

Material Availability and the Supply Chain: Risks, Effects, and Responses

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Many authors suggest that market forces are inadequate to successfully manage the problems of resource availability and use. The fundamental question is whether these inadequacies are intrinsic to the market or if they arise from a failure of firms to detect and respond to subtle market signals. This paper explores the latter by describing (1) mechanisms that can limit materials availability, (2) effects of such limits on the firm, (3) preliminary metrics to diagnose these risks, and (4) strategies to reduce a firm's risk exposure. Case analyses of two materials systems are used to suggest that private firm interests, when properly informed, can motivate strategies that drive toward sustainable materials use. These strategies include (1) improving production efficiency, (2) developing technology to use more sustainable substitute materials, and (3) facilitating a more effective materials recycling infrastructure.

Introduction

In 1995, the USGS estimated that total material and fuel resource use and consumption in the United States topped ten metric tons per person per year (1). Furthermore, although the level of global consumption was nearly eight times smaller, that level was growing two times faster. While these estimates are fraught with uncertainty, they point to one of the significant challenges that confronts engineers and scientists of the 21st century: how to deal with unprecedented rates of material resource use.

The deleterious effects of materials use include all forms of releases to air, water, and land. To reduce these effects, few debate the benefit of migrating toward a more cyclical materials system. However, the debate over the need to intervene in materials use is hotly contended. The debate roughly divides along the lines of those who believe that the current organization of industrial activity will compromise a sustainable existence and needs intervention and those who believe that economic mechanisms, if properly framed and implemented, are sufficient to preclude catastrophe.

In general, the debate over the issue of sustainable use has been framed in terms of aggregate social welfare. This paper represents an attempt to recast that debate around

those implications from the context of the firm. Specifically, this paper examines the question of materials vulnerability or, conversely, materials availability from the perspective of a supply-chain decision maker.

The importance of raw material availability is obvious to upstream firms that extract, refine, and process material into products. However, as this paper will demonstrate, materials availability is critical to all firms. If raw materials become difficult to acquire, market forces may shift demand to other goods and therefore other supply chains. Regardless of one's specific business, such shifts can lead to irreparable economic harm. Unfortunately, post facto responses are limited by the far-reaching effects of materials. Materials establish appropriate production technologies and the possible configuration of the supply chain. The extent of these effects means that solely reactive response will be limited and may be ineffective.

Through the use of detailed case analyses, this paper will suggest that there are specific outcomes, technological, operational, and geographic, that can be expected within supply chains when limitations on materials emerge, and that at least two mechanisms can drive limited access to materials. These results are complemented with an examination of metrics to diagnose vulnerability and a preliminary discussion of preventative strategies for the supply chain. These strategies, although driven by solely private interest, are actions that would also lead to a more sustainable materials system.

Historical Case Study

Global Outcomes from Decreased Availability of Cobalt in the 1970s. Historically, no case of significant global material depletion has been documented (2, 3). Nevertheless, supply chains have been impacted by specific examples of materials availability during the 20th century. This section examines one such case, the use of cobalt, to better understand how materials can influence supply chains and to suggest how to identify vulnerability to such risks.

Overview of the case. The price of cobalt has always been volatile. In fact, from 1966 to 1976 and from 1980 to 2002, the year-to-year price changes of cobalt were as high as 41%. However, even these levels of variability were small compared to the shock felt between 1977 and 1979, when prices increased 380%. The price spike occurred following a rebellion in Zaire, a country which at the time constituted only 0.009% of global GDP (4). In response to this price swing, products, production technologies, sourcing routes, and even national policies were changed. Information on historical events and data for this section were taken from refs 5–8.

Background: Cobalt Sources and Applications. To many, cobalt sounds like an exotic metal with limited practical value. However, cobalt is used in a broad array of products including aircraft engines, turbines, magnets, and cutting tools. In the early 1970s, 40% of world land-based cobalt reserves were located in Zaire. Consequently, Zaire and neighboring Zambia controlled about 2/3 of world production. The major mines were located in the southern Shaba province. The Benguela railway, which passed through Angola, was the main cobalt export path. During this period, the U.S. was the main world cobalt consumer and produced no primary cobalt domestically. One single dealer, African Metal Corps (AMC), supplied all Zairian cobalt to the U.S.

Political Events Surrounding the "Cobalt Crisis". Following World War II, the U.S. recognized the strategic importance

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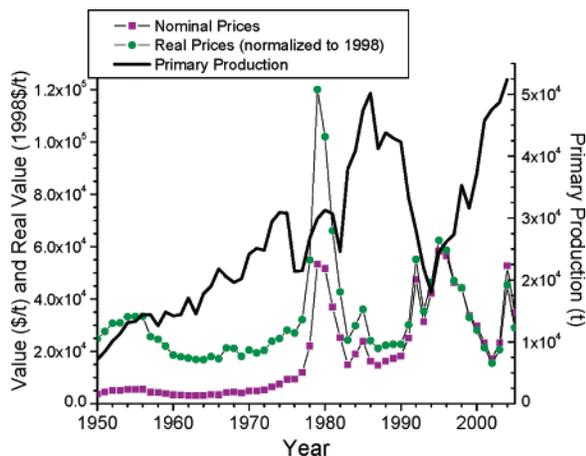


FIGURE 1. Cobalt average yearly prices and primary production 1950–2000 (8).

of cobalt and began a stockpile. The actual stockpile inventory at the end of 1973 was of 63 Mlbs; the U.S. yearly use was 18Mlbs. That same year, the U.S. decided to decrease its stockpile goal by selling cobalt to U.S. consumers.

Political instability around Zaire became a concern in 1975, when the Benguela railway was closed because of a civil war in Angola. Although a longer route had to be taken and consumer concern led to increases in consumer stocks, the supply disruption of cobalt from the downstream viewpoint was limited because of sales from the U.S. stockpile.

Continued uncertainty in the region led AMC to limit its shipments in 1976 to 125% of previous 15 months shipments. The U.S. government, concerned with cobalt availability, decided to restock and set a new stockpile goal of 85.4 Mlbs. Moreover, there was an increase in aircraft engine and drilling demand. Still, prices from 1975 to the end of 1976 only rose from \$8800 to \$11 880/t.

In May 1978, insurgents from Angola took over parts of the Shaba province. They cut the main power line to most major mining facilities. About 200 of the 2500 European expatriates employed as mining contractors were killed, and the remainder were evacuated.

Overall, the insurgents were in Zaire for about 2 weeks. Electrical power to the mines was lost for a total of 5 days. Because of flooding and the evacuation of most expert contractors, the mines in the area were slow to restore operation. Despite all of these issues, Zaire managed to produce *more* cobalt in 1978 than the average yearly production during the years 1975 to 1977.

However, during this same time period, there was a global economic upturn that led to increased demand for many primary commodities, including cobalt. The concern for supply shortages, along with real delays in transporting cobalt out to western countries, led to speculation. In February 1979, the price of cobalt hit \$55 000/t, with dealer prices reported at \$99 000/t. Prices remained high until 1982 (see Figure 1).

Outcomes of the Cobalt Crisis. During the period of high cobalt prices, interest in reducing the world's vulnerability to cobalt price volatility led supply chain stakeholders and consuming country governments to act. Emphasis here will be on private responses.

Upstream Responses. Short-term upstream efforts concentrated on shortening the lead times that had increased because of the political disturbance, leading to the use of air transport. Longer-term efforts in Zaire were aimed at stabilization and expansion of existing mining operations. Zambia increased its production capacity by adding to its refining capacity and by improving recovery techniques.

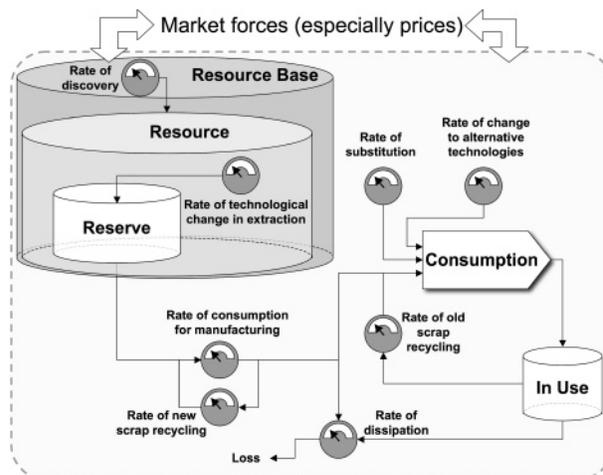


FIGURE 2. Flow analysis for materials availability. Key drivers of availability are indicated by rates.

U.S. mining companies considered domestic mine resources but did not lead to domestic production. However, both Zambia and Australia dramatically increased their primary production capacity reducing the importance of Zaire's mining of cobalt. Such changes meant that by 2004, Zaire only accounted for 31% of world mined cobalt.

Downstream Responses. Component and product manufacturers also reevaluated their production options in light of the price increases. The specific changes in cobalt use patterns are outlined in Table 1.

Substitution to lower-cobalt-containing alloys occurred quickly in the magnet industry in applications with limitations on weight, size, and energy (8). The reduction of cobalt use in superalloys was difficult because of limited substitutes and an increased demand for jet engines. In the short term, cobalt use in the transportation industry increased, with only some substitution to nickel-based alloys. A key change in cobalt use occurred with the development of a recycling process for scrap superalloy, resulting in a doubling of cobalt recovery after 1978.

Some substitution to iron- and nickel-based alloys also occurred in cutting tools; however, net machinery end-use of cobalt increased slightly. Cobalt use in ceramics and paints also dropped because substitution in these applications was straightforward.

Overall, as prices rose, the supply chain responded through materials substitution and development of new technology, source relocation, hoarding and rationing, supply mode changes, and recycling.

The events surrounding the supply disruption highlight some factors that increased the effect of the disruption, including poor geographic distribution of sources, monopoly market conditions, and lack of substitutions for critical applications.

This reflection upon the market and firm responses to the 1978 Zaire cobalt price excursion reveals the difficulties that firms can suffer in the face of resource scarcity, as well as the complexity of the resulting firm responses. While this retrospective demonstrates that resource risks can significantly impact the firm, it also underscores the importance of the tactical questions that such firms should consider: (1) how to make the best use of current information to assess the gravity of resource risks and (2) how to mitigate these risks.

An examination of the methods that theorists have devised to assess resource scarcity offers insights into how the framing of the problem of resource availability has evolved and can guide consideration of new approaches to its management.

TABLE 1. Cobalt Uses from 1975 to 1981 (4)

cobalt end-uses	1975–1977 average		1978		1979–1981 average	
	quantity (kt)	%	quantity (kt)	%	quantity (kt)	%
transportation (superalloys)	1.59	20	2.09	22.5	2.64	36
electrical (magnets)	2.00	25	2.09	22.5	1.27	17
machinery (cutting tools)	1.32	17	1.50	16	1.36	19
paints	1.23	16	1.73	19	0.95	13
chemicals	0.73	9	1.00	11	0.77	10
ceramics	0.82	10	0.73	8	0.27	4
other	0.23	3	0.14	1	0.09	1
total	7.92	100	9.28	100	7.35	100

TABLE 2. Measures of Institutional Efficiency

metrics and indicators	description
geographic structure based on supply (%) (10)	distribution of reserve size in top countries <i>assumption:</i> supply diversity increases efficiency
geographic structure based on production (%) (10)	distribution of production in top producing countries <i>assumption:</i> supply diversity increases efficiency
institutional structure based on production (%) (11)	distribution of control by most important company <i>assumption:</i> supply diversity increases efficiency
institutional structure based on use (%) (11)	distribution of applications and companies that use a given material, identification of new uses of the material <i>assumption:</i> demand diversity increases efficiency
recycling rate (%) (6,12)	scrap use divided by total use at a given time <i>assumption:</i> reliance upon recycled resource increases efficiency; greater confidence in supply
recycling efficiency rate (unitless) (12,13)	old scrap used divided by total material at end-of-life <i>assumption:</i> reliance upon recycled resource increases efficiency; greater confidence in supply
market price (\$) (10)	time trend and volatility of price. <i>assumption:</i> efficient markets

Identifying and Measuring Vulnerability to Availability

The problem for those attempting to ascertain resource scarcity is the complexity of a materials economy. The reduction of this complexity to a manageable set of indicators has been an ongoing effort. While a variety of simplifying abstractions have been employed to successfully tease out certain insights about resource scarcity, no single approach retains the generality necessary to cover all possible presentations of “scarcity.” The history of mercury serves as an example of this shortcoming. In 1972, mercury was identified as becoming critically scarce (9). However, through changes in economic and regulatory conditions, by 2004, mercury had a static depletion index (reserve base) approaching 200 years (8). Nevertheless, business decisions must continue to be made. This section and the next examine whether careful application of existing metrics can provide insights to guide a firm’s strategy.

Figure 2 depicts many of the fundamental elements of the frameworks that resource economists employ in their analyses of resource scarcity. These frameworks treat the materials economy as a network of resource flows, driven by the demand for applications that use the resource and moderated by the availability of substitutes and recycling. Underlying much of this dynamic are market notions, not only in terms of the segregation between resource and reserves but also in terms of the way that resource prices will influence demand, substitution and recycling.

The figure suggests that, when estimating the scarcity of a resource, there are a host of competing rates, which can also be viewed as “drivers of availability.”

Metrics must somehow assess the evolution of these rates against the amount of extracted and as-yet unextracted resource.

The most fundamental question of metric construction is “what does it mean to be ‘scarce?’” On the basis of the literature and the preceding case analysis, we propose two mechanisms that result in materials scarcity: *institutional inefficiency*, failures by markets, firms and governments that can result in transitory resource unavailability, and *physical constraints*, the amount and quality of a resource that is physically determined and ultimately limits resource availability

The cobalt case illustrates scarcity from purely institutional mechanisms. More conventional notions of scarcity can be traced at least as far back as the writings of Thomas Malthus (8). In his presentation, scarcity arises from physical constraints, occurring when extraction exhausts resources. In the early 19th century, economist David Ricardo refined this notion of physical constraints, based on the observation that resources exist in different levels of quality. As such, scarcity is not a consequence of exhaustion, but instead derives from the increasing difficulty and cost of access (11).

These perspectives on the mechanisms of scarcity provide a useful scheme to categorize metrics that have emerged over time in the literature.

Institutional Inefficiency Metrics. As the cobalt case study demonstrates, short-term problems, even in isolated areas of the world, can result in global disruptions to the supply of a material. Some scarcity metrics that derive from notions of institutional efficiency are outlined in Table 2.

The most broadly cited measures of vulnerability to institutional inefficiency focus on concentration within the supply chain, at either the national (12) or firm level (13).

In the cobalt case, the structure, both geographic and industrial, of supply and demand effected short-term material availability. Generally, the geographic distribution of reserves

TABLE 3. Measures of Physical Constraint Including Static and Dynamic Malthusian Metrics and Ricardian Metrics

	metrics	description
Malthusian static	static index of depletion (years) (7, 15)	time to use supplies at constant use rate: supply/(present use rate); $d_s = \text{supply}/C_{\text{present}}$. <i>assumption:</i> use rate constant; discovery and recycling rates negligible
Malthusian dynamic	exponential index of depletion (years) (7, 15)	time to use supplies at constant exponential growth of use rate: supply/(projected use), where future use can be modeled as having exponential growth; $d_e = 1/r \ln(r \text{ supply}/C_o + 1)$, where r is rate of growth <i>assumption:</i> use rate exponential; discovery and recycling rates negligible
	relative rates of discovery and extraction (unitless) (8, 16)	ratio of rate of discovery to rate of use <i>assumption:</i> recycling/reuse and substitution negligible; improvement in extraction technologies negligible
	time to peak production (years) (17)	time until this forecast peak is reached: based on models of future rates. <i>assumption:</i> rate of net use (demand less substitution) will grow faster than rates of discovery, technological improvement and recycling/reuse
Ricardian	average ore grade (%) (10, 13)	concentration of metal in a given ore body <i>assumption:</i> efficient markets in factors and capital; technological efficiency; accessibility effects negligible
	cost (\$) (10, 14, 18)	sum of technical costs (machines, fuel, labor, etc.), environmental costs, political costs, commercial costs (marketing, insurance, stock dividends) <i>assumption:</i> efficient markets in factors and capital; technological efficiency
	market price (\$) (10, 14, 18)	relative price, time trend. <i>assumption:</i> efficient markets

depends on geophysics, past depletion, and present exploration. Consequently, resource distribution is uneven, and in most cases, extraction is concentrated in a small number of countries. In the face of uncertain external factors (such as political events or natural disaster), concentration makes a resource more susceptible to institutional inefficiency and supply disruptions (12). Likewise, oligopsonistic markets are more vulnerable to fluctuations in demand, leading to market volatility.

An examination of the availability of secondary sources yields another perspective on supply chain concentration. In the cobalt case, recycling became an important supply source. The recycling rate can be an indicator of the importance of scrap as a resource (8). Thus, higher recycling rates can be an indicator of lower vulnerability.

The ability of a supply chain to modify availability through secondary sources is ultimately limited by access to such materials. The recycling efficiency rate (RER) metric provides insight into this issue (14). Unfortunately, RER is difficult to measure and data must be derived from prospective modeling.

The final metric of institutional inefficiency listed in Table 2 is the market price of the commodity of interest. As a number of authors have indicated, price is one of the best measures of scarcity insofar as the market embeds many of the issues outlined above (16). However, from the perspective of informing supply chain strategy, price is not a leading indicator. While price will ultimately be the trigger that initiates supply chain change, effective response strategies must already be in place.

Physical Constraint Metrics. The outcomes arising from institutional inefficiency in the cobalt case could also have occurred from physical constraints (12). In this section, metrics drawn from literature will be briefly discussed, but their interpretation will be made through the case study which follows.

Malthusian Metrics. The direct approach to measuring vulnerability to geophysical limits is to compare how much there is with how fast it is being used. These metrics attempt to balance a notion of the total amount of a resource that is available against the rate at which that resource is being used. Table 3 lists Malthusian-inspired metrics from the literature. The metrics are divided into two broad categories (static or dynamic), depending on the degree to which they treat the varying nature of the many interrelated rates (see Figure 2).

The static index of depletion is an estimate of the years to exhaust a material supply based on present use rates and one of the four estimates of available supply: reserve, reserve base, resource, or resource base (8, 21). The dynamic index of depletion is a simple extension that includes changing the use rate, for which the expected use is derived from historic data. A material is considered more vulnerable if it has a low index of depletion.

The simplicity of Malthusian metrics is a major advantage: depletion risk is related to how fast a non-renewable resource is used. Moreover, the required data is generally readily available.

The above metrics all assume a decreasing supply base for non-renewable resources. However, new discoveries, improved technology, increased recycling, and changes in resource economics have contributed to supply increases in the past. Taking this into account, one can classify materials with a rate of supply growth less than the rate of increasing use as vulnerable (10, 18). It has also been argued, especially for oil, that resource scarcity will occur when production peaks with Hubbert's peak for oil (19).

One criticism of these metrics is that, since many of the parameters are based on historical data, the effect of new technologies that may increase demand or improve efficiency are not considered. Additionally, the choice of defining supply as the reserve or resource appears arbitrary without an understanding of the technology and economics of extraction.

Ricardian Metrics. Malthusian metrics generally ignore variations in the quality of a source, which are tied to the level of effort required to obtain additional material. From a Ricardian viewpoint, scarcity should occur long before physical exhaustion as high quality sources would be preferentially used and future availability would decrease with increases in the difficulty of extraction (20). Ricardian metrics of global availability are presented in Table 3.

The ore grade is a physical measure of the quality of supply (12): in general, the lower the grade, the more earth is displaced, energy is expended, and waste is generated to extract the resource. Unfortunately, ore grade does not entirely capture the accessibility of the supply; an ore body at the surface is more accessible than one underground. Moreover, extraction from certain minerals is more difficult than from others (oxide minerals vs sulfide minerals).

A more informative measure of quality is the cost of extraction. Increasing extraction costs indicate the changing nature of the available resources and would be expected to correlate with increasing vulnerability. Barriers to using cost as a metric are lack of public data and the subjectivity involved in defining analytical scope. Because of the difficulty in obtaining complete cost data, reports have focused on energy, labor, or capital costs (12, 16). These simplifications can weaken the utility of cost as a metric of scarcity.

Metal prices are sometimes used for analyzing physical constraints. From a business perspective, price does not provide adequate notice to manage risk.

Exploring the Utility of Metrics: The Case of copper

This section explores the utility of the metrics described previously. Readers should note that many authors have pointed out that there are no significant examples of broad materials scarcity during the modern era and that even indirect evidence of scarcity is ambiguous (2, 3).

As such, it is not possible to characterize the diagnostic value of metrics directly. Nevertheless, decisions must be made. In light of that, this section proceeds by examining (1) a simple, imperfect screening metric, (4) the criteria for action on that metric, and (5) the use of more detailed measures for additional insight on risk. The approach that will be taken here is to evaluate indicators for resolution, computational challenge and intensity, and where appropriate, consistency, in the context of a specific, timely case study of copper.

Motivation of the case. Copper has been used for over eight millennia (15). Today, primary production of copper ranks third in terms of annual global metal tonnage, behind only iron and aluminum (17). Because of its role in construction, telecommunications and electricity (22), a country's copper use is an indicator of its economic development (2).

However, high rates of use also contribute to apprehension about copper's long-term availability (15, 18). Copper's economic significance suggests that global supply chains are sensitive to changes (real or perceived) in copper availability. This sensitivity and copper's low depletion index (as shown in Figure 3) mean that copper supply merits closer examination.

Metrics of Institutional Inefficiency. Simple Screening for Scarcity Vulnerability: Supply-Chain Concentration. Metrics of supply-chain concentration are broadly suggested indicators of vulnerability (12, 13). The authors suggest that these specifically point to vulnerability because of institutional efficiency. Of these metrics, the information needed to derive global geographic supply concentration is readily available (e.g., see ref 23), making geographic distribution a good first metric for institutional vulnerability. This metric is plotted in Figure 4 for a range of commodities for the years 1975 and 2004.

The geographic concentration of cobalt was not unique in 1975 (Figure 4a). However, Zaire's control of 45% of world

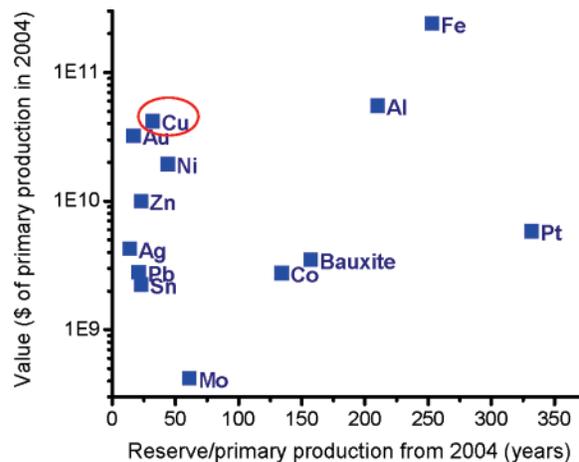


FIGURE 3. Positioning of metals. Malthusian static index of depletion based on reserves and global value of primary production (θ). Metals of increasing concern have high value and low depletion index.

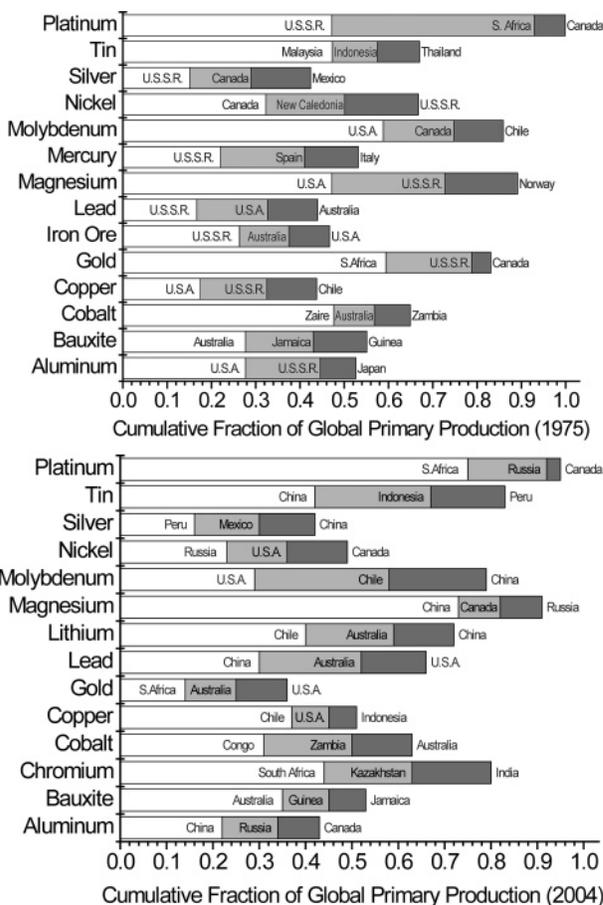


FIGURE 4. Geographic distribution of primary production for various metals. Top three producing countries for each metal in (a) 1975 and (b) 2004 (θ).

primary cobalt production in 1975 meant that the global cobalt market could not ignore Zaire's political disturbances. To effectively employ geographic concentration as a screening metric, decision-makers need threshold criteria to identify conditions of concern. One possible approach would be to look at the analyses of market concentration employed to measure the risks to competition in product markets. Guidelines applied by the U.S. Department of Justice suggest that moderate levels of concern exist when individual

suppliers reach market shares around 30% and high levels of concern exist when market shares approach 40% (24–26).

Using those guidelines, platinum and magnesium appear to be particularly vulnerable to risks deriving from institutional inefficiency (Figure 4b). Copper also merits attention because it exhibits an intermediate level of vulnerability with close to 40% of not only production, but also reserve and reserve base concentrated in Chile (23). Although it is more difficult to assemble, it is possible to complement this geography-based metric with information on institutional concentration within copper supply. Presently, no single firm controls more than 15% of global production, indicating that institutional concentration on the supply side does not add to vulnerability concerns (23, 27).

Further Investigation into Supply-Chain Risk: Recycling. Into the foreseeable future, the extraction of primary stocks will dominate the dynamics of most non-renewable materials use. As such, vulnerability of primary stocks represents the principal concern for most supply chains. Secondary supplies might play a role in mitigating institutional inefficiency risk for two reasons: (1) they can substitute for some primary applications and, therefore, effectively represent an additional source of supply, and (2) secondary stocks are often located and processed in different locations and by different institutions than primary.

Data from 1969 to 2004 show increasing overall secondary use (28), but the rate of growth of secondary use was modest and outpaced by the growth in total copper use. These observations indicate that growth of copper use has depended heavily on growth of mine production capacity. For example, old copper scrap accounted for only 17.5% of total world use in 1994, (representing 53% recycling efficiency rate) using estimates based on materials flow analyses (29).

These trends suggest that the secondary market does not dramatically reduce the vulnerability of the copper supply chain. Note that consistent secondary use and flow information for many metals is not publicly available.

Metrics of Physical Constraint. Simple Screening for Scarcity Vulnerability: The Static Depletion Index. The simplest way to screen for scarcity-based material vulnerability is to calculate the time to deplete the current supply, assuming no changes in the amount of material yet to be used or the rate of its use — a static depletion index. Of course, this metric does not reflect the dynamics of either the technology or the economics of extraction and its construction requires an arbitrary specification of the “unused but available” supply. The data that might be used to specify this supply are actually tied to the Ricardian concept that the total available quantity of any resource is inversely related to the economically acceptable quality of its source.

The smallest measure of available supply is referred to as reserves, a measure of economically and technically available primary metal. For copper, the amount available for economic extraction is apparently only sufficient to last 32 years (23). This low value contrasts strikingly with those of aluminum and iron, both of whose indices suggest more than 100 years to depletion (17).

This most conservative static estimate is indicative of the time frame within which new technologies for extraction or new sources must be found to continue the present yearly use under present economic conditions. With changes in economic or technological conditions (increased prices, decreased costs), these index values could instead reflect the tapping of the reserve base, leading to a static index of **64 years**, or eventually the resource, leading to a static index of **more than 100 years**. Finally, at the far end of the spectrum, the static depletion index based on resource base is estimated at one hundred million years. This may indicate that the amount of copper in Earth’s crust is so great that any concern for depletion of primary stocks lies in the distant future.

However, the resource base incorporates minerals of such poor quality that complete extraction would require a prohibitively large energy, capital, environmental, and land cost.

Limits for Concern. The first question that arises concerning the static depletion indices for copper is what index values indicate a need for action? Unfortunately, the real answer to that question derives from the complex interaction of the characteristics of known and unknown resources, the evolution of future demand and production technology, the effectiveness of secondary recovery, and changes in cost, price and the elasticity of substitutes. The development of such models is the subject of active research, but is currently only undertaken for the most strategic of global resources, typically energy resources.

Nevertheless, non-fuel supply chains must make decisions about when to allocate resources to mitigate material price risks. For this purpose, we would propose an inferential strategy for establishing the gravity of a particular depletion index value. In particular, the reserve-based index value should be compared against industry rules of thumb for establishing reserve capacity. Several authors have examined the issues that drive reserve management decisions, particularly exploration and technology development (12, 21). Although there is variation in their analyses, all point to a figure of about 30 years for the magnitude of the managed reserve life compared to current use. Accumulating stocks beyond that level does not seem to provide sufficient discounted revenues to offset exploration costs and market uncertainties. Thus, 30 years may serve as a threshold indicator for concern. Greater values would represent conditions where the primary industry is unmotivated to address geophysical scarcity, while values around or below 30 years would indicate a need for further evaluation.

On the basis of this criterion, copper, with a static depletion index of 32 years, sits on the border of concern. Using a model of oil reserves and their use, Pindyck observed that prices increased significantly before reductions in the static depletion index were noticeable (30). In light of this, current information would suggest that strategic decision makers should pay careful attention to resources whose economic availability sits in this region.

Further Investigation into Supply-Chain Risk: Dynamic and Ricardian Measures. Dynamic Depletion Index. Copper use over the past century has increased steadily and is expected to continue increasing as countries in developing East Asia and elsewhere industrialize. In fact, between 1969 and 2004, global copper use increased exponentially ($R^2 = 0.9643$), with a total increase of 124% and an annual average growth rate of 2.3% (28). Primary use has also grown exponentially during this period ($R^2 = 0.9567$) with an annual average growth rate of 2.5%.

Extrapolating these use growth rates, relevant dynamic measures of copper depletion time fall to 20 to 50 years, indicating that dynamic metrics of depletion do not contraindicate vulnerability (17). All of the values necessary to compute dynamic depletion indices are freely and readily available for most commodities.

The Nature of The Available Resource. Malthus’ dismal statement regarding sustainability was made based on the observation that population appeared to be growing at a faster rate than the capacity to produce food. For copper, concern about use would be reduced if exploration and recycling rates grew in parity.

Upstream supply chain stakeholders are well aware of the importance of the copper supply and are taking action to manage availability through exploration and technology improvements. Spending on copper exploration grew from \$340M to \$825M between 2003 and 2005 (8, 31). There has been a 460% addition to copper reserves since 1930. As a

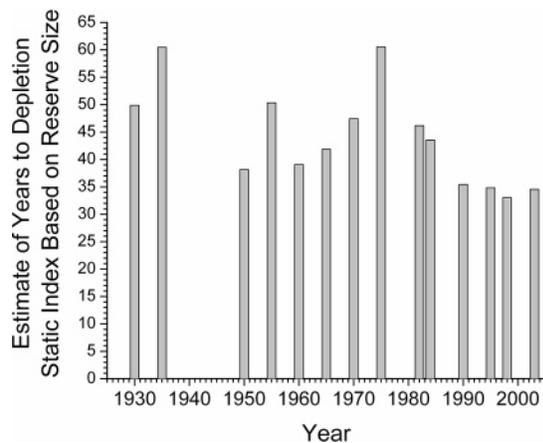


FIGURE 5. Change over time of estimate of future depletion year based on static index of copper reserve (8).

result, copper reserves have nearly kept pace with use, despite exponential growth in primary production. In fact, for the past decade, depletion indices have remained at or above the criterion for concern at slightly above 30 years (See Figure 5.). The ability of suppliers to manage reserve size would mitigate concern over vulnerability of copper supplies. All of the values necessary to compute changes in global reserves are freely and readily available for most commodities.

Ricardian Measures. The family of Ricardian metrics that consider resource quality, state of technology, and market valuations offers additional perspectives into the state of resource vulnerability. Technological improvements have made it economically feasible to exploit lower grade ores, increasing reserve size and postponing depletion. Between 1970 and 1993, when US copper grade remained a relatively constant 0.5%, the costs of western world copper mining decreased, illustrating the effect of improving technologies (15, 32). Copper prices decreased over the same period of time, until 2006, when they reached the past half century historical high (8).

However, copper ore grade has decreased for the U.S. since 1880 from 3% to 0.5%, plateauing at 0.5% copper from 1970 to 1993 (15). These trends would indicate that copper supplies are shifting into a regime of increasing vulnerability. While information on rates of discovery can be inferred from readily available sources (23), unfortunately, data on ore grade are not generally available for all commodities.

Availability of Substitutes. As stated in the discussion of institutional efficiency metrics, current practices would have to be significantly improved for secondary copper to provide a significant substitute for current primary. Therefore, current trends do not indicate that the secondary market dramatically reduces the vulnerability of the copper supply chain.

Modeling Scarcity. Further understanding of the risk for increased scarcity would require models to project additional metrics, such as time to peak production.

For copper, a few such models have been prepared. One estimate gives a 15 year time frame before copper primary production will no longer be able to continue increasing (15). For comparison, the US Department of Energy forecasts an analogous peak for oil in 31 years (33).

Understanding Supply Chain Roles in Addressing Copper Vulnerability. What businesses should take from the above analysis is that, while the complete depletion of copper is *not* imminent, most of the metrics indicate that the risk of copper disruption is significantly greater than for other major metals (e.g., iron and aluminum) and is at or near to a historical high. A proactive business that depends upon copper materials will understand that there are actions that should be considered to mitigate these risks.

Lessons Learned

Recent price swings have placed a renewed spotlight on the business implications of raw materials (8). This raises two key questions for firms: (1) are threats to materials availability a serious business risk, and (2) if so, how can threats be identified and the risks managed?

The 1978 cobalt case study illustrated that activities throughout the supply chain could experience permanent changes, specifically, **technological** changes such as, materials substitution and process efficiency; **geographic** changes such as, mining exploration and source relocation; and **operational** changes such as, transportation modes, increased inventory, and development of a recycling infrastructure.

The cobalt case also suggested a mechanism that constrains materials availability, *institutional inefficiency*, in addition to the classical mechanism of global *physical constraint*.

The materials scarcity literature suggests a number of metrics that indicate increased risk of limited availability. The problem for those attempting to ascertain risk is the complexity of a materials economy. Reducing this complexity to a manageable indicator requires simplification and abstraction. Ultimately, no single approach retains complete generality and none captures all of the dynamics of materials use.

Nevertheless, the copper case illustrates that careful application of metrics offers insights that should help guide a firm's strategy. The range of metrics explored proved to be both analytically feasible and able to distinguish materials as being potential sources of risk for firms. Exercising the breadth of risk metrics against copper offered a nuanced look at the nature of the risk. This exercise suggests that firms that utilize materials at risk should undertake more sophisticated assessments that comprehend the many inter-related dynamics of supply, demand, and substitution.

Given the breadth of the impacts that can derive from limited materials availability, post facto responses are unlikely to be effective. Supply chain-managers need to assess their risks to materials availability and, when appropriate, prepare for possible future problems. Fortunately, specific strategies exist to mitigate this risk.

Dealing with risk and uncertainty within the supply chain is a topic addressed by a growing literature intended to drive more robust and resilient supply chains (34–38). First of all, this literature suggests that supply-chain managers must know their supply chain (34, 35). In the case of materials availability, this includes not only monitoring metrics of risk but also fostering the existence and exchange of information to ensure accuracy of those metrics. Armed with information, managers can identify how and when to modify their supply chain practices.

One such modification is to add flexibility. Conventionally, this is achieved by having multiple suppliers or keeping inventory (36, 38). In the case of materials, flexibility can also be added through substitution and recycling. Both of these require that technological competency and infrastructure be in place before a response is needed.

A second modification is to increase robustness to materials availability events by slowing primary use. This can be accomplished by developing processes that are more efficient or, as with flexibility, ensuring that an effective recycling infrastructure exists.

Knowledge, flexibility, and robustness are broad measures to reducing supply chain risks. Although motivated solely by private concerns, the actions that support these strategies could (1) decrease use of primary stocks, (2) facilitate transition to more sustainable substitutes, and (3) ensure

viable recycling. Together, these actions drive toward a more sustainable materials system.

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Supporting Information Available

Detailed timeline of the Cobalt Crisis and additional historical data trends. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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