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Mapping supply chain risk by network analysis of product platforms

Philip Nuss [a,*,1], T.E. Graedel [a], Elisa Alonso [b], Adam Carroll [b]

[a] Center for Industrial Ecology, Yale School of Forestry & Environmental Studies, 195 Prospect St., New Haven, CT 06511, USA
[b] Oak Ridge National Laboratory, Oak Ridge, TN, USA

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ABSTRACT

Modern technology makes use of a variety of materials to allow for its proper functioning. To explore in detail the relationships connecting materials to the products that require them, we map supply chains for five product platforms (a cadmium telluride solar cell, a germanium solar cell, a turbine blade, a lead acid battery, and a hard drive (HD) magnet) using a data ontology that specifies the supply chain actors (nodes) and linkages (e.g., material exchange and contractual relationships) among them. We then propose a set of network indicators (product complexity, producer diversity, supply chain length, and potential bottlenecks) to assess the situation for each platform in the overall supply chain networks. Among the results of interest are the following: (1) the turbine blade displays a high product complexity, defined by the material linkages to the platform; (2) the germanium solar cell is produced by only a few manufacturers globally and requires more physical transformation steps than do the other project platforms; (3) including production quantity and sourcing countries in the assessment shows that a large portion of nodes of the supply chain of the hard-drive magnet are located in potentially unreliable countries. We conclude by discussing how the network analysis of supply chains could be combined with criticality and scenario analyses of abiotic raw materials to comprise a comprehensive picture of product platform risk.

1. Introduction

Today's exchanges of raw materials, manufactured goods, money, and information are global and highly interconnected [1], and recent supply shortages in metals, coupled with high demand, have led to an increased interest in examining issues of supply risk under the framework of resource criticality assessments [2–4]. An obvious example of recent supply disruptions is the magnitude 9.0 earthquake and associated tsunami that struck Northern Honshu, Japan, on 11 March 2011, severely disrupting Japan's mineral production of high-purity aluminum, cadmium, smelted and refined copper, ferronickel, titanium dioxide, and other metal products [5,6]. The same disaster caused disruption of titanium dioxide supplies used to make black and red paints, which resulted in interruption of the production of red and black vehicles until substitute suppliers could be identified [6,7]. In a different example, the decision of China to restrict export of rare earth metals has threatened the manufacture of a spectrum of products, from hybrid vehicles to low-carbon energy technologies [8]. Technological growth combined with rising population and wealth is expected to lead to increasing use of a wider array of materials. In and of itself, this trend is expected to strain existing material supply chains but when coupled with natural disasters and/or policy actions supply disruptions could become more frequent, protracted and serious.

Some resources are obviously of more concern than others. In 2008 the U.S. National Research Council proposed a framework for evaluating material “criticality” based on a metal's supply risk and the impact of a supply restriction [4]. Since that time, a number of organizations worldwide have built upon that framework in various ways ([2,3,9,10]; IW [11–14]). A complementary approach to these ideas involves assessing supply risk in raw materials resource supply chains [15,16]. Supply chains may be defined as including all stages involved in producing and delivering a final product or consumer good from the supplier's supplier to the customer's customer, including managing supply and demand, sourcing raw materials and parts, manufacturing and assembly, and warehousing and inventory [17,18]. A supply chain assessment involves tracking the flow of resources from mine to use in final product, and potentially also through to the recycling and disposal stages.

At the level of economic sectors or countries, information from economic input output (EIO) models and trade data is increasingly used to look at the flow of commodities among different economic sectors at national [19–24] and multiregional scales [25,26], but such information is difficult to disaggregate to the level of companies or production sites involved.

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* Corresponding author.
E-mail address: philip@nuss.me (P. Nuss).
URL: http://www.philip.nuss.me (P. Nuss).

[1] Philip Nuss is now working with the European Commission, Directorate-General Joint Research Centre (DG JRC), in Ispra, Italy.

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At the level of companies, supply chains can be constructed based on information collected directly from the companies involved [27,28], or from online databases looking at specific industry sectors (e.g., the Marklines Automotive Information Platform used by [29] to investigate the Toyota automobile supply chain).

Although often depicted as a series of steps leading to the distribution of a final product, supply chains more closely resemble a network. In the context of supply chain analysis, the use of network analysis is still relatively new [28,30–35]. However, formal network measures have been used, for example, to understand the interconnectedness and resilience of the U.S. economy [36], to examine the robustness of the world wide web [37], to investigate food web structure [38], and to study metabolic networks [39] and communications networks [40].

A small number of recent studies make use of physical input-output tables [16] or trade data [15] to investigate metal supply chains, network topology and related supply chain risks. However, in part due to the difficulty of obtaining supply chain data and information for materials and products at the firm level [6,27–29], today's resource criticality assessments do not generally account for risk aspects related to the topology of the supply chains. Despite these challenges, the need for better mapping of material supply chains has been recognized, e.g., in the context of American national security [41].

In this study, we investigate metal supply chains for five product platforms: (1) cadmium telluride solar cells, (2) germanium solar cells, (3) turbine blades, (4) lead acid batteries, and (5) hard drive magnets. These represent platforms consisting of a wide range of different metals and involving different producers. The supply chains were built with a data structure designed to evaluate industrial capabilities at a national level which was then analyzed using indicators from network analysis (Nooy et al. 2011; Scott 2000; Wasserman 1994). We first describe supply chain mapping for five technology platforms. Next, we describe the network metrics used and discuss how to interpret them in terms of supply chain risk. Finally, we present network analysis results for the five technology platforms and present a plausible composite risk analysis tool.

2. Material and methods

2.1. Supply chains

One of the goals of this study is to build upon critical materials assessments of risk by including supply chain network data. As such, we developed a methodology that could be used on a variety of products and materials and that would use accessible, non-proprietary data. For this study, risk was assessed from the perspective of the United States, rather than the perspective of an individual company or the whole world.

In a business context, supply chains are generally described as consisting of companies that produce and supply materials and parts and those that transform them into products [27]. In that context, companies are perceived to be linked to each other based on supplier-customer relationships, and an efficient and resilient supply chain is important to achieve market advantage [42]. For assessing industrial capabilities, a supply chain for a technology platform may be described more generally as consisting of all companies that have the capability to produce materials and parts and transform them into products, regardless of individual supplier-customer relationships. The data structure used to assess the five technologies presented in this paper should be viewed within the context of industrial capabilities as opposed to distinct supplier-customer relationships. In other words, this paper presents the realm of plausible supply networks rather than actual ones (although we note that the same methodology described in this paper using network analysis can also be applied to specific supply chains if information on the individual supplier-customer relationships is available, e.g., to a company or government agency).

The supply chain for each of our five technology platforms consists of several metals, as summarized in Table 1. The platform complexity ranges from two elements (Ge solar cell) to thirteen elements (turbine blade). Because the focus of this study is on the interpretation and use of network metrics in the context of supply chain analysis, we consider only a preliminary list of metals when mapping the supply chains for each technology platform. All platforms considered represent semi-finished products as production of the final (finished) product would, in most cases, require further downstream steps and additional materials/subassemblies. Additional details on each supply chain, and the relevant data sources, are provided in the Supporting information: Section 1. The supply chains investigated in this paper are all based on publicly available information.

The data structure customer-supplier relationships, which are generally business-confidential, were not the focus of this assessment. Instead, we use a network mapping methodology entitled SMART (Strategic Materials Analysis & Reporting Topography). The SMART supply chain network data structure [60] consists of two main types of relationships. In the materials focus component, materials are linked from ore to oxide to parts to the technology platform. In the corporate focus component, companies and facilities are linked to these materials to indicate their capability to produce and transform the materials into the technology platform. Under this data structure, material types (e.g., material, element, part, platform), organization types (e.g., company, industry), and site types (e.g., deposits, mining or refining facility) are mapped as individual nodes. These nodes are then linked to each other by describing the relationship between each pair of nodes as shown in Table 2, thereby creating a directed (but non-weighted) network. A schematic figure illustrating the data structure is shown in Fig. 1 for the CdTe solar cell platform.

In the Fig. 1 network, material nodes are connected to each other via links that represent physical transformation steps. The material type nodes are linked to their respective producers (e.g., mine, smelter, and refinery) and to the organizations involved in operations. Additional information can be incorporated into the network by using different link styles between material types, organization types, and site types, describing, for example, ownership of an organization, materials stockpiled by an organization, or organizations with subsidiaries. In the present study we focus on a limited number of metals in each product application but the same approach to building and analyzing the network can also be applied to other abiotic and biotic resources, as well as to more complex product platforms (consisting of more materials).

2.2. Network analysis

2.2.1. Network metrics

All supply chains were constructed according to the SMART data structure and then imported into the Gephi 0.8.2 beta network analysis software [61] for further analysis. The Gephi software allows the visualization and analysis of networks of various sizes using network metrics. As shown in Table 3, we use four network metrics (discussed below) to investigate the characteristics of a technology platform in its supply chain network.

2.2.1.1. In-degree centrality. In-degree centrality is a measure of the complexity of the product platform with regard to the number of incoming materials (link attributes: “linked to”, “produced into”, and “used to produce”). For example, a turbine blade clearly requires many more metals or metalloids to function (in-degree = 13) than, e.g., a lead acid battery (in-degree = 2). The in-degree value will obviously depend on the completeness of the supply chains with regard to the number of materials considered in a product platform. It nevertheless can allow an initial comparison across a variety of product platforms. We note that material nodes with higher in-degree may be more likely to encounter supply challenges simply because of the larger number of upstream materials