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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

Table 1
Product platforms, data sources, and commodities. Only a limited number of metals are considered in each product platform with the goal to represent a range of different metals. Platforms can be considered as semi-finished products (i.e., additional materials and transformation steps would be necessary to provide the finished product).

Platform #	1	2	3	4	5
Platform	Cadmium telluride (CdTe) solar cell	Germanium (Ge) solar cell	Turbine blade[a]	Lead-acid battery	Hard drive magnet[b]
Elements considered	Cd, Te, Cu	Ge, Cu	Ni, Co, Al, Cr, Ta, W, Mo, Re, Hf, Y, B, Pt, Zr	Pb, Sb	Nd, Fe, B, Sm, Co
Primary commodities	Cd: companion from Zn Te: companion from Cu Cu: host element	Ge: companion from Zn, coal[c] Cu: host element	Ni: host element Co: bachelor element[d] Al: host element Cr: bachelor element[d] Ta: host element W: bachelor element[d] Mo: host element Re: companion from Mo Hf: companion from Zr Y: companion with other rare earths B: bachelor element[d] Pt: host element Zr: companion from Ti	Pb: host element Sb: host element	Nd, Fe, B (NIB) Sm, Co (SmCo)
Data Sources	[43]; [44]; [45]; [46]; [47]	[48]; [49]; [50]; [51]; [52]; [45]; [53]	[46]	[54]; [45]; [55]	[56]; [45]; [46]

[a] See for example [57] for a list of elements used in turbine superalloys and [58] for elements commonly used in coatings (e.g., Zr, Y, and Pt).

[b] The magnetic material currently used in hard-disk heads is a neodymium-iron-boron alloy which has largely replaces the samarium-cobalt magnet developed in the 1960s [59]. In this paper both types of magnets are considered.

[c] Zinc is sometimes a byproduct of coal combustion (fly ash) from energy generation.

[d] A host element is one that typically contains other elements in its ores. A companion is an element that is recovered from host element ores. A bachelor element is one that occurs by itself in geological deposits.

required. The in-degree measure could be enhanced by also including information on the number of materials potentially substitutable in the assessment. For a number of first and second end-uses such information is given, for instance, in [62].

2.2.1.2. Out-degree centrality. Out-degree centrality refers to the linkage of a material node with other material or site-type nodes. A higher out-degree relates to a larger number of organizations involved in the manufacture of the product platform. For example, the lead-acid battery is widely manufactured (out-degree = 35), and supply disruption is less likely than, e.g., a germanium solar cell or turbine blade, both of which are produced by only a few manufacturers globally (Supporting information: Table S7). Similarly, the measure of degree centrality (the sum of in- and out-degree centrality for a node) can be applied to any of the other material nodes along the supply chain to obtain a first impression of materials potentially supplied only by a few supply chain actors.

2.2.1.3. Closeness centrality. The measure of closeness in a network can be used to determine the length of the average shortest path between the product platform and all other nodes in the network. Product platforms with smaller closeness centrality are connected to shorter supply chains and are thus less likely to encounter distortion in physical and information flows. As such, their supply chains are at lower risk.

2.2.1.4. Eccentricity. This measure considers how far the product platform is from the furthest other supply chain actor. It reflects the maximum number of physical transformation steps needed to produce the product platform.

Table 2
Example of nodes and links used in this study.
(Source: [60])

Nodes	Link example
Materials and components	Ore “produced into” oxide
Platform	Materials and components “produced into” platform
Company	Company “operates” refining facility or “produces” oxide
Deposit	Ore “occurs in” a deposit
Facility	Oxide “produced at” facility

2.3. Producer country and production share

The network resulting from the SMART topology consists of physical flows and information flows, but does not include data on the strength of the linkages (i.e., information on quantity of flow of materials (or information) from one material node to another). Because the quantity of material exchanged between different nodes is important in order to highlight important supply chain actors (e.g., some companies may supply the bulk of a raw material and are therefore crucial for the overall functioning of the supply chain) but because exact linkage strengths may be corporate confidential, we use ordinal ranking to include country information and producer size in the analysis.

To address the supply risk imposed by facilities located in challenging countries or production sites contributing a large share of physical material flow to a material node, we incorporate a producer risk avoidance rating (RAR) metric (Table 4). In general, the larger the share of a material resource supplied by a single producer or manufacturer, the greater the risk that supplies of that resource could become unavailable for some reason. In our approach we indicate qualitatively (i.e., we distinguish between small, medium, or large producers) the contribution of site type nodes (or organizations if the information at site level is not incorporated into the assessment) involved in producing a material.

Information on the supplier country (i.e., where a node is geographically located) is also incorporated into the assessment. This is done by using the location of each site-type and organization-type node and approximately specifying the relationship of the supplier country to the United States (e.g., the node located in the United States or another very reliable country, in a reliable country, in a somewhat reliable country, or in a potentially unreliable country). For this determination we used the US Department of Defense (DOD) Manufacturing and Industrial Base Policy (MIBP) nomenclature [63]:

- “very reliable” refers to the United States, Australia, Canada, Finland, Italy, the Netherlands, Sweden, and the United Kingdom (these countries have a Security of Supply arrangement with the United States);
- “reliable” refers to New Zealand, Japan, South Korea, and all EU-28

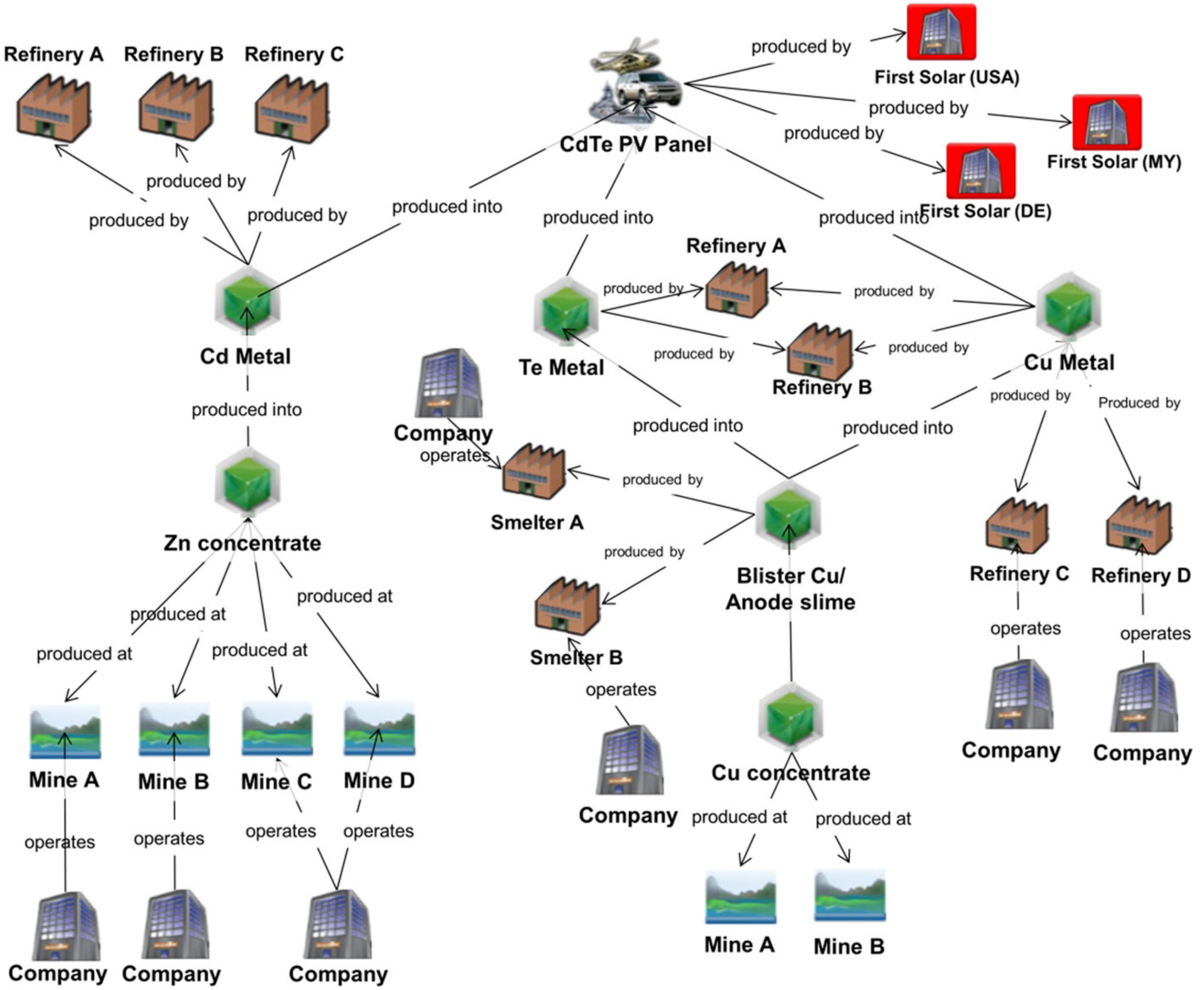


Fig. 1. Schematic diagram of the supply chain for the CdTe solar cell platform, as generated by the SMART system. Data sources for mines, smelters, and refineries, as well as the companies controlling these facilities are given in the Supporting information.

countries except the ones' listed above;
- “potentially unreliable“ refers to Russia, China, Iran, North Korea, and Ukraine (as of fall, 2015);
- “somewhat reliable” refers to all other countries.

Table 3
Network metrics proposed in this work to compare different product platforms with each other. Each metric can be derived for specific product platform nodes in the supply chain network. The network metrics are described in detail in the Supporting information: Section 2.

	Product complexity (in-degree)	Producer diversity (out-degree)	Average supply-chain length (closeness centrality, undirected)	Maximum number of physical transformation steps (eccentricity, directed)
Description of network metric[a]	Number of incoming links represent the number of materials (e.g., elements, materials, parts, or components) required to obtain the platform.	Number of outgoing links represent: (1) the number of downstream material-nodes (in cases where the node is not a final platform) and (2) number of production sites.	The average steps from the node under investigation to any other node in the network. Indicator of physical transformation steps and contractual relationships.	Indicates physical transformation steps only.
Supply chain risk interpretation[a]	Higher in-degree centrality translates into higher product complexity.	Higher connectivity translates into higher producer diversity or multiple downstream uses.	More physical transformation steps increase the likelihood for distortion. Each contractual relationship adds a layer of information or monetary flows.	More steps translate into increased likelihood for distortion of physical flows.

[a] Each network metric is interpreted in the context of the supply chain ontology provided in Fig. 1 and Table 2.

Table 4
Producer risk avoidance rating (RAR). The production share refers to the physical quantity of material contributed by each site or organizational node to a particular material. The production quantity is judged by the analysts to be either, small, medium, or large. Information on the supplier country is collected together with the nodal data. Both are then translated into a reliability rating following a diagonal rating pattern.

Supplier country	Size of organization or firm		
	Small	Medium	Large
Potentially unreliable	6	8	9
Somewhat reliable	3	5	7
USA or very reliable	1	2	4

The resulting overall producer risk avoidance rating (RAR) (incorporating production quantity and supplier country) is then derived as shown in Table 4, with a higher score indicating higher risk.

For example, 5N and Umicore produce the majority of Ge metal and Ge wafers used in Ge solar cells (i.e., they are large producers) [48,49,53]. Their facilities are located in the United States and Canada ("USA or very Reliable"). The resulting risk avoidance score would thus equal four.

Finally, it should be noted that we only construct and analyze the supply chain as a "snapshot" in time. However, in reality supply chains may change over time, e.g., nodes can emerge or disappear, and therefore a supply chain graph constructed for one year may not be representative of the situation in any of the given years. If data exist to map supply chains in multiple years, the same network metrics can be applied to capture the situation in each year and a resulting risk score may be the average or highest score found for each indicator over the years analyzed. Furthermore, our networks do not capture possible dynamics due to decisions taken by individual supply chain actors ("agents"). For example, different end-users of materials may be able to pay more for a certain material than others. Such dynamics could be included in the future using tools from agent-based modeling [64,65].

3. Results and discussion

3.1. Product platform comparison

The results of the network analysis for the five platforms are shown in Table 5. One of the networks is visualized in Fig. 2 as an example, with all the other network visualizations presented in the Supporting information: Section 3.1.

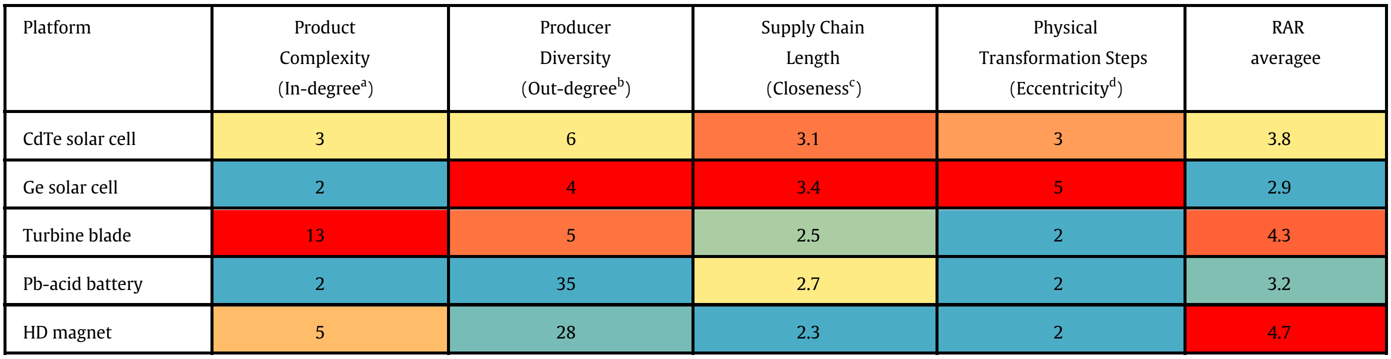
In the five product platforms, the number of nodes ranges from 250 for the lead acid battery supply chain to 672 for the turbine blade (Supporting information: Section 3.1). Four of the network measures, in-degree, out-degree, normalized closeness centrality, and eccentricity (Table 3), allow direct comparisons across product platforms.

For example, a hard drive magnet is an average of 2.26 steps away from any other node in the network, while the Ge solar cell on average requires approximately one additional step (closeness = 3.44) to reach the other nodes in the network.

At first consideration, it may be surprising that the turbine blade, having a relatively large network with 672 nodes (Supporting information: Fig. S9), is found to be the platform with the second lowest closeness centrality (closeness = 2.51). However, this can be explained by the fact that the turbine blade platform is located near the center of the graph and has direct connections to all materials, while the germanium solar cell (Supporting information: Fig. S8) is located closer to the periphery of the graph, by virtue of its reliance on germanium, a byproduct metal.

We find that the Ge solar cell is a maximum of 5 steps away from all material nodes while the turbine blade, lead acid battery, and hard drive magnet are only a maximum of 2 steps away from other material nodes in the network. It should be noted that a larger number of transformation steps translates into an increased likelihood of supply disruptions.

Table 5
Comparison of network metrics for the five product platforms (semi-finished products).



Platform	Product Complexity (In-degree[a])	Producer Diversity (Out-degree[b])	Supply Chain Length (Closeness[c])	Physical Transformation Steps (Eccentricity[d])	RAR averagee
CdTe solar cell	3	6	3.1	3	3.8
Ge solar cell	2	4	3.4	5	2.9
Turbine blade	13	5	2.5	2	4.3
Pb-acid battery	2	35	2.7	2	3.2
HD magnet	5	28	2.3	2	4.7

[a] Higher in-degree indicates increasing product complexity. (higher = riskier). Note that a finished product would consist of a combination of materials and semi-finished products (sub-assemblies) where for the latter nodes in-degree > 1 (a semi-finished product itself has inherent product complexity). In such cases, the final product complexity score could be calculated, e.g., as the sum of the product complexity scores of all material-type nodes linked to the product platform.

[b] Higher out-degree indicates a larger number of producers of the product platform and/or downstream demand for the material (lower = riskier).

[c] Normalized by dividing closeness with the total number of nodes N-1. A higher score means that the product platform is further away from all other supply chain actors. (higher = riskier)

[d] Higher eccentricity denotes more physical transformation steps. This measure considers all material-material linkages from the material node investigated to the starting material (e.g., raw material) extracted from nature. (higher = riskier)

[e] Producer Risk Avoidance Rating (RAR) takes into account the producer countries and production quantity of each material in those countries. See Table S11 in the Supporting Information for more details. The table shows the average RAR score for each supply chain (i.e., the average over all nodes with an associated RAR score). (higher = riskier)

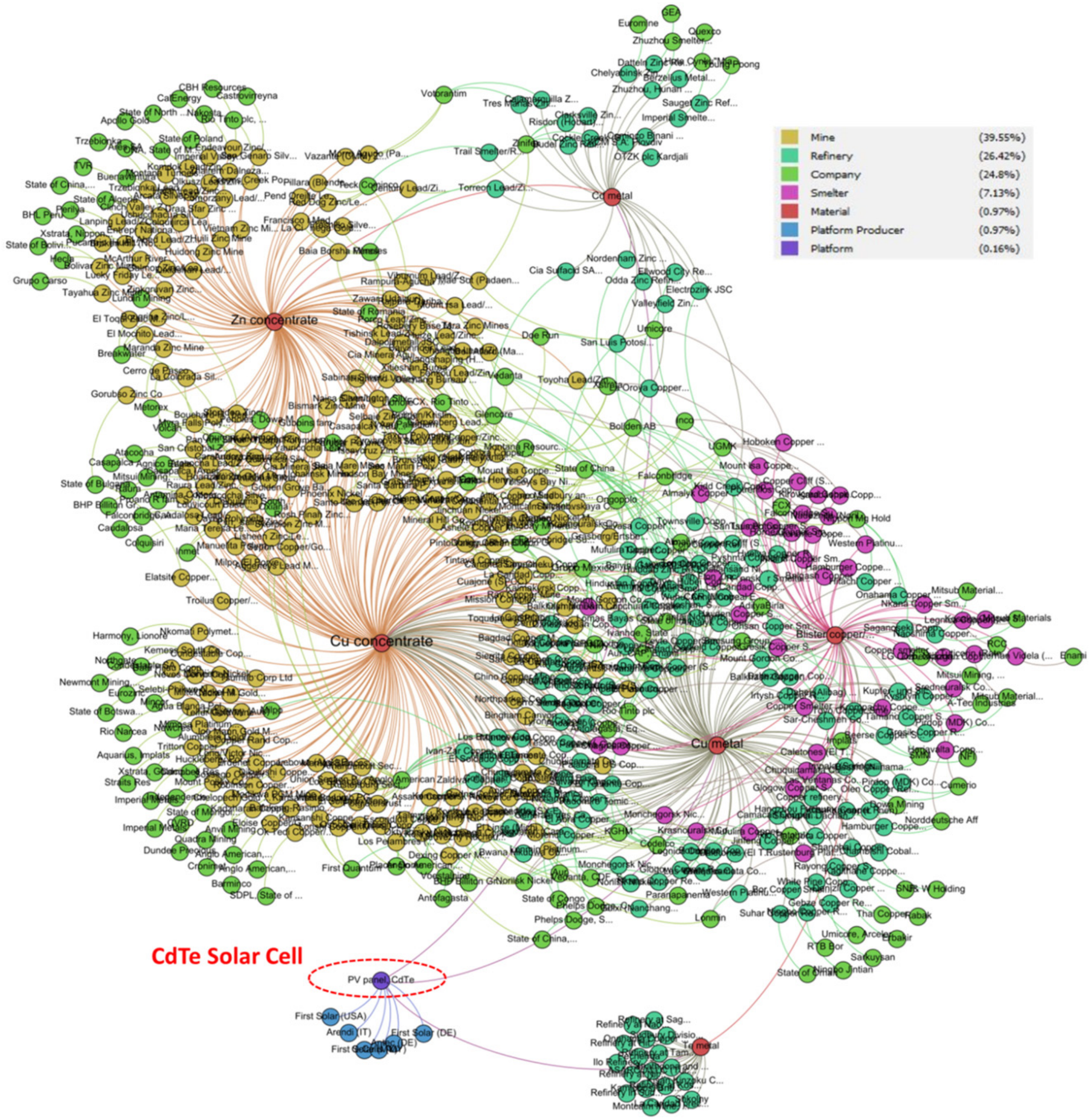


Fig. 2. Visual representation of the supply chain of the CdTe solar cell, number of nodes: 617, number of edges (links): 999. The network is laid out using force-directed algorithms [66,67].

Overall, the Ge solar cell seems to be more prone to supply disruptions than the other product platforms investigated. This is due to the fact that only few producers of the product platform exist and more supply chain steps are involved in order to reach the final product platform. On the other hand, for the hard drive magnet and turbine blade product platforms a larger fraction of supply chain actors are located in challenging countries, or rely on production sites contributing a large share of physical material flow (indicated by a high RAR score). It should be noted that the network metrics provide only a partial picture of the supply risk associated with a material and should be complemented with additional indicators, e.g., from raw materials criticality analysis (see also Conclusions and outlook).

Please also note that in order to allow proper comparisons, supply chains should be constructed with a similar level of detail. For example, including an additional material transformation step taking place within the same facility as a separate step in the network would increase measures such as eccentricity and closeness centrality. For a comparative analysis, technology platforms should ideally also be assessed at the same position in the supply chain (e.g., at the level of the semi-finished or final product).

3.2. Highlighting important actors: organizations (Table S8)

3.2.1. Degree centrality

Network measures calculated for organization- and site-type nodes can also be used to identify important supply chain actors. For organizations, out-degree centrality indicates the number of linkages to site-type nodes that are owned or operated by a particular company. A higher score is interpreted as reflecting lower risk (from the perspective of the node investigated), because of a higher ownership (operation) of production sites. As shown in Table S8, companies identified by high out-degree centrality are usually multinational companies (e.g., Grupo

Mexico, Codelco, Anglo American) or countries (e.g., China, India) having a large number of mines, smelters, and refineries. These supply chain actors operate or own a diversified portfolio of production sites and are less likely to suffer supply chain disruptions (e.g., closure of a mine due to strikes, changes in legislation, or natural disasters) than organization-type counterparts that are connected to fewer production sites or materials. If these actors experience a supply chain hiccup at one location a sufficient number of other production sites remain to continue operations. For example, in the Ge solar cell supply chain, Grupo Mexico (company) and China (country) are both highlighted as having influence over a large number of production sites (as indicated by their elevated out-degree centrality scores).

3.2.2. Closeness centrality

Organization nodes with high closeness (Table S8) are located at the periphery of the supply chain network, far away from other supply chain actors. For these nodes, the probability of supply disruptions due to the interruption of physical flows and/or information exchange is high. For example, in the lead-acid battery supply chain, Kyrgyzstan is involved in the ownership of only a single antimony mine and thereby located at the periphery of the network (closeness = 4.98). Removing this single connection would disconnect the country from the remaining network. In addition, several steps are required to move from the production of antimony to the manufacturing of the lead-acid battery. On the other hand, China owns numerous production sites (mines and smelters) which provide lead concentrate and metal. The country is therefore more closely connected to the other nodes of the network (closeness = 3.34) and will have a larger influence over the supply chain than Kyrgyzstan. Note, however, that the closeness measure is most useful in highlighting the average distance of the product platform to all other supply chain actors.

3.2.3. Betweenness centrality

Betweenness centrality measures the number of shortest paths that pass through a specific node from all nodes to all others (Supporting information; Section 2.4). Nodes with high betweenness centrality act as bridges between other nodes. In the case of organizations, a high betweenness centrality indicates, for instance, ownership or operation of multiple production sites. The removal of a node with high betweenness centrality is more likely to result in the interruption of material or information flows than if a random node were removed. Again, large multinationals and a few countries (China, India) tend to have high betweenness centrality. (Table S8). For the Ge solar cell supply chain, for example, Umicore Optical Materials (USA), a large producer of Ge wafers, is among the top-five organizations in terms of betweenness centrality. Table S13 and Fig. S17 show the position of China in the Germanium supply chain using the betweenness centrality measure. China is involved in the operation or ownership of a variety of production sites which, themselves, are linked to material nodes that are either highly interconnected (including loops) or located close to the center of the graph. As a result, both the organization-type node entitled “State of China” and some directly connected site-type nodes display high betweenness centralities. These nodes can be seen as important actors in the supply chain because they are involved in the provisioning of more than one material either directly via production or indirectly through ownership by the same organization (i.e., country or company). The removal of any of these nodes is likely to affect the functioning of the overall supply chain network, and highlighting these nodes is therefore important.

3.3. Highlighting important actors: production sites (Table S9)

As mentioned in the previous section, applying network metrics across all production sites can help identify important facilities (mines, smelters, refineries) across the five supply chain networks that we considered (Table S9). Higher degree centrality indicates sites that either produce more than one material or that are operated/owned by a larger number of organizations, thereby translating into lower risk (from the perspective of the site-type node). For example, in the Ge solar cell supply chains the Ilo copper/smelter refinery, located in Peru, produces both blister copper/anode slime and copper metal, and is operated by both Grupo Mexico and Glencore (Fig. S15). Closeness centrality identifies those production sites that are located either at the periphery (high closeness) or closer to the center of the graph (low closeness). For example, in the Ge solar cell supply chain the site-type nodes with the highest closeness centralities are those involved in coal ash recovery containing germanium, as shown in Fig. S16, because they are farthest away from all other nodes of the supply chain. Finally, betweenness centrality identifies production sites that can act as bottlenecks. High betweenness centrality indicates producers that are involved in the production of multiple materials affecting a larger fraction of the supply chain. An example is given in Fig. S18 for the germanium solar cell in which the Tesoro copper mine and refinery located in Chile is involved in mining copper metal and also producing the final copper metal product. The removal of a node with high betweenness is thus likely to affect the functioning of the overall production network.

3.4. Production quantity and supplier country (Table S10)

Production levels, sourcing countries, and the resulting Risk Avoidance Rating (RAR) scores are shown in Table S10 for the top eight nodes of each supply chain. It should be noted that our assessment uses partly 2005 company data for the mining, smelting, and refining stages [45] which may not capture recent developments in sourcing countries, e.g., China has become a major supplier for a number of the metals and metalloids included in the assessment. The production sites and organizations identified with the RAR measure are located in potentially unreliable (higher risk) supplier countries (e.g., China, Russia, Ukraine) that contribute a large fraction to the overall supply of a material. Finally, Table S11 shows the fraction of nodes with a RAR score ≥ 8. For the hard drive magnet, approximately 23% of the nodes with an assigned RAR score have a RAR score of 8 or higher while only 3% of the nodes of the germanium solar cell display a RAR score ≥ 8. This difference is due to a higher number of metals in the hard drive magnet such as rare earths, cobalt, and boron being produced in significant quantities in potentially unreliable countries (see also Table S10).

3.5. Visualization of analysis results

All results of the network analysis can easily be visualized to illustrate the position of companies, production sites, materials, and product platforms in the overall SMART supply chain network. Visualization examples and a detailed discussion for the germanium solar cell supply chain, are provided in the Supporting information: Section 3.6.

4. Conclusions and outlook

Supply chains for five technology platforms that use a variety of potentially critical metals were generated from publically available data by a newly-developed network metrics methodology. Network metrics were assessed for these platforms and provided information about product complexity, number of producers, average and maximum distance of a product platform to all other supply chain actors, and the level of challenge related to securing materials from potentially unreliable sourcing countries. In addition, this methodology can highlight supply chain actors that may act as potential ‘hot spots’ or ‘gatekeepers’. By doing so, the proposed metrics can provide information that would not be easily obtainable by a simple visual inspection of the supply chain.

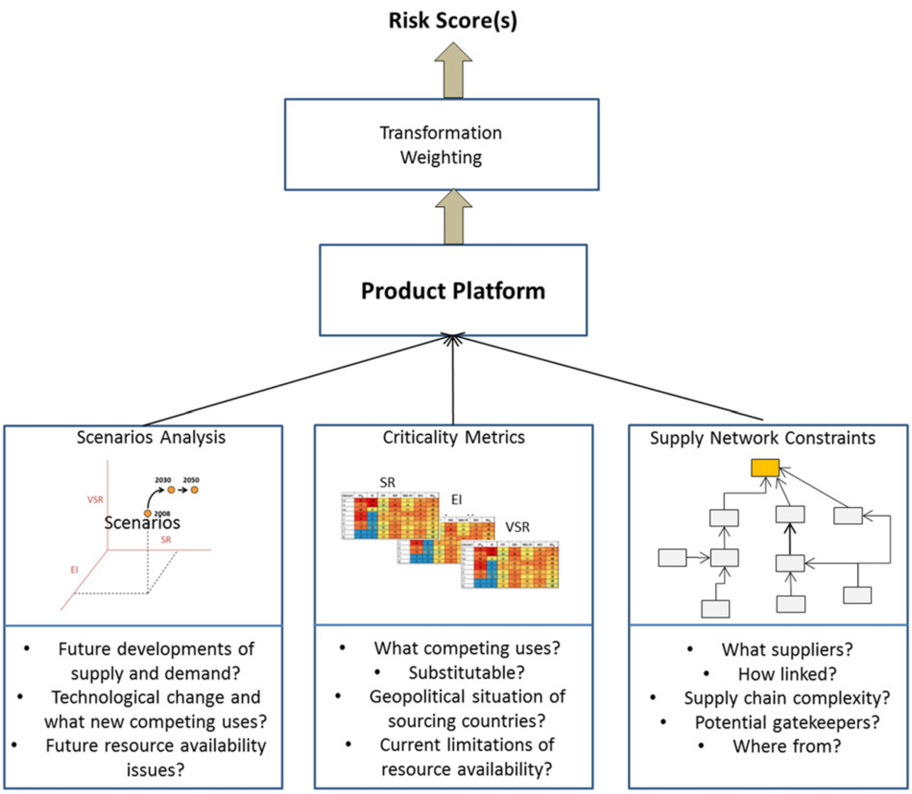


Fig. 3. Possible schematic framework for the evaluation of composite risk for a material combining scenario analysis, resource criticality analysis, and supply chain network analysis with each other. SR: Supply Risk, EI: Envirommental Implications, and VSR: Vulnerability to Supply Restriction [3].

Supply Chain Network Analysis is also shown to be effective in providing insights into potential supply constraints and bottlenecks for supply chains where the data structure illuminates industrial capabilities at a national level. These network metrics could build upon resource criticality assessments which would provide important information relating to substitutability potentials, environmental implications of production, and limitations of resource availability ([2,3,9,10]; IW [11–14]).

Finally, a comprehensive assessment for providing a measure of which materials are of more concern than others should, in our view, also incorporate aspects that relate to anticipated future metal supply and demand using various scenario storylines (see for example [68, 69]). We can thus imagine a “Composite Risk Methodology” for metal supply chains that would consist of (a) Supply Chain Network Analysis, (b) Criticality Assessment, and (c) Scenario Analysis of future metals supply and demand (Fig. 3). Applying *Scenario Assessment* in risk measures can be particularly effective for defense and security purposes: (a) Many current high-technology products with long service lifetimes (e.g., jet engines) are designed around the continued availability of particular metals so as to enable full long term performance with replacement material upgrades over periods of 10–30 years; (b) New platform designs are dependent on the continuing availability of particular metals during their manufacture, which for large platforms (e.g., in aerospace) can take years or decades from design to deployment.

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Appendix A. Supplementary data

Details of the network metrics, data sources, and additional supply chain visualizations, can be found in the Supporting information. Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.susmat.2016.10.002.

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