Employing Considerations of Criticality in Product Design

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Abstract

With no agreed-upon definition of critical materials, product and process designers have been unable to systematically address the critical materials issue. Utilizing a comprehensive methodology, we have determined the criticality of 62 metals and metalloids – about two-thirds of the periodic table. We illustrate how the analyses were performed, provide an overview of criticality at the global level for all elements, and then present examples of how the criticality information could be used in making material-related choices in product and process design.

1. Introduction

"Criticality" is the quality, state, or degree of being of the highest importance, and is of particular interest in the case of metals. The concept is far from straightforward: it must deal with a wide variety of factors such as geological deposits, geographical concentration of deposits or processing facilities, social issues, regulatory structures, geopolitics, environmental issues, recycling potential, and sustainability, to name only some that have been utilized. The factors that are selected can be aggregated in various ways. Unlike precise scientific analysis, there is no perfect set of factor choices.

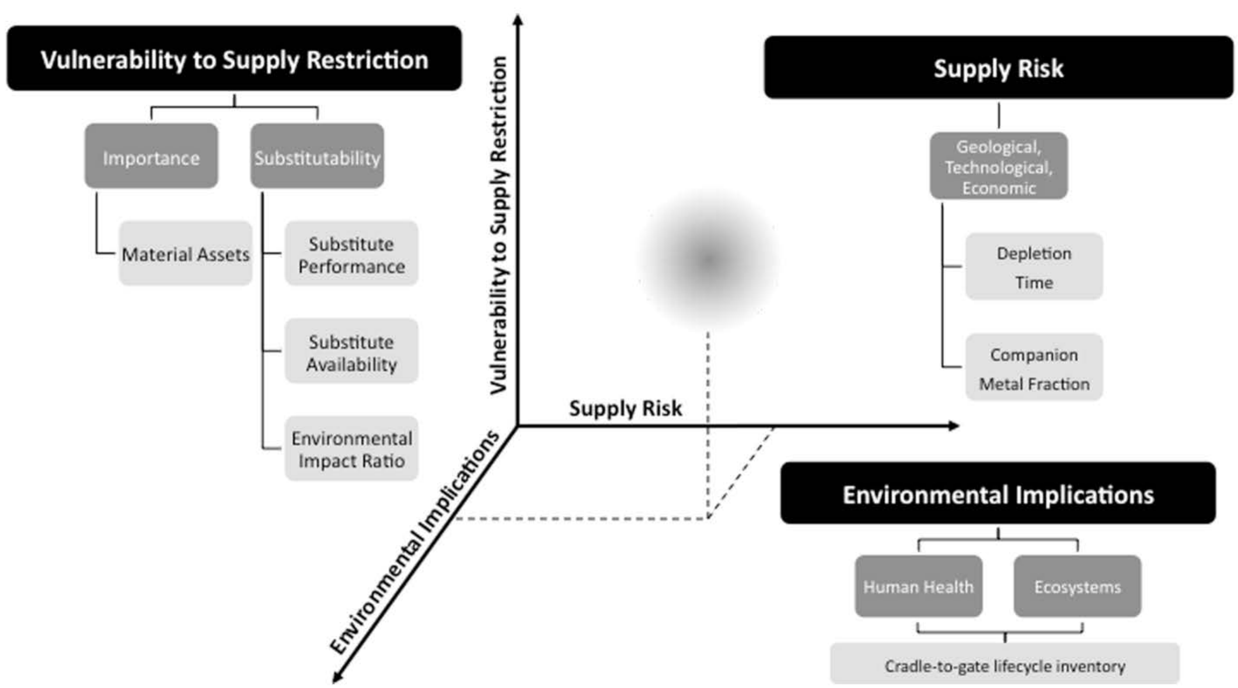
The study of the criticality of metals is a response to what Kaplan [1] termed the "three risk questions": (*i*) What can happen? (*ii*) How likely is it? (*iii*) What are the consequences? From that perspective, the response to the first question is "The metal that is desired will not be routinely available in sufficient quantities at affordable prices". The second question inspires two others: What is the prospect that metal demand will not be met? (where the answer is some function of geology, culture, regulation, and international trade), and "Even if metal demand could be met, might we choose not to do so? (where the probable degree of environmental consequences resulting from responding to the demand is deemed to be too high). Kaplan's third question requires that one define the entity that could suffer the consequences (a particular corporation, the planet, etc.) and then determine for that entity what consequences might ensue. In the context of metal criticality, we seek to respond to this question.

In this paper, we present a detailed methodology that addresses the criticality issue in detail, choosing characteristics of criticality that appear to have the greatest validity and the most widespread support. We then apply this perspective to the consideration of materials selection in engineering design.

2. Characterizing the Criticality of a Metal: An Example

Metal criticality can be, and has been, assessed by different methodologies (e.g., [2], [3]). A variety of metrics can be chosen, and aggregation may be performed in different ways (e.g., [4]). Our methodology aims to locate metals in what we term "criticality space". Criticality space consists of three axes: supply risk (SR, one facet of the likelihood of unavailability), environmental implications (EI, a second facet of the likelihood of unavailability), and vulnerability to supply restriction (VSR, the assessment of consequences) (Figure 1).

Figure 1. The Yale three-dimensional criticality methodology at the global level (taken from [5]) with the metrics described in detail in ref [6]).



Each axis is comprised of equally weighted components that, in turn, are comprised of equally weighted indicators. The evaluation of those axes is not the same for all inquirers, as different inquirers have different degrees and types of vulnerabilities. In analyses at the corporate level, a particular metal may be crucial to the product line or operations of some corporations, but of little or no importance to others. Similarly, countries with a strong industrial base will value certain metals more than may technologically depauperate countries. As a consequence, we have developed related but different methodologies at the corporate, national, and global levels. For clarity of presentation, we restrict ourselves here to the global level, a choice that thereby eliminates consideration of factors such as local regulations or the trade of resources that would be part of a geographically-specific analysis. Examples of criticality evaluations at national and corporate levels appear elsewhere [7], [8].

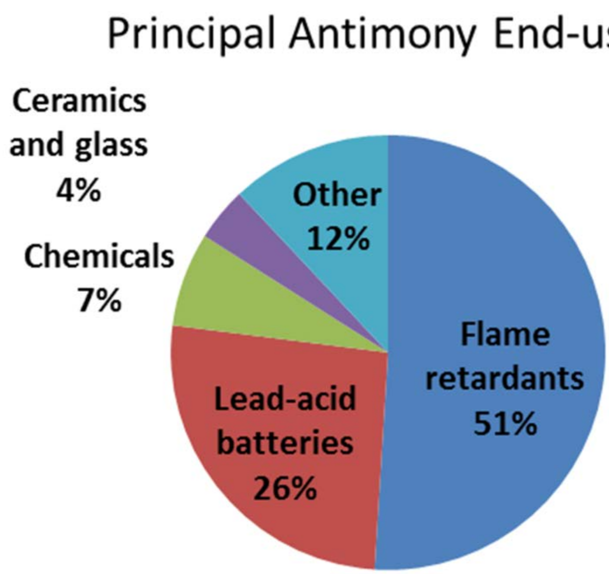
Employing the methodology described above is a detailed exercise, and as the details are described elsewhere [6], [9] they need not be dwelt upon here in detail. However, a brief summary is appropriate. We locate individual metals in criticality space on the basis of a number of criticality-related indicators, each measured on a 0-100 scale. In some cases it was necessary for us to collect or derive information not previously published [10].

Temporal complexities related to criticality are also important, because a number of the evaluating metrics may evolve over time – geologically-accessible stocks, recycling rates, and technological transformations involving different materials approaches, to name a few. As a consequence, no single approach is suitable for all time scales or all interested parties. Criticality is thus a snapshot in time for a particular user of the information.

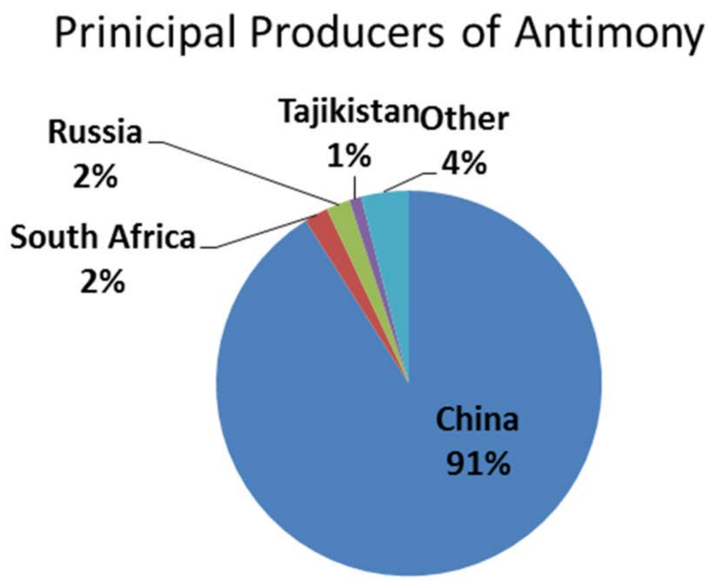
To illustrate the results of a typical analysis, we present an example of carrying out such a process for antimony, a trace constituent of lead and copper ores. Antimony's major uses are as a flame retardant in plastics and as an accumulator (grid) in lead-acid batteries, with smaller employment in ceramics and glass and chemicals [11], as shown in Figure 2(a). Nearly all antimony production occurs in China (Figure 2(b)). The geological reserve base (that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices) is somewhat more widely distributed, but China still hosts more than half the global amount (Figure 2(c)). This geographical concentration of ore deposits and active production is, in itself, enough to raise warnings of potential criticality.

Figure 2.

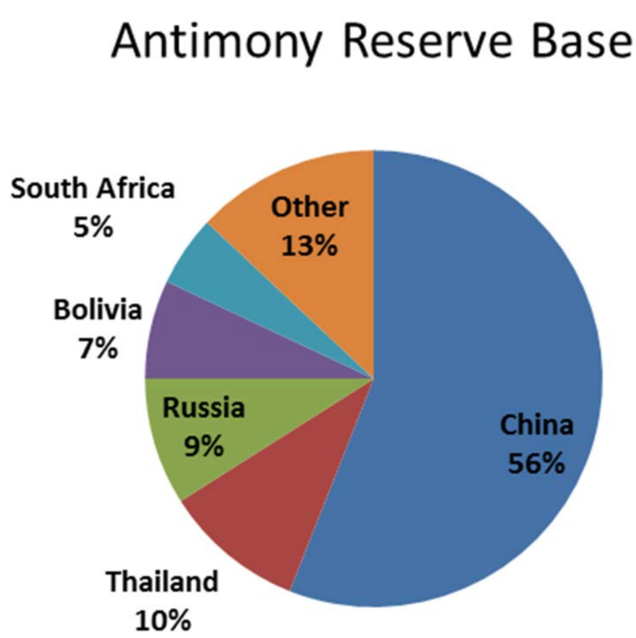
(a) The principal uses of antimony in technology. The data are from Roskill [11].



(b) The principal countries producing antimony. The data are from the US Geological Survey [12].

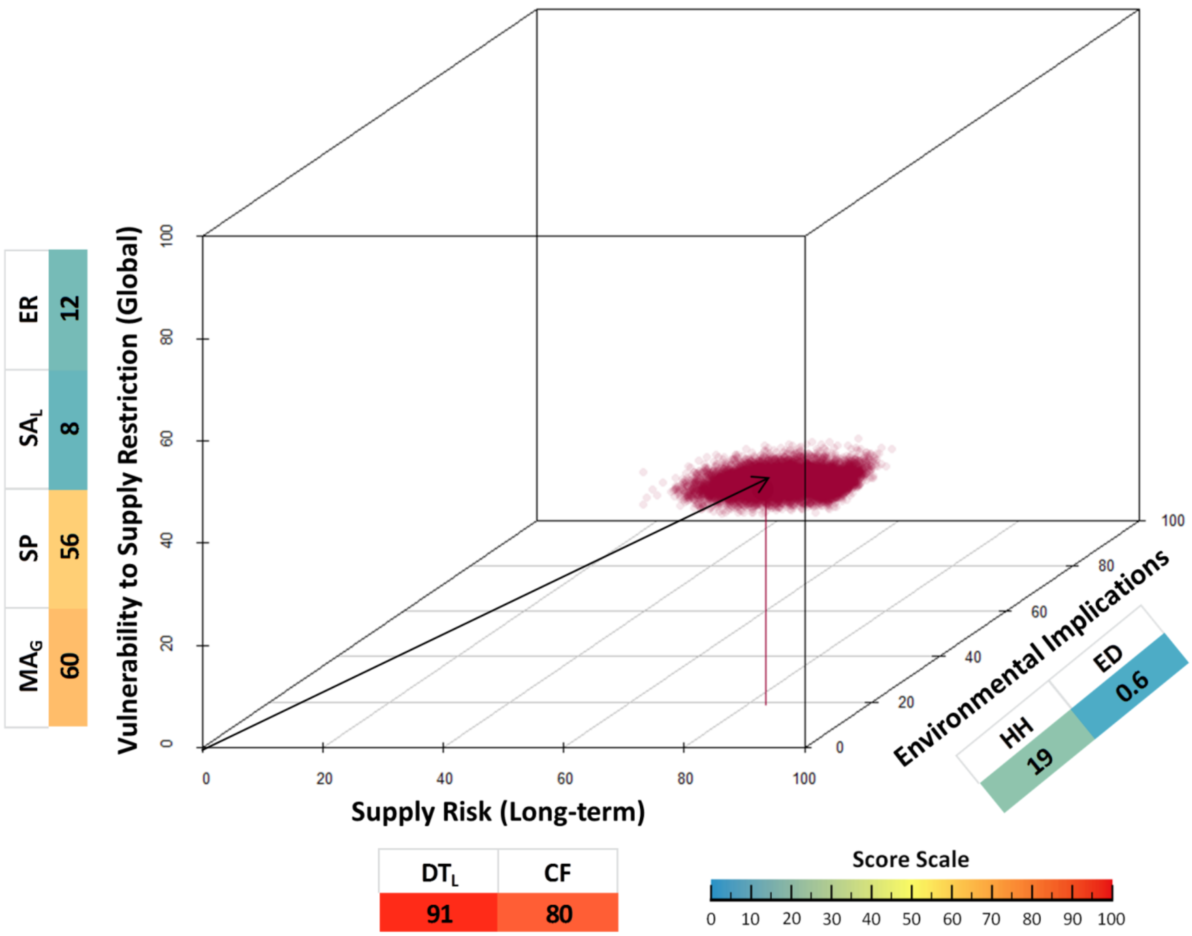


(c) Antimony reserve base estimates for highest magnitude countries. The data are from the US Geological Survey [13].



The criticality assessment for antimony is depicted in Figure 3, with the individual indicator values rendered by color on a 0-100 scale. The details of each individual evaluation are presented in detail by Panousi et al. [14]. For the Supply Risk axis, the individual evaluations include depletion time (with reserve base) and companion metal fraction (i.e., the percentage of a metal obtained together with another host metal). With a score of 91 for depletion time and 80 for companion metal fraction, respectively, both indicators were found to be quite high (Figure 3). The Environmental Implications for antimony are in the lower third of the 0-100 axis (which has been designed to display all 62 elements investigated in our criticality assessments). Vulnerability to Supply Risk is generally moderate: the metal is of mid-level importance but adequately-performing substitutes for most uses are available [14]. Monte-Carlo simulation is used to derive an “uncertainty cloud” around the criticality mean value in Figure 3.

Figure 3. Assessment of individual contributing metrics and overall criticality evaluation for antimony for year 2008, global level (Panousi et al., 2014). The arrow is the criticality vector magnitude, a factor discussed in the text. The uncertainty of each of the three axis is derived using Monte-Carlo analysis and plotted in 3-D space to derive an "uncertainty cloud". DT_L = Depletion Time (global) (using reserve base), CF = Companion Metal Fraction, HH = Human Health Damage, ED = Ecosystem Damage, MA_G = Material Assets (global), SP = Substitution Potential, SA_L = Substitute Availability, ER = Environmental Impact Ratio. Environmental Impacts were derived using the ReCiPe 1.10 H/H Endpoint Impact Assessment Method and represent the damages to human health and ecosystems after normalization and weighting. Please note that because of the global normalization factors, ecosystem damage is significantly lower than human health implications. Substitutes included in the Vulnerability to Supply Restriction (VSR) analysis include alumina, calcium, tin, and titanium [14].



A measure of overall criticality may be derived by calculating the "criticality vector magnitude" $\|C\|$ as follows [6]:

$$\|C\| = \frac{\sqrt{SR^2 + EI^2 + VSR^2}}{\sqrt{3}} \quad (1)$$

where SR = Supply Risk (long-term), EI = Environmental Implications, VSR = Vulnerability to Supply Restriction (VSR) (global), and the square root of 3 in the denominator is used as a normalization factor.

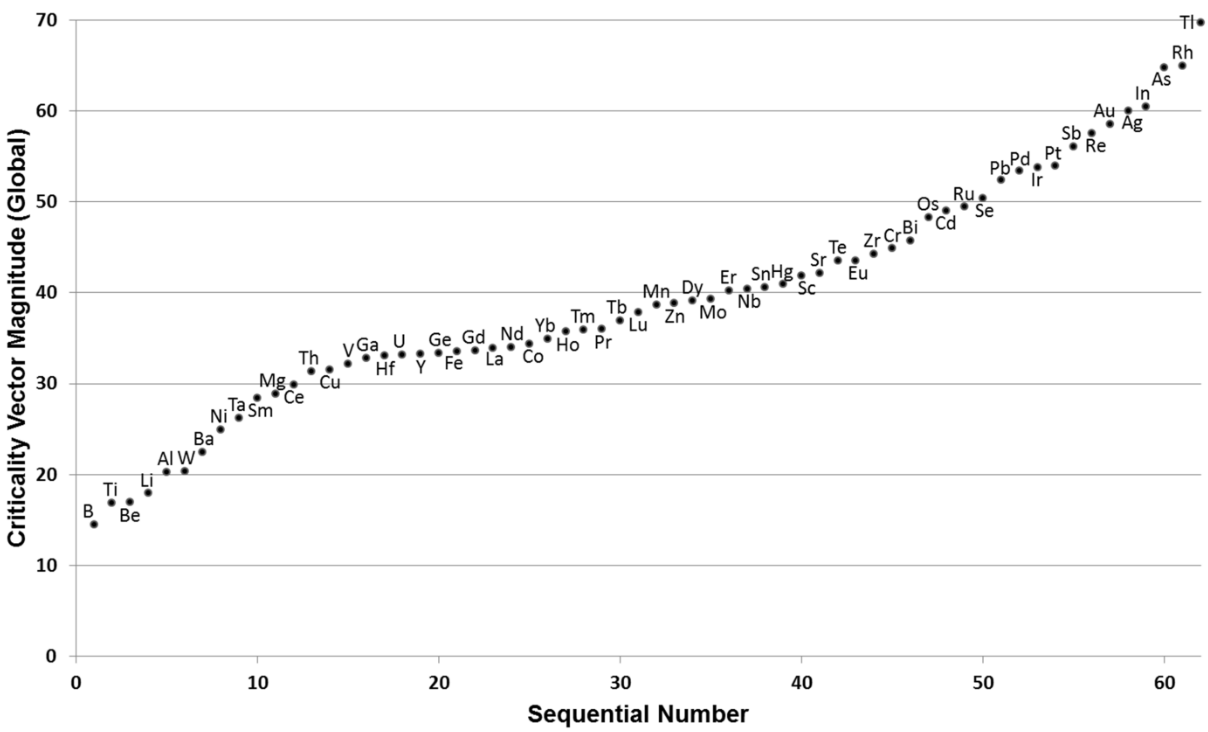
The criticality vector magnitude (CVM) is indicated on Figure 3 by the black arrow from the ordinate to the center of the uncertainty cloud.

3. Criticality of Metals: A General View

Because product and process designers make use of a very wide range of materials, we have characterized the criticalities of 62 different metals and metalloids (termed "metals" hereafter for brevity). The list includes essentially all the elements except the highly soluble alkalis and halogens, the "grand nutrients" (C, N, P, S), the noble gases, and highly radioactive species. For each of the 62 metals we evaluated some 25 indicators in order to generate rankings on the three axes in criticality space, as illustrated in Figure 3 for antimony. The detailed results of these efforts are reported separately [7]–[9], [14]–[16].

In this paper we rely upon the criticality vector magnitude (CVM) as the most appropriate indicator of criticality, as it is the most comprehensive, encompassing all of the indicators (SR, EI, VSR) in a single value. The CVM_G ("G" for global) values from lowest to highest for 62 metals at the global level for year 2008 are shown in Figure 4. Most of the metals are not highly critical, nor minimally critical, but form a large grouping near the middle values of the metric. We identify several elements at the extremes, however: thallium, rhodium, arsenic, indium, silver, gold, and rhenium as "most critical" and boron, titanium, beryllium and lithium as "least critical".

Figure 4. Criticality vector magnitudes (CVM_G) for 62 metals, year 2008, global level.



The elements with high CVM values share several common criticality properties. The first is that they are available largely or entirely as "companion metals"; that is, they are seldom or never mined for themselves, but instead are available largely or entirely as byproducts of the ores of more abundant metals. This is potentially problematic, as their supply is dependent largely on the level of demand for their host metals rather than on demand for themselves. Conversely, light demand for the by-products can lead to oversupply of some metals. A second characteristic of the high-CVM metals is that there are few or no suitable substitutes for their principal uses [5]. Finally, they are generally used in small quantities in complex products, rendering their recyclability often challenging [17].

4. Employing Considerations of Criticality in Product Design

The choice of materials in product design begins with their technical attributes (tensile strength, thermal conductivity, and so forth). As Ashby and Johnson [18] point out, however, technical attributes are only the starting point. Other considerations include regulations, workability, and cost, to name a few. In recent years, incidences of supply restriction (e.g., [19], [20]) have brought metal criticality to the attention of product designers. The challenge has been to understand how to respond to a cacophony of concerned voices offering little in the way of specific guidance, especially over the longer term.

An important perspective is to compare metal criticality with toxicity. It is rather easy to say whether an element is highly toxic (mercury, osmium) or of negligible toxicity (aluminum, iron). The difficulty is with materials whose toxicity is between these extremes – how is a decision to be made on whether to consider their use? Criticality is similar in character to toxicity – some metals are demonstrably scarce and have high embodied energy (platinum, rhenium), while others are the opposite (vanadium, zinc). Again the challenge for the product designer is how to consider metals with intermediate properties (criticality, in this case).

We demonstrate above that for each metal we have derived a value for Supply Risk, Environmental Implications, Vulnerability to Supply Restriction, and Criticality Vector Magnitude (along with a great deal of supporting information). How might a product or process designer make use of such resources? We suggest here a few thoughts in order to respond to this question.

Table 1 presents five lists of metals, divided into groups on the basis of their global CVM scores. Those metals in Group 1 can be considered to have negligible criticality (CVM_G scores between 14 and 25), those in Group 5 to have high criticality (CVM_G scores between 59 and 70). Unless the product or process under design demands physical properties that only occur in Group 4 or 5 metals, metals in lower groups should be considered. For example, a jewelry designer might favor copper (Group 2) over silver (Group 5) in a moderately-priced jewelry design. For a more complex situation where metals are used in combination but where the attention is on elemental properties, a slightly more nuanced evaluation is possible. Figure 5 illustrates the approach for two thin-film solar cell options – cadmium telluride (using Cd, and Te) and copper-indium-gallium-selenide (CIGS) (using Cu, In, Ga, and Se). In the former example, cadmium falls into Group 4 and tellurium into Group 3. In the latter case, the group memberships are mixed, but indium is a Group 5 member. Overall, there is perhaps a slight preference for the CdTe option so long as a watchful eye is kept on the cadmium situation.

Table 1. The grouping of metals by critical vector magnitude (CVM) values

Group	Criticality Range (CVM_G)	CVM_G Group Members*
1	14 to 25	B, Li, Be, Al, Ti, Ni, Ba, W
2	26 to 36	Mg, V, Fe, Co, Cu, Ga, Ge, Y, La, Ce, Pr, Nd, Sm, Gd, Ho, Tm, Yb, Hf, Ta, Th, U
3	37 to 47	Tb, Lu, Mn, Zn, Dy, Mo, Er, Nb, Sn, Hg, Sc, Sr, Te, Eu, Zr, Cr, Bi
4	48 to 58	Se, Ru, Pd, Cd, Sb, Re, Os, Ir, Pt, Pb
5	59 to 70	As, Rh, Ag, In, Au, Tl

* Listed in atomic number order. Group 1 metals are the least critical and group 5 metals are the most critical.

Figure 5. Criticality evaluations of thin film solar cells and engineering alloys.

Application	CdTe Solar Cell		CIGS Solar Cell			
Element	Cd	Te	Cu	In	Ga	Se
CVM_G[1]	49	44	32	61	33	50
CVM Group	4	3	2	5	2	4
SR_L[2]	70	53	22	98	50	74
SR_L Group	4	3	2	5	3	4
Application	Galvanized Carbon Steel			301 Stainless Steel		
Element	Fe	Mn	Zn	Fe	Cr	Ni
CVM_G[1]	33	39	39	33	45	25
CVM Group	2	3	3	2	3	1
SR_L[2]	0	1	46	0	44	1
SR_L Group	1	1	3	1	3	1

[1]Criticality Vector Magnitude calculated from supply risk, environmental implications, and vulnerability to supply restriction scores for each element at the global level.
[2]Supply risk (long-term) calculated using the depletion time (with reserve base) and companion metal fraction for each element.

A still more complex challenge is that of alloys, the material form in which most metals are used. Consider a product that could employ either galvanized carbon steel (using Fe, Mn, and Zn) or alloy 301 stainless steel (using Fe, Cr, and Ni). Figure 5 shows the metals and their CVM_G groups. The similar group ratings of the metals involved makes the choice between both alloys difficult from a criticality perspective, but chromium may be an element to investigate further (its CVM_G is slightly elevated because of issues with substitutability, e.g., in the element's use in industrial machinery operating at high temperatures or corrosive environments [8]).

Another option for some products could be to regard environmental issues as not relevant, and to consider that any vulnerability issues can be addressed by developing alternative metal sources, improving metal utilization in manufacturing, and/or developing enhanced product recycling [21]. The criticality analysis then reduces to Supply Risk only, with groupings as shown in Table 2. The analysis for thin-film solar cells in this latter approach is similar to that for the CVM analysis – a very slight preference for the CdTe solar cell alternative. For the engineering alloys, however, limiting the criticality evaluation to Supply Risk renders the ratings for the two alloys essentially equivalent.

Table 2. The grouping of metals by supply risk (SR_L) values

Group	Criticality Range (SR_L)	SR_L Group Members*
1	0 to 20	Li, Be, B, Mg, Al, Ti, Mn, Fe, Ni, Ba, W, Pt, Au, Hg
2	21 to 40	Cu, Ta, U, Rh, Nb, Pd
3	41 to 60	Sc, V, Cr, Co, Zn, Ga, Ge, Sr, Y, Mo, Ru, Sn, Te, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Re, Os, Ir, Pb, Th
4	61 to 80	Se, Zr, Ag, Cd, Bi
5	81 to 100	As, In, Sb, Tl

* Listed in atomic number order. Group 1 metals are the least critical and group 5 metals are the most critical.

5. Discussion

Criticality is an important consideration in materials selection, but it is not the *only* consideration. This is particularly true at this point in time, with criticality a rather newly-recognized concern, and evaluation approaches still being assessed. Issues of data availability and data quality remain; to a different degree for different metals. As a consequence, our suggestions for a materials selection methodology based on criticality information remain preliminary. Nonetheless, in most cases it is likely that the general thrust of information now at hand is relatively clear, and that choices based on that information can be expected to hold up over time.

Our methodology is best regarded as appropriate for moderate (5-10 years) or longer (10-20 years) time scales; that is, we do not attempt to capture such short-term features as economic fluctuations, natural disasters, or the like. Formally, the results that follow are for a "snapshot in time": the year 2008. We are now in the process of updating our database to 2012, but anticipate only very modest revisions in the data, and regard the results that we present here as fully applicable over the medium and longer time scales we have aimed to capture.

A final word is appropriate: there is no such thing as "critical" or "not critical. There are, however, metals that are more critical than others under some conditions, for some users, and for some time scales. Particularly in the case of products with long life spans during which parts replacement would ideally utilize identical copies of the originals (e.g., aircraft turbine blades), criticality considerations would seem to be an important aspect of materials choice. Using materials of low to moderate criticality, where possible, has the potential both to benefit corporations and to play a role in minimizing long-term disruption to the supplies of truly critical materials.

6. References

[1] S. Kaplan, "The Words of Risk Analysis," *Risk Anal.*, vol. 17, no. 4, pp. 407–417, Aug. 1997.

[2] B. Buijs and H. Sievers, "Critical Thinking about Critical Minerals: Assessing risks related to resource security," CIEP (Clingendael International Energy Program) and BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), 2012.

[3] B. Achzet and C. Helbig, "How to evaluate raw material supply risks—an overview," *Resour. Policy*, vol. 38, no. 4, pp. 435–447, Dec. 2013.

[4] EC, "Report on Critical Raw Materials for the EU," European Commission (EC), Brussels, Belgium, 2014.

[5] T. E. Graedel, E. M. Harper, N. T. Nassar, and B. K. Reck, "On the materials basis of modern society," *Proc. Natl. Acad. Sci.*, vol. 112, no. 14, pp. 6295–6300, 2015.

[6] T. E. Graedel, R. Barr, C. Chandler, T. Chase, J. Choi, L. Christoffersen, E. Friedlander, C. Henly, C. Jun, N. T. Nassar, D. Schechner, S. Warren, M. Yang, and C. Zhu, "Methodology of Metal Criticality Determination," *Environ. Sci. Technol.*, vol. 46, no. 2, pp. 1063–1070, Jan. 2012.

[7] N. Nassar, R. Barr, M. Browning, Z. Diao, E. Friedlander, E. M. Harper, C. Henly, G. Kavlak, S. Kwatra, C. Jun, S. Warren, M.-Y. Yang, and T. E. Graedel, “Criticality of the Geological Copper Family,” *Environ. Sci. Technol.*, vol. 46, no. 2, pp. 1071–1078, Jan. 2012.
[8] P. Nuss, E. M. Harper, N. T. Nassar, B. K. Reck, and T. E. Graedel, “Criticality of Iron and Its Principal Alloying Elements,” *Environ. Sci. Technol.*, vol. 48, no. 7, pp. 4171–4177, Apr. 2014.
[9] E. Harper, G. Kavlak, L. Burmeister, M. Eckelman, S. Erbis, V. Espinoza, P. Nuss, and T. Graedel, “Criticality of the geological zinc, tin, and lead family,” *Press J. Ind. Ecol.*, 2014.
[10] P. Nuss and M. J. Eckelman, “Life Cycle Assessment of Metals: A Scientific Synthesis,” *PLoS ONE*, vol. 9, no. 7, p. e101298, Jul. 2014.
[11] Roskill, *Antimony: Global Industry Markets and Outlook*. London: Roskill Information Services, 2012.
[12] USGS, “2010 Minerals Yearbook,” U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia, 2010.
[13] USGS, “Mineral Commodity Summaries 2009,” U.S. Deparment of the Interior, U.S. Geological Survey, Reston, Virginia, 2009.
[14] S. Panousi, E. Harper, P. Nuss, M. Eckelman, A. Hakimian, and T. Graedel, “Criticality of seven specialty metals,” *J. Ind. Ecol. Accept.*, 2014.
[15] N. Nassar, X. Du, and T. Graedel, “The criticality of the rare earths,” *J. Ind. Ecol. Press*, 2014.
[16] E. Harper, Z. Diao, S. Panousi, P. Nuss, M. Eckelman, and T. Graedel, “The Criticality of the Nuclear Energy Metals,” *Rev.*, 2014.
[17] UNEP, “Recycling Rates of Metals - A Status Report,” United Nations Environment Programme (UNEP), Paris, 2011.
[18] M. F. Ashby and K. Johnson, *Materials and Design*, *Second Edition: The Art and Science of Material Selection in Product Design*, 2 edition. Amsterdam; Boston: Butterworth-Heinemann, 2009.
[19] A. Chipman, “A commodity no more,” *Nature*, vol. 449, no. 7159, pp. 131–131, Sep. 2007.
[20] D. Hanson, “Concern Grows Over Rare-Earths Supply,” *Chem. Eng. News*, vol. 89, no. 20, pp. 28–29, 2011.
[21] S. J. O. Duclos Jeffrey P.Konitzer.Douglas G., “Design in an Era of Constrained Resources,” *Mech. Eng.*, vol. 132, no. 9, pp. 36–40, Sep. 2010.