Materials availability and recycling

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40.1 Focus
The financial future of firms that depend on materials can be permanently compromised if the availability of those materials is constrained. This chapter examines how limited materials availability can affect a firm; how a firm can know whether it is using materials that are at risk of becoming of limited availability; and what can be done to mitigate that risk. One mitigation strategy is to foster an effective recycling system. The chapter concludes by exploring the benefits of expanded recycling and some of the remaining challenges to making that happen.

40.2 Synopsis
Resource scarcity is a topic that has challenged scientists, engineers, and economists for centuries. Current interest in this topic stems from the central role of natural resources in our economy, the inherently finite supply of those resources, and the unprecedented rate of resource consumption.

Will limited resource availability limit economic growth? The answer to this question is complex: resource consumption or use occurs in a complex and dynamic system in which the actions of governments, firms, and consumers, as well as the geological endowment of the resources, play a role. While there has never been a documented case of a material “running out,” the finite nature of the resources has implications for global material markets. For example, materials are geologically distributed unevenly, their supply may be controlled by only a few institutional entities, and they require varying amounts of effort (and cost) to extract.

On the demand side, materials-selection decisions are often made early in the product development life cycle and are not easily changed. Thus, supply disruptions can significantly damage manufacturers’ profits and even result in permanent changes to a material’s market and the firms that depend on that material. Strategies to mitigate such risks to firms need to be considered when materials-selection decisions are being made. Since many firms use dozens of different materials and are limited in resources, any strategy for dealing with the risk of scarcity should begin with screening for strategic materials before taking a more involved approach.

One example of a strategy to mitigate resource-availability risk is recycling. Recycling reduces primary-resource depletion and, generally, reduces the environmental impact of production. Additionally, recycling can reduce material costs and diversify the supply chain, reducing the impact of limited availability. However, technological, societal, and economic considerations vary for different products and materials, and recycling’s benefits must be carefully evaluated and fostered for each situation.
40.3 Historical perspective

Throughout time, the use of materials has been a defining feature of humankind’s effort to survive and thrive. As we have become more ingenious in the ways in which we manipulate those materials, we have also dramatically increased the magnitude of our use of materials. As you learned in Chapter 7, industrialization has led to a more than ten-fold growth in the per-capita usage of material resources. Within that trend, society has also transitioned from reliance on renewable biomass to dependence on nonrenewable minerals. As an example, the United States Geological Survey estimates that, only 100 years ago, about 40% of domestic raw-materials use came from renewables. Today, that figure is closer to 5%.

Although the use of renewables is not without its own challenges, this reliance on nonrenewable resources has raised concerns about the sustainability of modern society. Can economic growth continue indefinitely? Will we run out of some critical resource? Interestingly, these questions are not new. Formal treatment of these issues dates back at least to the eighteenth-century economist Thomas Malthus, who raised concern about whether available farming resources would ultimately limit society’s growth (possibly in the form of catastrophe). Interestingly, such concerns have haunted reflective societies for millennia. In fact, Tertullian, a second-century theologian, remarked on a “world, which can hardly supply us from its natural elements” due to our “teeming population.” Since the times of Tertullian and Malthus, we have learned a lot about resource availability and how it affects our world, but we have also dramatically changed the rate at which we tap those resources.

We have learned that economics and technology temper the impacts of increasing resource use and declining resource stocks. As the cost to acquire resources grows, so does the impetus to develop technologies to use that resource more efficiently and to switch to alternatives. Such mechanisms are often insufficient when the resource is a common good (e.g., a fisheries stock) or is not marketed (e.g., clean air). Nevertheless, even for more conventional cases, those who use materials should realize that limited materials availability, even if only temporary, can still present real economic risk. Interestingly, many of the strategies to mitigate that risk serve the dual purpose of reducing the environmental burden of resource use.

One such strategy that is familiar to most is recycling. Clearly recycling reduces primary-resource consumption, but also can provide attendant reductions in energy consumption and emissions. Contrary to some current perceptions, recycling is itself not a new phenomenon. In fact, recycling surely dates as far back as the use of materials by man. When resources are costly to acquire, they are discarded reluctantly and reused assiduously and ingeniously. Thus, valuable resources such as metals and even stones were reused or recycled wherever possible. This was mostly an informal process that depended heavily on individual manual segmentation of valuable resources. We still see this today in some parts of the world where “rag-pickers” make a subsistence living by manually sorting out recyclables from municipal solid waste (MSW). Generally, however, with affluence most societies transition away from careful segmentation and reuse, instead shipping most of their waste resources to landfills or incinerators. The past few decades have witnessed a departure from this trend. Since at least the 1970s, organized recycling programs have been expanding not on the basis of their private economics alone, but to address some of the social costs associated with removing resources from the economy. As we will discuss in more detail later, despite this development, many developed countries still “throw a lot away.” Using the USA as an example, while we now recycle more than 60 million tons of MSW, we still landfill more than 130 million tons.

40.4 Introduction

The challenges facing engineering today are not those of isolated locales, but of the planet as a whole and all the planet’s people. Meeting all those challenges must make the world not only a more technologically advanced and connected place, but also … more sustainable, safe, healthy, and joyous …

National Academy of Engineering Grand Challenges Committee

In fact, some studies estimate that in the USA raw-materials usage is approaching 100 kg per person per day [2]. In the face of a still growing and increasingly affluent world population, such estimates have raised important questions. Will resource availability limit economic growth?

In this context, few debate the need to move toward a more cyclic materials system. However, the debate over the need to intervene in materials use is hotly contended. One side of the debate contends that economic mechanisms inherently allocate scarce resources and most efficiently cope with decreasing resource availability; as resources become scarcer, prices rise, and users find ways to use less or to shift to substitutes. Others contend that markets fail to fully reflect the long-term (not to mention broader social) value of resources and, therefore, cannot drive efficient resource decisions.

1 Sections 40.6–40.8 of this chapter are based substantially on [1].
In general, these debates have been framed in terms of aggregate social welfare (see Figure 40.1). This chapter does not attempt to pick either side of this debate, but rather takes another perspective: it examines the question of materials vulnerability, or conversely materials availability, from the perspective of an individual firm.

Materials availability is critical to all firms, not just those that extract, refine, and process materials into products. If raw materials become difficult to acquire, market forces may shift demand to other goods. The economic impact of such shifts means that some firms would not survive. Unfortunately, reacting after the fact, after a shift has begun, might not work because materials influence so much about the way a firm does business.

This raises some difficult questions, which this chapter will attempt to answer. (1) How does limited materials availability affect a firm? 2) How can a firm know whether it is using materials that are at risk of becoming of limited availability? (3) What can that firm do to mitigate that risk? One of the answers to question (3) is to foster an effective recycling system for at-risk materials. The chapter concludes by exploring the benefits of expanded recycling and some of the remaining challenges to making that happen.

Before attempting to answer these questions, the chapter begins with a number of key definitions.

### 40.5 Definitions and terminology

#### 40.5.1 Geological definitions for primary supply

This section will quickly review some of the geological terms used when discussing nonrenewable materials. The allocation of nonrenewable materials in Earth's
crust is determined by geological processes, and exploration is the means of obtaining information on the resource distribution and concentration in Earth's crust and on the ocean floor.

Geologists subdivide primary sources of metals by how well they have been identified and measured and by how economic and technically viable it is to extract them today (Figure 40.2).

The materials that are mined today form part of the global reserves. The reserves incorporate all ore bodies at a given ore grade, ore type, and location such that it is technically and economically or marginally sub-economically viable to extract. The ore grade is the concentration of the desired material in the ore body that is being extracted and is generally given as a percentage by weight. The size of global reserves changes as prices change, as new ore bodies are discovered, as extraction technology improves, and as minerals are extracted. The accuracy of the reported data on reserve size depends on how recently the numbers have been updated, how responsive individual mines are to reporting, and how statistically accurate the geological methods for identifying ore-body characteristics are.

In geological terms, the word “resource” has a very specific meaning. The resources include the reserve base and the rest of the sub-economic deposits as well as estimates of the quantity of material that has not yet been properly characterized. There is much more uncertainty in the size of the resources than in the size of the reserves.

The largest number that defines primary material sources is the estimated size of the resource base, which includes all material content in Earth's crust (to a certain depth) and oceans, at all concentrations. The size of the resource base can be several orders of magnitude greater than the size of the resource for a given metal, but is generally not a number that is used in analyses of depletion.

### Figure 40.2. Fundamental characteristics of materials reserves and resources [4].

<table>
<thead>
<tr>
<th>Economic and recoverable</th>
<th>Demonstrated</th>
<th>Resource base</th>
<th>Inferred and undiscovered</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reserve</strong></td>
<td>Higher grade: occurring naturally at potentially recoverable concentration in Earth's crust</td>
<td>No specified concentration</td>
<td></td>
</tr>
<tr>
<td><strong>Resource</strong></td>
<td></td>
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</table>

#### 40.5.2 Secondary supply: recycling

When products reach the end of their life, they may be disposed of or collected for recycling. End-of-life products effectively become a resource. Secondary resources, a term used for all recycled materials, including industrial scrap (new scrap) and post-consumer scrap (old scrap), can be categorized so that economical ones can be identified and exploited through recycling. The concentration and distribution of the materials that form the secondary resources depends on where the products are discarded, how many products reach their end-of-life state, and the amount of material contained in the product. In general, many of the world's secondary resources are found in industrialized countries, which account for most of the world's consumption.

The recycling rate will here be defined as the amount of secondary material used as a fraction of the total amount of material used. The recycling rate has sometimes been referred to as the static recycling rate or recycled content. The recovery rate will be defined as the amount of old scrap collected and recycled as a fraction of the amount of total material disposed of and recycled, landfilled, or otherwise dispersed without recovery. A high recovery rate means that very few end-of-life products are reaching landfills. The recovery rate can also be called the recycling efficiency or dynamic recycling rate. An efficient recycling system is one in which the recovery rate is high, which means that most of the material in products reaching their end-of-life state is being reused. A high recovery rate could still result in a low recycling rate if the product lifetime is long and demand is growing rapidly.

### 40.6 A historical case study: global outcomes from decreased availability of cobalt in the 1970s

No historic case of global materials depletion has been documented. Nevertheless, firms have been impacted by specific examples of limited materials availability during the 20th century. This section examines one such case: the use of cobalt. This case will help us to answer our first question: How does limited materials availability affect a firm? It will also provide some suggestions for how we might judge vulnerability risk and respond to mitigate vulnerability.

#### 40.6.1 Overview of the case

Information on historical events and data for this section were taken from [5][6][7][8].

For millennia, cobalt compounds have been used because of the blue color they impart to ceramics and glasses. In the industrial era, cobalt has also become important in many applications, including aircraft
engines, turbines, magnets, and cutting tools. (See Figure 40.3 for a historical perspective.) More recently, cobalt has also become critical to many electronic devices and even the electrification of transportation because of its use in lithium-ion batteries.

For at least the last 50 years, the price of cobalt has always been volatile. However, between 1977 and 1979, cobalt prices experienced an unprecedented shock, rising by 380%. In response to this price swing, many aspects of the production and use of cobalt changed; in some cases, permanently.

The price spike occurred following a rebellion in the Republic of Zaire (now known as the Democratic Republic of the Congo), which at the time was home to only 0.6% of the world’s population, but controlled more than 40% of world production of cobalt. In May 1978, insurgents from Angola took over parts of the Shaba province in Zaire. They cut power to most major mining facilities and killed many workers. Overall, the insurgents were in Zaire for only about two weeks, but, because of flooding and the evacuation of most expert contractors, the mines were slow to restore operation.

During this period, a surging world economy pushed up demand for many materials, including cobalt. The concern for supply shortages in the midst of the upturn, together with real delays in transporting cobalt out of Zaire, led to speculation. In February 1979, the price of cobalt soared and prices remained high until 1982 (see Figure 40.4).

These events and the resulting price spike led both firms and governments to act to reduce the ultimate economic impact. In the short term, “upstream” firms, that is firms in the mining and refining sector, changed their operations (e.g., using air rather than land transport) to speed available material to market. As part of a longer-term response, firms in Zaire, Zambia, and Australia expanded production capacity through changes in operational practices and new technology. Because of these changes, by 2004, Zaire accounted for only 31% of the world’s mined cobalt.

“Downstream” firms, such as component and product manufacturers, also reevaluated their production options in light of the price increases. The specific changes in use pattern for cobalt are shown in Figure 40.3.

Substitution to lower-cobalt-content alloys occurred quickly in the magnet industry in applications with limitations on weight, size, and energy [8]. Reducing cobalt use in superalloys was difficult because of the limited availability of substitutes and an increased demand for jet engines. In the short term, cobalt use in the transportation industry increased, with only some substitution by nickel-based alloys. A key change in cobalt use occurred with the development of a recycling process for scrap superalloy.
Some substitution by iron-based and nickel-based alloys also occurred in cutting tools; however, net end use of cobalt for machinery increased slightly. Cobalt use in ceramics and paints also dropped because substitution in these applications was straightforward.

Overall, as prices rose, the cobalt supply chain responded through:

- materials substitution and development of new technology,
- source relocation,
- hoarding and rationing,
- supply-mode changes, and
- recycling.

Looking back at the events of 1978 in the cobalt market and how they affected firms in many industrial sectors, it is clear that limited materials availability can have real economic impacts. It is also clear that many of the responses that can reduce that impact take time to implement (e.g., developing new technology or implementing a recycling system) or are very expensive to implement once prices are high (e.g., hoarding). Clearly, it would be beneficial to recognize the risk early and develop strategies ahead of time. The next section explores some metrics of risk.

40.7 Identifying and measuring vulnerability to availability

The problem for those attempting to ascertain the risk of limited resource availability is the complexity of a materials economy. Identifying risk metrics – that is, quantities we could measure to test for risk – for such a system has been an ongoing effort. Unfortunately, no single metric retains the generality necessary to reflect 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, changes in the market for mercury have meant that now, nearly 40 years later, the world has identified mercury resources sufficient to last more than 200 years [8]. Clearly, identifying resources at risk is rife with ambiguity. Nevertheless, despite this ambiguity, firms that use materials must make business decisions.

Figure 40.5 depicts many of the fundamental elements of a materials economy, particularly those that are relevant to questions of materials availability. A materials economy consists of a network of resource flows (e.g., bauxite ore or aluminum) that move among resource stocks (e.g., resource-base or in-use stocks). The magnitude of these flows (depicted by the valve gauges schematic in Figure 40.5) is driven by the demand for applications that use the resource (e.g., aluminum cans) and moderated by the availability of substitutes (e.g., PET bottles) and recycling. The rates of these flows are ultimately dictated by the economy. As such, they are dynamic and constantly shifting.

As Figure 40.5 suggests, there is a host of competing rates within a materials economy, 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 resources.
Most discussions of scarcity focus on physical constraints and raise the following question: when will we run out of, or exhaust, a resource? This perspective dates back at least to the eighteenth-century economist Thomas Malthus. In the early nineteenth century, the economist David Ricardo refined this notion of physical constraints by making the observation that resources exist in different levels of quality. Hence scarcity is not a consequence of exhaustion, but instead derives from the increasing difficulty and cost of access. This realization is critical to our understanding of scarcity today. We now realize that firms and individuals react to these economic signals to use less or shift to other resources (substitutes). However, as the cobalt case demonstrates, the economic nature of scarcity means that even temporary limitations in availability can significantly affect how firms produce and use materials.

Given that context, there are clearly two mechanisms that must be considered in evaluating the risk of scarcity.

- **Institutional inefficiency**: failures by markets, firms, and governments can result in transitory resource unavailability. Such events temporarily close or tighten key valves in the system.
- **Physical constraints**: the amount and quality of a resource are physically determined and ultimately limit resource availability. Physical reality means that eventually the stocks will decline or the valves constrict.

These perspectives on the mechanisms of scarcity provide a useful scheme to categorize metrics that have emerged over time in the literature. Sources of, and a more in depth discussion of, these metrics can be found in [1].

### 40.7.1 Institutional inefficiency metrics

Table 40.1 lists some useful metrics to test for risk of institutional inefficiency within a materials economy. The most broadly cited measures of vulnerability to institutional inefficiency focus on concentration within the supply chain, at either the national or firm level.

Generally, the geographical distribution of reserves depends on geophysics, past depletion, and present exploration. In the face of uncertain external factors (such as political events and natural disaster), a higher level of concentration makes a resource more susceptible to institutional inefficiency and supply disruptions. Likewise, oligopsonistic markets are more vulnerable to fluctuations in demand, leading to market volatility.

Secondary production (i.e., recycling) can reduce institutional inefficiency risk for two reasons: (1) secondary production provides an additional source of supply (diversification); and (2) secondary stocks are often located and processed in different locations and by different institutions from those for primary stocks. The recycling rate is a broadly available indicator of the importance of recycled material as a resource. 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) is a metric that provides insight into this issue. Unfortunately, the RER is difficult to measure, and data must be derived from prospective modeling.

The final metric of institutional inefficiency listed in Table 40.1 is the market price of the commodity of interest. Price is one of the best measures of scarcity insofar as the market embeds many of the issues outlined above into pricing. However, price is often not a leading indicator; while price will ultimately be the trigger that initiates supply-chain change, effective response strategies must already be in place before prices go up.

### 40.7.2 Physical-constraint metrics

The outcomes arising from institutional inefficiency in the cobalt case could also have occurred from physical constraints. In this section, metrics of physical-constraint risk will be briefly defined, but their interpretation will be made through the case study which follows.

**Malthusian metrics**

The direct approach to measuring risk to geophysical limits is to compare how much of a resource is known to be available with how fast it is being used. Table 40.2 includes Malthusian-inspired metrics. The metrics are divided into two broad categories (static or dynamic).

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STATIC</strong></td>
<td>Static index of depletion ($d_s$, years)</td>
</tr>
<tr>
<td>Dynamic (exponential) index of depletion ($d_e$, years)</td>
<td>Time to use supplies at constant exponential growth of use rate: supply/ (projected use), where future use can be modeled as having exponential growth; $d_e = \frac{R}{C_{\text{present}}} + \left(\frac{1}{r\ln(r)} - 1\right)$, where $r$ is the rate of growth. Assumptions: use rate exponential; discovery rate negligible</td>
</tr>
<tr>
<td>Relative rates of discovery and extraction (unitless)</td>
<td>Ratio of rate of discovery to rate of use Assumptions: recycling/reuse and substitution negligible; improvement in extraction technologies negligible</td>
</tr>
<tr>
<td>Time to peak production (years)</td>
<td>Time until this forecast peak is reached: this metric is based on models of future rates. Assumption: rate of net use (demand minus substitution) will grow faster than rates of discovery, technological improvement, and recycling/reuse</td>
</tr>
<tr>
<td><strong>RICARDIAN</strong></td>
<td>Average ore grade (%)</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>Sum of technical costs (machines, fuel, labor, etc.), environmental costs, political costs, commercial costs (marketing, insurance, stock dividends) Assumptions: efficient markets in factors and capital; technological efficiency</td>
</tr>
<tr>
<td>Economic metric: market price ($)</td>
<td>Relative price, time trend. Assumption: efficient markets</td>
</tr>
</tbody>
</table>

After [1].
depending on the degree to which they treat the varying nature of the many interrelated rates (see Figure 40.5).

The static index of depletion is an estimate of the years to exhaust a material supply on the basis of present use rates and one of the four estimates of available supply: reserve, reserve base, resource, or resource base [8][10]. The dynamic index of depletion is a simple extension that includes changing use rate, for which expected use is derived from historical data. A material is considered more vulnerable if it has a low index of depletion.

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

These metrics all assume a decreasing supply base for nonrenewable resources. However, new discoveries, improved technology, increased recycling, and changes in resource economics have contributed to increases in supply 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 [11]. 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 is not considered.

Ricardian metrics

From a Ricardian viewpoint, scarcity should occur long before physical exhaustion since the difficulty and therefore cost of extraction increases [12]. The ore grade is a physical measure of the quality of supply [13]. In general, the lower the ore grade, the more earth will be displaced, energy will be expended, and waste will be generated to extract the resource. Ore grade alone, however, does not capture entirely 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 extraction from others (e.g., oxide minerals vs. sulfide minerals).

A more informative measure of quality is the cost of extraction. Increasing extraction costs would be expected to correlate with increasing vulnerability. The primary barrier to using extraction cost as a metric of risk is the public availability of data. Owing to the difficulty in obtaining cost data, many rely on incomplete proxies such as energy use, or labor or capital costs.

Market price is often viewed as the ultimate Ricardian metric. As was noted previously, variations in price might not provide enough time for a firm to react to changes in availability of materials.

40.7 Exploring the utility of metrics: the case of copper

This section demonstrates the use of metrics in the context of copper. Copper is a key building block of modern life and technology. As the y axis of Figure 40.6 shows, the value of global copper use is second only to those of aluminum and iron. This high value and the high rates of use that drive it contribute to apprehension about copper’s long-term availability.

Specifically, we will examine (1) a simple, imperfect screening metric, (2) the criteria for action on that metric, and (3) the use of more detailed measures for additional insight on risk. (Data for this section largely derive from [14][15].)

40.7.1 Screening for risk

The simplest way to screen for scarcity-based material vulnerability is to calculate the time to deplete the current supply – a static depletion index. The smallest measure of available supply is referred to as reserves, a measure of economically and technically available primary metal. Looking back at the x axis in Figure 40.6, we can see that the static depletion index based on reserves of copper is small, only 34 years.

Of course, this metric does not reflect the dynamics in the market, the changes in consumption, or the emergence of economically viable sources. This most conservative static estimate is indicative of the time frame within which new technologies for extraction or new sources must be found in order to continue the present yearly use under present economic conditions.

The first question that arises concerning the static depletion indices is as follows: what index values indicate a need for action? Unfortunately, there is no single or simple answer to that question. Several authors have examined this question and all suggest a figure of about
30 years for the magnitude of the managed reserve life relative to current use. Figure 40.7 shows that, while the static depletion index for copper reserves has oscillated over the last century, it has frequently returned to around 30 years. Thus, 30 years may serve as a threshold indicator for concern; greater values would represent conditions under which the primary industry is unmotivated to address geophysical scarcity, while values around or below 30 years would indicate a need for further evaluation. In terms of this criterion, copper sits on the border of concern.

Metrics of supply-chain concentration are useful indicators of vulnerability due to institutional inefficiency and can be readily calculated (e.g., see the US Geological Survey’s minerals commodity summaries published by the US Department of the Interior). This metric is plotted in Figure 40.8 for a range of commodities for 2009 guidelines applied by the US Department of Justice concerning supply concentration within a market. It suggests 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% [16][17][18]. Using those guidelines, copper merits attention.

While recycling can provide an alternative source for materials, into the foreseeable future, for most materials, primary production will remain the dominant source. This appears to be the case for copper. Recycling of old scrap accounts for less than one-fifth of global copper use. This suggests that at present recycling does not dramatically reduce the vulnerability of the copper supply chain. This represents an opportunity for firms to reduce their risk by fostering more copper recycling.

Further investigation into supply-chain risk: Ricardian measures
Throughout history, technological improvements have made it economically feasible to exploit lower and lower grades of ore. Between 1970 and 1993, when US copper grade remained a relatively constant 0.5%, the costs of western-world copper mining decreased. Although the impact of technological improvement is impressive, the overall trend in ore grade would indicate that copper supplies are shifting into a regime of increasing vulnerability. Technological improvements will have to keep pace even at lower ore grades in order to keep costs in

Figure 40.7. An estimate over time of the static depletion index based on reserves (in years) for copper. (After [1], updated data from [8].)

Figure 40.8. Geographical distributions of primary production for various metals, showing the top three producing countries for each metal in 2009. (After [1], updated data from [8].)
check. Unfortunately, data on ore grade are not publically available for all commodities.

Substitutes can come in many forms. The simplest source of a substitute is a recycled raw material. In addition, materials can sometimes be substituted for one another. In the case of copper, aluminum (also a good conductor of heat or power) and optical fibers (good conductors of information) are frequently considered substitutes. Finally, substitution may occur at the application level, with new products removing demand for those products that contain copper. A thorough discussion of this topic is beyond the scope of this chapter, but would be critical in any assessment of the risk exposure of a given firm.

40.7.2 Understanding 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 disruption to copper supplies 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 in order to mitigate these risks.

40.8 Responses to risk: preparing for limited availability

Because materials are so fundamental to the way in which a company operates, changing materials takes time and resources. Waiting until availability is limited probably means leaving it until it is too late to take that action. Managers need to assess risks to materials availability and, when appropriate, prepare for possible future problems.

Dealing with risk and uncertainty within the supply chain is a topic addressed by a growing literature [19]. First of all, this literature suggests that firms must “know” their supply. In the case of materials availability, this includes not only monitoring metrics of risk, but also fostering the exchange of information to ensure the accuracy of those metrics.

Additionally, firms should act to add flexibility (resilience). Conventionally this is achieved by having multiple suppliers and/or keeping inventory. In the case of materials, flexibility can be added by keeping inventory (which is expensive), developing alternative sources of supply, developing substitutes, and recycling. The latter two options take time to develop and must be in place before a crisis occurs.

Finally, firms should act to increase robustness with respect to materials-availability events by slowing primary use. This can be accomplished by developing processes that are more efficient or, as with flexibility, by ensuring that an effective recycling infrastructure exists.

Knowledge, flexibility, and robustness are broad measures for 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. The next section will explore one modification – increased recycling – in more detail. Increasing recycling could make a supply chain more flexible and robust, and might provide environmental benefits.

40.9 Recycling

Few discussions of strategies to address modern-day environmental challenges are complete without praise for recycling. Therefore, recycling is well established in the consciousness of citizens throughout the developed world. Nevertheless, few are familiar with the specific benefits and barriers associated with recycling or, more precisely, increasing recycling. Before discussing those in detail, it is important to point out that, like all activities, recycling is not universally beneficial. While most recycling produces real environmental benefits and all regions of the world could improve aspects of their recycling systems, there are and always will be cases in which the environmental cost of recycling outweighs any demonstrable environmental benefit [20]. This issue will be revisited later, but the next section will focus on the bulk of cases in which benefit outweighs cost and much room for improvement exists.

Before getting to those issues with recycling, it is useful to pause and consider the following question: how effectively do we recycle? As with many things, the answer is that it depends on various factors. First, let's consider how much waste we generate. In 2010, residents of OECD countries collectively generated well over 600 million tons of municipal solid waste. Rates of generation, however, vary widely, with countries such as Norway and the USA discarding more than 2 kg per person per day while Mexico, Poland, and others discard less than 1 kg [21]. Culture, income, and policy also drive vastly different practices regarding that waste. For example, in Switzerland in 2009, 51% of MSW was recovered for recycling or composting [22]. In the USA in 2008, a little over 33% of MSW was recycled or composted [23]. The effectiveness of recycling also varies dramatically by product. As Figure 40.9 shows, recycling rates in the USA can vary from nearly 100% for automotive batteries to below 30% for plastic and glass bottles. As these figures indicate, there is still a lot of room to increase the recycling of many products and materials.
Benefits of recycling

The societal benefits of recycling when compared with other forms of waste management (i.e., landfilling or incineration) can be grouped broadly into five categories. These can include:

- avoiding resource depletion,
- reducing energy consumption and emissions,
- economic returns,
- diversified institutional risks,
- market stabilization.

Avoiding resource depletion

The first benefit of recycling is definitional in nature. When we use secondary raw materials we avoid the use of primary raw materials. In doing so, we leave an additional unit of primary resource undisturbed for future use. Global statistics on recycling are not uniformly available. Nevertheless, from what information we have, it seems clear that recycling is growing for most major commodities. Considering aluminum as a representative example, recovery of aluminum from secondary sources has more than tripled in the last 30 years. Unfortunately, overall demand for aluminum has matched that growth over the same period, such that today recycled aluminum accounts for roughly the same fraction of total production as it did in 1980. See Figure 40.10.

Reducing energy consumption and emissions

It is well documented that for many materials, and particularly for metals, the substitution of primary with secondary resources, i.e., those recovered from manufacturing waste or end-of-life products, decreases energy consumption and the attendant environmental burden of production (Figure 40.11). Aluminum, the material selected as a case for this chapter, serves as an excellent example due to the large energy differences between primary and secondary production: 175 MJ kg\(^{-1}\) for primary compared with 10–20 MJ kg\(^{-1}\) for secondary [24]. However, aluminum is by far not the most extreme case. For some precious metals, such as gold and platinum, the energy difference can exceed two orders of magnitude.

Economic returns

Recycling is an activity that has gone on for as long as humankind has used materials. This is true because, for many materials, recycling saves money. On looking at Figure 40.11 it is clear that the self-same energy benefit...
that provides an environmental driver to recycle can provide a (sometimes dramatic) economic driver as well. To get a sense of the magnitude of the economic benefit, consider these facts. In 2009, the Aluminum Association (the industry association for aluminum producers) estimated that in the USA approximately 41 billion aluminum cans were landfilled. If that material alone were recovered, it could have displaced nearly 1 billion dollars’ worth of primary aluminum production.

Unfortunately, for many products, the economic incentive by itself is not sufficiently large to fund an effective recycling system. For these commodities, government policies may be implemented to increase recycling rates. Generally, such programs come at a cost to taxpayers. However, authors of a range of studies have demonstrated that there are generally secondary economic returns from recycling programs. These may come from additional employment, savings for downstream processors, or the avoidance of social costs associated with pollution. Whether the benefits outweigh the costs depends upon the commodity, the characteristics of the collection system, and the scope of effects included [20]. For organic commodities, it is always important to consider whether energy recovery rather than strictly defined recycling may be the more fiscally prudent alternative [25].

Diversified institutional risks
As was discussed earlier, one characteristic of a material system that makes it more vulnerable to economically significant availability-related crises is the diversity of sources that provide that material. More diversity reduces the risk of a major crisis. The nature of geography, geology, and consumption means that, for many materials, where primary processing happens is not where secondary processing happens. Because primary production is generally more energy-intensive, primary processing facilities tend to be located where energy is least expensive. This is moderated by all the normal considerations that go into the geography of supply chains, but seems to capture a general trend. These primary production sites are often far from the wealthy countries where most consumption and, therefore, retirement of products occurs.

Considering our example system of aluminum, Figure 40.12 shows how global secondary production is more distributed, and distributed differently, than primary production.

Market stabilization
Materials markets are subject to all of the vagaries that confront any business, but are especially exposed to price variation due to their strong tie to (unpredictable) economic cycles, their position at the end of the supply chain [26], and the difficulty and expense associated with adding or removing capacity. Recent empirical evidence suggests that recycling can mute this effect in a materials market. Specifically, by more nimbly expanding and contracting capacity, secondary production allows materials markets to be more resilient with respect to natural oscillations in demand [27].

40.9.2 Issues to consider
While recycling can provide real economic and environmental benefits, realizing those benefits requires overcoming the challenges and barriers that hold down recycling rates.

Technological issues
Over the last two centuries, the minerals and mining industries have been developing the infrastructure to economically win useful materials from primary resources. Although these resources can be compositionally heterogeneous, the technologies in place have been tailored to those specific compositional challenges. Unfortunately, the forms of heterogeneity associated with secondary raw materials are very different from that of mineral ores, so heterogeneity remains a fundamental challenge to any form of recycling.

Additionally, some authors, e.g., [28] have raised concerns that the repeated recycling of a resource compounds this heterogeneity, degrading the resource and making it increasingly difficult to reuse. This is due to the accumulation of certain elements, compounds, or microstructural changes in the material stream. The mechanisms for accumulation are varied. Many materials, particularly metals, contain alloying elements that are added purposefully in order to achieve desired properties in the final product. Joining that occurs during product manufacturing can mix materials due to welds,
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rivets, nails, and adhesives as well as impairing separation at the product’s end of life. Elements from cutting machinery, typically iron from steel cutting instruments, can be introduced during fabrication. Many materials become mixed during collection at their end of life as well. Other sources include end-of-life processing such as crushing, shredding, and paint removal. Fiber length, an important property for paper, decreases with increased recycling. Similarly, organics suffer degradation of chain length (or relative molecular mass) as well as introduction of impurities during their service life or through the rigors of recycling.

Regardless of the mechanism, there is a variety of operational and technological solutions that firms can employ to mitigate the impact of heterogeneity and accumulation. These include dismantling of end-of-life products, sorting of scrap, and “filtration” technologies that remove elements in the melt, such as fractional crystallization and vacuum distillation. Although it is clear that such strategies provide technical benefit, they are not always economically viable.

Consumer participation
For many materials, the largest barrier to increased recycling is one that is rarely mentioned by engineers and scientists. That is consumer participation. Given the current price of resources, if a consumer does not place a product into the recycling stream, the resources in that product are not recovered. Unfortunately, for many materials consumer recycling remains limited [29].

Limited consumer participation partly occurs because of the high cost of collection [30][31]. This cost limits the availability and scope of curbside programs and the availability of alternative collection points for recyclables. To expand recycling, it is necessary to remove or reduce these disincentives to return and collect secondary material. Finally, consumer participation is often limited by knowledge or attitudes about recycling. Although it is not a cure-all, the engineering community must work to ensure that accurate information about the benefits to recycling is available. One approach that has proven to be effective in encouraging consumer recycling is creating a financial incentive. As an example, in the USA, states that have deposit systems for beverage containers average a recycling rate over 74% (fraction of containers recovered). In contrast, those states without deposit systems have an average recycling rate of only 24%. As noted previously, the costs and benefits of recycling must always be evaluated for each case. Nevertheless, this clearly shows that much higher levels of recovery are achievable.

Economic and energetic issues
Despite all of the benefits of recycling, it is still true that some effort must be expended to separate particular waste streams and get them to appropriate processing systems so that resources can be recovered and recycled. In most cases, this requires additional energy and comes at an added cost compared with conventional waste disposal (which generally must occur whether recycling happens or not). These energy and financial costs derive from the cost of separate collection infrastructure (e.g., recycling centers and trucks), transport of recyclables to generally more geographically distributed recycling facilities, pre-processing of recyclables to segment them and remove contamination, and, finally, from the recycling process itself. Although in many cases these additional costs are more than offset by the benefits of recycling, they should always be carefully considered.

40.10 Summary
Recent price swings have placed a renewed spotlight on the business implications of raw materials. This raises three key questions for firms. (1) How does limited materials availability affect a firm? (2) How can a firm know whether it is using materials that are at risk of becoming of limited availability? (3) What can that firm do to mitigate that risk?

When a limited-availability event occurs, the supply chain could experience significant changes, specifically:

- **technological**: materials substitution and process efficiency;
- **geographical**: mining exploration and source relocation; and
- **operational**: in transportation modes, increased inventory, and development of a recycling infrastructure.

In some cases, even if availability is limited for only a short period of time, these changes can be permanent.

It is important to note that the availability of materials can be limited by institutional inefficiency, in addition to the classically discussed mechanism of global physical constraint.

The materials-scarcity literature suggests a number of metrics that indicate an increased risk of limited availability. Unfortunately, due to the complexity of any materials market, no one metric captures all aspects of risk. Nevertheless, careful application of metrics offers insights that should help guide a firm’s strategy.

One strategy that would benefit most firms that depend on materials is recycling. Recycling provides environmental and economic benefits. Nevertheless, increasing recycling can be challenging, given the heterogeneity of materials in most modern products, lagging customer participation, and challenging economics that militates against investment in technology.

As technology advances, we tap into a broader swath of the periodic table. In many cases, this means relying
on elements with less well-developed extraction technology and infrastructure. Engineers and scientists should carefully understand the structure and vulnerabilities of the resource supplies on which they depend and foster the technology and infrastructure for making those supplies reliable and sustainable.

40.11 Questions for discussion

1. In what way(s) would limited availability for material X affect a firm that uses X in the products it produces? If the availability of material X became constrained, how would we expect the firms that make use of X to respond? What changes would we expect in the various supply chains (that is, the collection of firms that work together toward the production of a given good) that make use of X?

2. In most parts of the world, there are formal and informal systems designed to recycle aluminum cans and other metal packaging. What are the benefits of recycling systems like this? What are some of the issues that should be considered before a new recycling system is created?

3. Name three specific challenges that confront the increased recycling of any material.

4. How could a limited environmental capacity for pollution be considered as creating another form of limitation on materials’ availability?

5. Albeit imperfect, the static and dynamic depletion indices are easy-to-calculate screening metrics for physical availability risk. Basic information to calculate these metrics is freely available from the United States Geological Survey within the Mineral Commodities Summaries (MCSs) that are published annually. (As of the publication of this text, these can be found at http://minerals.usgs.gov/minerals/pubs/mcs/ or you can search for USGS mineral commodities summaries to find the current link.) Each summary contains the most recent estimate of mine production and reserves (and often the reserve base).

(a) Using the data for the 2009 MCS (in the 2010 reports), calculate values of the static depletion index for cobalt, nickel, and tin.

(b) Assuming that the mine production rate for cobalt has been growing approximately 10% per year, estimate the dynamic (exponential) depletion index.

6. Your colleague has told you that the dynamic depletion index for mercury is larger than the static depletion index. Is this possible? If so, how? That is, what characteristics of the magnitude of resources or usage of mercury would likely lead to such relative metric values?

40.12 Further reading


40.13 References


41.1 Focus

Life-cycle assessment (LCA) evaluates the energy and material requirements and resulting environmental impacts of a product or process over its entire life cycle from raw-material extraction to disposal. This examination across the life cycle provides a systems perspective that can aid decision making for product optimization, product selection, and supply-chain management.

41.2 Synopsis

Life-cycle assessment evaluates the environmental impacts of a product or process over its entire life cycle. It can provide an environmental profile of a system or process through the evaluation of inputs, outputs, and potential environmental impacts. There are generally two approaches to conducting an LCA, namely, a process-oriented approach and an economic input–output approach. In a process-oriented assessment, the inputs and outputs are itemized for each step in the process. Specifically, the five steps considered are raw-material acquisition or extraction, material processing, product manufacturing, use, and recovery and retirement. An optional transportation stage can also be added. In contrast, the latter type of assessment considers the required materials and energy resources (inputs) of a process to estimate the resulting environmental emissions (outputs).

When completing an LCA, there are typically four steps. These include goal definition, life-cycle inventory, life-cycle impact assessment, and interpretation of results. The goal definition identifies the types of information and data that are needed and the appropriate level of accuracy. The inventory identifies and quantifies the relevant inputs and outputs. The impact assessment characterizes and assesses the environmental burdens identified in the inventory. The interpretation improves understanding of results to aid decision making.

Life-cycle approaches to problem solving have informed other decision-making tools, including life-cycle cost analysis and life-cycle management.