice called revert which allowed them to reuse casting waste. Second, GE developed a chemical process that enabled them to reuse grinding chips of rhenium for high value alloys. Third, GE developed a cleaning process to recycle material from products that have reached end of life. Finally, GE developed two new alloys that require significantly less rhenium content.

Having successfully reduced rhenium usage, GE entered the recovery stage. Based on the information available, it's difficult to gauge the long-term impact of the rhenium supply disruption to GE but two conclusions can be drawn. First, although the turbine engines manufactured with the new alloys developed during the recovery phase of the supply disruption did successfully operate, they were ultimately unviable from a business standpoint because the reduction of rhenium resulted in decreased fuel efficiency (Duclos, 2016). Second, despite the market failure of the new alloys, GE was still able to mitigate risk by using internal data and resources to minimize material waste and increase utilization efficiency.

In addition to understanding the mechanics of a supply disruption over the course of its impact on an individual firm, broader market dynamics must be considered. One important example of this is the supply chain and its many interdependencies, as illustrated by the bullwhip effect. A phenomenon in which inventory levels get out of sync with demand, the bullwhip effect causes companies to over- or under-order from suppliers, and results in artificially amplified demand over time. The underlying disconnect between buyers and sellers throughout the supply chain leads to increasing operational inefficiencies such as excess inventory, lack of inventory, lost production time, lost sales, and, ultimately, lost profit and market share.

Lee et al. have identified four underlying mechanisms that cause the bullwhip effect: demand forecast updating, order batching, price fluctuation, and rationing and shortage gaming (Lee et al., 1997a; Lee et al., 1997b). Demand forecast updating is a process in which firms determine future operational needs (e.g. materials, capacity, production

scheduling), based on historical sales. When a firm places an order based on this information, the next level of the supply chain bases its production, including safety stock, on that signal. Order batching happens when firms order periodically rather than based explicitly on demand and when firms experience surges in demand (e.g. a new product is more popular than forecasted). Rationing happens when demand exceeds supply and producers ration their products in response. Shortage gaming is when customers exaggerate their orders to compensate for rationing.

The triggering event of the bullwhip effect is an increase in demand at the downstream end of the supply chain (in this case, aircraft orders from airlines). Represented by the yellow line in the conceptual model in Figure SI.2, inventory levels begin to diverge after a modest increase in demand at the retail level followed by increasing amplification further up the supply chain. The retail inventory and backorder quantities fluctuate the least followed by the wholesale level, the distributor level, and finally the factory level. The areas of the graph in which some levels of the supply chain have positive inventory levels and some have backorders highlight potential areas for supply disruption. For example, in the middle of the graph, the factory backlog is extremely high and all other supply chain actors are reducing their backlogs. In response, both the factory and the distributor next develop safety stocks that far surpass subsequent inventory levels at the wholesaler and retailer levels of the supply chain. These fluctuations and mismatches across supply chain actors result in inefficiencies that threaten a firm's stability such as higher raw material costs, carrying costs due to excess inventory, increased labor costs due to overtime needed to fill overdue orders, and poor customer service.

The relevance of the bullwhip effect to firms that rely on critical materials, and therefore often face supply disruptions, is an increase in the degree of uncertainty in risk measurement. Firms can use performance metrics such as backlog (i.e. undelivered goods), fill rate (i.e. ratio of on time orders to late orders), zero-replenishment (i.e. the absence of orders from a tier in the supply chain during a regular order period), and slope metrics (i.e. bullwhip slope, inventory instability slope, and work in process instability slope), to mitigate risk in their own inventory and supply levels, but they have to rely on market signals to measure this same risk beyond the first tier in their supply chain (Cannella et al., 2013). This means that when the supply chain experiences a bullwhip, each tier of the supply chain is faced with this same dilemma, and the degree of uncertainty in risk measurement increases with each tier.

Fig. 3.2.3 illustrates two of these key parameters for firms that greatly influence the impact on them in the face of a supply disruption. The bullwhip effect can be illustrated by the order penetration point, i.e., where in a typical process the firm lies in terms of delivering its product. In the aerospace examples, those firms design to order and are therefore at the highest order penetration point. In comparison, most consumer products and electronics are made to be shipped directly to

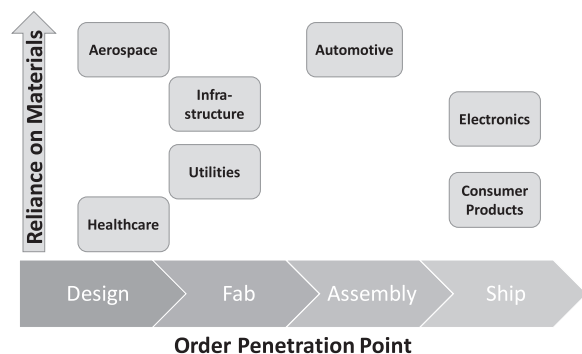


Fig. 3.2.3. Example order penetration point and reliance on materials for various industries based on (Agarwal et al., 2012; Gaustad et al., 2018; Olhager, 2003; Schoolerman and Mathlener, 2011).

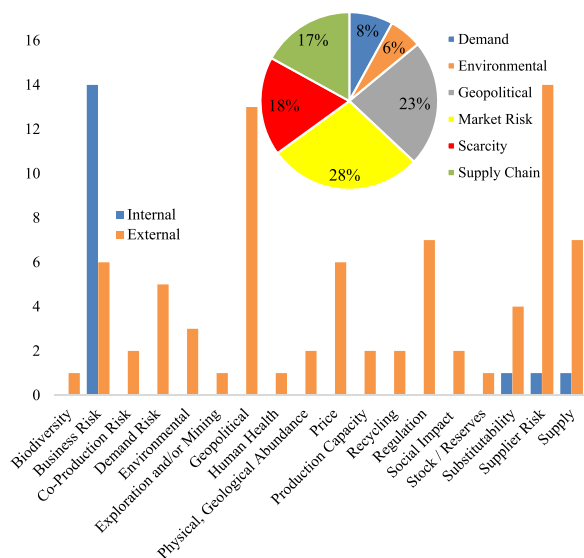


Fig. 3.3.1. Firm-level indicators by category & sub-category.

customers and have a low order penetration point (to the right of the Figure). On the y-axis is the reliance of the industry on materials as it relates to profitability. Both aerospace and the automotive industry for example, rely heavily on material price margins in order to deliver on profitability. One can see that the aerospace case is therefore somewhat of an extreme- a combination of both high order penetration point and high reliance on materials in their product.

3.3. Firm-level indicators

A comprehensive set of indicators spanning six broad categories (i.e. demand risk, environmental risk, geopolitical risk, market risk, scarcity, and supply chain), was identified in our analysis of existing firm-level criticality assessment methods. In general, these indicators were distributed fairly evenly as shown in Fig. 3.3.1., with the highest percentage of indicators being found in the Market Risk category. Although these indicators incorporate all three of the core facets of sustainability (i.e. social, environmental, and financial), only 18% of them can be considered internal indicators, meaning that they can be derived from data generated at the firm level. Conversely, 82% of the indicators found can be characterized as external indicators. This finding is consistent with our assertion that current criticality assessments rely primarily on external data. Although external indicators—such as investment in mining, static reach reserves, and sourcing and geopolitical risk—are important and pertinent to criticality assessment at all levels, they can rarely be influenced by individual firms.

In order to address the gap in firm-level criticality assessment methods we further analyzed our findings and identified four sub-categories of internal indicators among the 11 firm-level studies reviewed: business risk, substitutability, supplier risk, and supply. As shown in Fig. 3.3.1., 14 indicators concern business risk, one concerns substitutability, one concerns supplier risk, and one concerns supply. This is instructive because it gives an indication of what data and metrics are important and relevant to individual firms. For example, all of the business risk indicators fall into the broader category of market risk which is a determinant of the market viability of products.

Using product viability in the context of market risk as a starting point, the emphasis of our assessment framework is definitively on a firm-level scope rather than a market, industry, national, or global one. The indicators themselves are correlated to three key functions present in any firm: profitability, design and product concept viability, and production. Each of these business elements has organization-wide impact and relies on resources and processes from multiple areas across

a firm. In addition, vulnerability in one or more of these areas can constitute a threat to business sustainability. The purpose of this design is to produce information that has universal relevance to firms, a connection to the fundamental tenets of business noted above, a representation of cross-functional organizational dynamics (i.e. finance, procurement, marketing, and production), and the availability and accessibility of the underlying data in the regular course of business. A list of the indicators is presented in Table 3.3.1.

In the form presented in Table 3.3.1., this set of internal indicators does not stand alone. Because each firm has unique needs and circumstances (e.g. firm size, segment, industry, type and number of products), each organization necessarily has different assessment needs. The matrix in Table SI.1, which includes example risk values for illustrative purposes, is meant to address this variability and provide a framework for a firm-level criticality scorecard that can be uniquely adopted by any organization. A fundamental characteristic of the matrix is that it does not specify the scope of criticality or risk to be measured. It can be used to focus on a specific raw material; a particular product or group of products; product or segment profitability; sales volume; research and development; or other priorities.

In general, the risk levels defined by each firm are most useful when they correspond to a range of quantitative metrics. This is important because the risk level and underlying ranges of values represent another way that firms can operationalize the matrix to suit their individual needs. For example, the dispersion of supplier reliability values may be wider for a firm with readily accessible secondary suppliers compared to a firm with only one supplier for a particular material or component. Similarly, a firm that relies on a critical material for 5% of its revenue has more relaxed constraints compared to a firm that relies on a critical material for 50% of its revenue.

A further consideration regarding criticality risk assessment is the relationship between the indicator and the timing of the decision(s) that it informs. Generally, business performance management consists of both leading and lagging indicators. Leading indicators are predictive in nature in that they are meant to inform decisions that precede an economic impact or change. For example, substitutability—the extent to which it is possible to substitute another material for a critical material—is something that can be evaluated prior to a supply disruption. If there is a high level of substitutability, supply disruption risk is low and a firm can expect to be able to effectively manage such an occurrence by simply using an alternative, readily available material. In this case the firm may decide to start or continue production of a technology involving critical materials. If there is a low level of substitutability, a firm can use this information to make decisions about whether it will manufacture a product at all and, if so, what kind of commitments it will make to its clients (e.g. number of products manufactured per period), and how much margin it is willing to absorb if a supply disruption increases the cost of delivery to the client. Conversely, lagging indicators are meant to inform decisions that follow an economic impact and to substantiate trends and patterns. For example, price volatility—the percentage difference in the price of a material over a given period of time—is an indicator of market stability. By monitoring price volatility a firm can make decisions about which products to produce when and in what quantities, based on the levels of uncertainty and risk reflected in historical data.

While there is latitude with regard to how a given organization can implement the firm-level criticality matrix, there are a number of considerations to be made. First, although historical trends may be useful in understanding and assessing criticality, the matrix is designed to be used on a more dynamic basis. For instance, the use of internal metrics (which are generated and available in the normal course of business), is intended to shorten the time between data generation and criticality assessment in order to improve the timeliness of firm response to a predicted or observed supply disruption. The matrix should be updated quarterly at a minimum. Second, the matrix can and should be used to inform a firm's mitigation strategy choices. For example, the

Table 3.3.1
Criticality indicators.

Profitability			
	Indicator	Definition	Relevance
Finance	Revenue	Income from sales of products relying on critical material	An indicator of risk exposure relative to products that do not require critical material
Procurement	Price Volatility	The percentage difference in the price of a material over a given period of time	An indicator of market stability; high levels of volatility signal high levels of uncertainty and risk
Marketing	Price Elasticity	The ratio of percentage change in quantity demanded to percentage change in price	An indicator of the responsiveness of demand to changes in price; changes in price that don't impact demand are inelastic vs. changes in price that do impact demand which are elastic
Production	Substitutability	The extent to which it is possible to substitute another material for a critical material	Higher substitutability allows firms to use alternative materials when faced with supply disruptions due either to cost or scarcity
Design & Product Concept Viability			
	Indicator	Definition	Relevance
Finance	Material Fraction of Total Material Cost	Percentage of total product cost from critical materials	Indicator used to evaluate the importance of a given critical material with regard to product functionality and value
Procurement	Supplier Risk	Availability of suppliers with limited conduct violations	If publicized, use of suppliers with poor conduct can threaten the viability of an entire firm
Marketing	Segment Market Share	Percentage of total sales in a given market segment	Market share is an indicator of relative competitiveness and capacity to scale operations
Production	Material Utilization	Ratio of the raw material weight used in production to the weight of the finished product	An indicator of material waste; higher utilization reflects more efficient and economical production
Production			
	Indicator	Definition	Relevance
Finance	Gross Margin	Percentage of revenue retained as gross profit	The higher the percentage, the more sales dollars retained which can be used to cover costs and service debts; a measure of organizational stability
Procurement	Inventory Variance Ratio	Ratio between inventory variance magnitude and demand variance ratio	A quantification of inventory fluctuation that signals changes in holding and backlog costs, and can be used to measure inflated average inventory cost per period; higher ratios signal higher holding and backlog costs
Marketing	Supplier Reliability	The percentage of deliveries that are on time and complete orders	Production delays due to raw material delay can be extremely expensive
Production	Production Efficiency	Ability to produce the highest quantity with the least resources at the lowest cost and the highest profit	A decrease in production efficiency could signal a supply problem

price volatility metric can be used in combination with the material fraction of product cost and price elasticity to determine whether a firm should invest resources to redesign a particular product or simply maintain modest safety stock. Similarly, a firm could use segment market share and supplier risk to negotiate long-term contracts with suppliers. Finally, the matrix is designed to leverage existing internal business data to give the firm information that it can use to directly influence internal outcomes. Although there are salient external factors and data sources related to material criticality, the focus here is on factors over which firms have some degree of control.

3.4. The role of the organization

Critical material risk assessment and mitigation have been extensively studied from perspectives external to individual firms such as physical availability, geopolitical conflict, global demand, and environmental hazards (see Table 1.2.1.). While relevant and impactful at the firm level, these factors are largely outside the control and influence of individual businesses. Conversely, firms can influence internal factors (e.g. product allocation, capital expenditures, supply chain strategy, research and development investment), that drive their individual profitability, design and product concept viability, and production efficiency. In fact, business organizations routinely compile data and prepare both internal and external reports to do so. Some of these include quarterly and annual financial reports, legally mandated tax and SEC filings, accounting audits, and assurance audits. It follows then that, conceptually, firms should be able to leverage existing data and reporting structures to assess criticality risk. In practice, however, there is little evidence of this approach. One reason for this may be that, just as the impacts of supply disruptions effect areas across an organization, remedies are also influenced by multiple areas and therefore can't be implemented by any one department or functional area alone. That is, the organizational structure of a firm plays a central role in its ability or inability to assess and mitigate criticality risk.

One practical demonstration of this dynamic is the dependency between research and development and procurement. Without information from a firm's research and development resources, procurement won't be able to contract the correct quantities and types of materials. Without procurement, research and development won't know what alternate materials are available in what quantities and at what cost. Both of these scenarios limit a firm's ability to effectively respond to a supply disruption. The former situation could, for example, result in production delays and compromise profits. Similarly, the latter situation could lead to the development of a new material that is cost prohibitive to implement at scale. Using the internal criticality indicators in Table 3.3.1. and Table 3.4.1. provides several examples of the relationship between organizational structure and risk assessment in an individual firm.

The information in Table 3.4.1. highlights the definitive challenge faced by firms contending with criticality assessment and mitigation: effective cross functional communication and collaboration. Across 16 indicators in three primary business functions there are a minimum of 33 types of information needed from five major functional areas and 11 organizational roles. Although some pieces of data are used for multiple indicators (e.g. sales volume, revenue, material pricing), only one of 16 indicators does not require information from at least two organizational positions. Further complicating matters is variation in data units (e.g. quantitative, qualitative, discrete, binary, ordinal, etc.), reporting baselines, and the timeliness of available information, all of which undermine the goal of criticality assessment and mitigation.

A comprehensive assessment of a firm's risk environment is an important objective of the firm level criticality indicators such as those in the matrix in Table SI.1. However, in order to accomplish this, risk monitoring and mitigation must be integrated into broader firm practices and a complementary ethos must be diffused throughout the organization. Without management support and a firm culture congruent

with cross-functional collaboration and information sharing, the firm-level approach to criticality is likely to fail, particularly in organizations that follow a silo structure or a rigid hierarchical structure. In addition to firm culture and organizational structure, the success of firm level criticality mitigation is dependent on communication with management and key decision makers. Given the complexity of criticality, the importance of clear, concise communication about supply risk and mitigation to management cannot be understated. Particularly in cases where the appropriate mitigation strategy is cost and resource intensive (e.g. product re-design or new material development), leadership buy-in is crucial.

4. Conclusion

In this paper, we presented a review of literature addressing firm-level criticality and conducted a gap analysis to better understand the differences among current approaches and scopes of criticality. The first component of the research gap that this work attempts to fill is to understand how individual firms currently monitor critical material supply risk. We found that critical material supply risk assessment at the firm level has two primary characteristics. The first is the quantification of externally driven risk factors such as geological and economic availability; policy and regulation; geopolitical risk; environmental risk; etc. Although different firms do use some of the same indicators, they also use some unique indicators. The second is that criticality is generally addressed on an aggregate basis (e.g. global, national, industry), rather than on an individual firm basis. While fundamentally relevant to criticality, we assert that external factors can't be directly controlled by individual firms. Similarly, criticality challenges faced by firms necessarily vary from those faced at the industry level or above. Finally, because firms inherently differ in size, scope, and resources, the focus on external factors also presents a challenge to successful criticality mitigation at the firm level.

The second and third components of the research gap addressed by this work are how individual firms can use existing, internal, firm-level data to monitor supply risk, and how individual firms can use that same information to mitigate supply risk. To accomplish these goals we relied upon risk analysis, a process through which we determined potential threats to an uninterrupted material supply (e.g. price volatility, supplier reliability, substitutability), and identified correlations between potential events and likely outcomes (e.g. loss of revenue due to a price spike in a material needed to produce a good with a high material fraction of product cost).

Following these findings, the main contribution of this paper is a criticality assessment matrix that uses dynamic micro-level internal indicators to guide firm decision making related specifically to criticality risk at the firm level. Although we contend that all of the metrics proposed in the firm-level criticality matrix are relevant to all firms, there are no doubt metrics not included that are necessary for some firms and not others, as well as some metrics in our matrix that are more or less relevant across firms. Therefore, the matrix needs to be integrated into individual firm decision-making processes and adapted as appropriate; this requires some interpretation and analysis by individual firms. For example, selection criteria and indicator weightings will vary across and within firms based on things like which critical materials are used and the market characteristics of the products being manufactured with those materials. One application may be more susceptible to low production efficiency and another may be more vulnerable to price elasticity.

As shown in the criticality assessment tool, some indicators will have higher risk than others. Sensitivity analysis should be conducted to determine the appropriate risk levels for each indicator used to assess criticality at a given firm. A similar approach is recommended for evaluating supply risk mitigation strategies which will impact firms differently. For example, one firm may benefit greatly from using long-term supply agreements whereas another firm may be better off

Table 3.4.1
Internal criticality indicator data and sources at the firm level.

Profitability Indicator	Information Needed	Source of Information	Org. Position
Revenue	Products containing critical materials # of units sold / sales volume \$ per unit, per product	Research & Development Accounting and Finance	Materials Engineer Accountant
Price Volatility	Material pricing data over time	Marketing Procurement	Marketing Manager Cost Estimator
Price Elasticity	Supplier contracts Sales volume Pricing data over time Ability to pass on cost increase	Procurement Accounting and Finance Procurement Marketing	Purchasing Agent Accountant Accountant Cost Estimator
Substitutability	Product material composition Change-order cycle time Technical feasibility of substitution	Research & Development Production Research & Development	Market Research Analyst Materials Engineer Industrial Engineer Materials Engineer
Design & Product Concept Viability Indicator	Information Needed	Source of Information	Org. Position
Material Fraction of Total Material Cost	Product material composition Cost of critical materials used Total cost of materials used	Research & Development Procurement	Materials Engineer Purchasing Agent
Supplier Risk	Number of suppliers Supplier contract details Lead time by supplier	Procurement Procurement Procurement	Purchasing Agent Purchasing Manager Purchasing Agent
Segment Market Share	Revenue per product / business unit Total segment revenue Sales volume	Accounting and Finance Marketing	Accountant Market Research Analyst Accountant
Material Utilization	Design specified composition Actual composition Ability to reclaim materials Materials reclaimed	Research & Development Production Research & Development Production	Materials Engineer Industrial Engineer Materials Engineer Industrial Engineer
Production Indicator	Information Needed	Source of Information	Org. Position
Gross Margin	Revenue Cost of goods sold	Accounting and Finance Accounting and Finance	Accountant Accountant
Inventory Variance Ratio	Fluctuations in net inventory Fluctuations in demand	Production Marketing	Supply Chain Manager Market Research Analyst
Supplier Reliability	Sales lost to supply issues Rate of delivery delay / failure	Production Procurement	Supply Chain Manager Purchasing Agent
Production Efficiency	# of goods produced / # of goods scheduled to be produced Margin of goods produced / margin of goods scheduled to be produced Technical feasibility of substitution	Production Accounting and Finance Research & Development	Production Manager Accountant Materials Engineer

developing a substitute material or increasing material utilization. Integration of the matrix also requires buy-in from internal stakeholders throughout the organization, starting with management. Similarly, internal data related to supply is still, to some extent, contingent on the knowledge and activities of stakeholders up the supply chain. That is, some “internal” data requires external input and insight. For example, material cost data can be elusive and time consuming to identify in large supply chains, especially when firms purchase components and parts rather than raw material. This lack of supply chain transparency is an anticipated barrier to successful implementation of the matrix.

There are many opportunities to expand upon the research presented in this paper. Primary among these, future work should test the matrix by implementing it in one or more firm cases to further understand its capabilities and impacts. Such cases should be chosen to reflect different critical materials, different applications, and different industries. Applying the framework to real world data would allow us to explore different ways that firms might use and interpret the indicators in general. For example, can the indicators be used to effectively identify thresholds or tipping points beyond which risk exceeds a firm's tolerance? Which indicators do firm's find most useful? Does the utility of a given indicator vary across market segments or industries? Another area of exploration is the impact of integrated supply chains on criticality mitigation. Can large conglomerates actually influence the production of critical materials, or are broader market forces that cause supply disruptions more powerful? Are there manufacturing companies that own mines or rights to mines used to produce critical materials? If so, is this strategy cost effective? Future research should also address how firms might use modular manufacturing to mitigate risk; is it feasible to design technologies with contingency components in case of supply disruption?

This work is very price focused due to its emphasis on the impact of criticality on firms. However, it's important to think about how environmental regulations might disrupt supply chains. Future work should investigate firm risk on the basis of exposure to environmental issues which may include soil, air, and water contamination, radioactive waste, and carbon emissions. Finally, future work should apply a formal systems thinking approach to identify interdependencies within a firm that impact criticality mitigation. This should focus on the organizational design, communication, and culture within a specific firm, and how those elements impact effective business practices and critical material supply chain resilience.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.resourpol.2018.12.008](https://doi.org/10.1016/j.resourpol.2018.12.008).

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