Global Supply Chains of Coltan

A Hybrid Life Cycle Assessment Study Using a Social Indicator

Daniel Moran, Darian McBain, Keiichiro Kanemoto, Manfred Lenzen, and Arne Geschke

Keywords:

conflict minerals
hybrid life cycle assessment
industrial ecology
multiregion input-output analysis
social supply chain
structural path analysis

Summary

The spot price for tantalum, a metal used in high-performance consumer electronics, spiked in 2000, triggering a boom in artisanal mining of surface deposits in the Democratic Republic of Congo (DRC). The profit from columbite-tantalite ore, or coltan, is alleged to have funded militants during that country's civil war. One warlord famously claimed that in 2000, coltan delivered a million dollars per month. While coltan mining was neither a necessary nor sufficient cause for the civil war, there is nevertheless a clear association between mining and conflict. In order to trace global flows of coltan out of the DRC, we used a high-resolution multiregion input-output (MRIO) table and a hybrid life cycle assessment (LCA) approach to trace exports through international supply chains in order to estimate a "coltan footprint" for various products. In this case study, our aim is to highlight the power and utility of hybrid LCA analysis using high-resolution global MRIO accounts. We estimate which supply chains, nations, and consumer goods carry the largest loads of embodied coltan. This hybrid LCA case study provides estimates on illicit flows of coltan, estimates a coltan footprint of consumption, and highlights the advantages and challenges of using hybrid monetary-physical input-output/LCA approaches to study and quantify a negative social impact as an input to production. If successful, the hybrid LCA approach could be a useful and expedient measurement tool for understanding flows of conflict minerals embodied in supply chains.

Introduction

Tantalum is a rare metal important in modern high-performance electronics, including mobile phones and laptops. The Democratic Republic of Congo (DRC) is endowed with large surface deposits of the ore. But mining in the country is largely controlled by paramilitary groups, and the profits are alleged to have substantially fueled civil war in the country (UNSC 2002). The mineral has often been likened to blood diamonds, and electronics manufacturers and consumers have taken an increasing interest in avoiding "conflict coltan."

Tantalum is highly heat and corrosion resistant and a good conductor. It is an important component in a variety of alloys and is used in a range of specialized applications, including electronic and medical devices, prosthetics, optical lenses, aerospace engines, and cutting tools (Tantalum-Niobium International Study Center 2012). Its most important use, however, is in high-performance capacitors, particularly in devices where size and weight are at a premium. Whereas pure tantalum is a conductor, oxidized tantalum is a resistor; thus, a single tantalum pellet with an oxidized exterior can be used as both the anode and the dielectric in a capacitor, eliminating the need for a separate dielectric material. Together with its high heat resistance, this means that tantalum capacitors can be made small and dense, making them valuable for size-constrained, high-performance electronic devices, including laptops and cell phones.

Australia, Brazil, and Canada are the largest producers of columbite-tantalite ore. Those countries were estimated to have supplied 47%, 17%, and 5.5%, respectively, of total production

Address correspondence to: Daniel Moran, Programme for Industrial Ecology, Gamle Fysikk building, NTNU, Trondheim, Norway 7026. *Email:* daniel.moran@ntnu.no

DOI: 10.1111/jiec.12206

Editor managing review: Sangwon Suh

Volume 00, Number 0

in 2000 (USGS 2002). We identify DRC-sourced columbite-tantalite ores (12.5% of total production in 2000) by calling them *coltan*. In 2000, the price of tantalum spiked tenfold, rising from US $30/lb (pound) to US$300/lb (USGS 2001a). The exact reasons for this spike are not clear: Sharply rising demand for laptops, speculation and hoarding, a new generation of battery-intensive mobile phones, and the popularity of the Sony PlayStation 2 have all been floated as potential triggers (Nest 2011). Most tantalum is delivered by long-term contracts between mining corporations and refiners. The DRC holds substantial easily accessed surface deposits (which can be worked similarly to manual surface gold mining), and the price spike incentivized artisanal miners to supply coltan on the spot market. With a government already shattered by years of civil war, armed groups promptly found ways to capitalize on this mining.

The United Nations (UN) issued a series of reports (UNSC 2001, 2002, 2003, 2008; UN High Commissioner on Human Rights 2010) identifying coltan mining as funding armed conflict in the DRC and called the international companies buying illegal coltan "the engine of the conflict in the DRC" (UNSC 2001, §IV.215). There was a strong focus on identifying how the export of coltan helped fund and support warlords and factions in the DRC. The UN reports linked artisanal mining in the DRC with social ills, including extortion, use of child labor, unacceptable labor conditions, violent contests over mines, and environmental degradation, including thousands of elephants and gorillas killed as bushmeat for mining camps (Hayes and Burge 2003).

The human toll was even greater. Civil war in the DRC resulted in approximately 350,000 violent deaths between 1998 and 2001 (Roberts et al. 2001) and has induced an estimated 2.5 to 9 million excess casualties since 1998 (Coghlan et al. 2006; Roberts et al. 2001) resulting from war-related social disruption, primarily reduced health care availability, and the related spike in child mortality.

Coltan mining was neither entirely responsible for, nor linearly driving, conflict-induced deaths in the DRC. A recent study from The Hague Center for Strategic Studies (Usanov et al. 2013) investigated the links between coltan and conflict and paints a more nuanced picture of the causal links between mining and conflict. Mining was neither a sufficient nor necessary cause of the civil war. Conflict deaths would have no more dropped to zero were coltan banned than has elephant hunting ceased since the ivory trade was outlawed. But there is an association between deaths and mining output. Were mining stopped (or, more realistically, exports banned), warlords would have had to turn to marginally less profitable income sources, thus reducing the intensity of the civil war. Warlords proceeded through a number of funding sources, including diamonds, hardwood, and other resources, to fund their militias (Nest 2011). One cannot say that cutting the trade in coltan in half would have reduced deaths by half, but reducing the trade in coltan would have reduced the militias' funding options and would arguably have thus—at least at the margin—reduced the aggressors' ability to wage war. It has been argued that a total ban on coltan could cause more economic harm to workers than militias (Dizolele 2012; Aronson 2012). But the recent passage of §1502 of the Dodd-Frank Act by the U.S. Congress expresses a contrary opinion, namely, that reducing trade in conflict coltan is desirable.

We sought to estimate global flows of embodied coltan in the year 2000 using hybrid life cycle assessment (LCA) methods. In addition to providing interesting retrospective findings we are interested to see how effective hybrid LCA multiregion input-output (LCA-MRIO) methods can be for tracing hard-to-quantify social impacts. Hybrid LCA studies could be conducted comparatively quickly and could prove to be a useful method for organizations to study social impacts associated with production.

Tools from the field of industrial ecology (IE) (Graedel and Allenby 1995) have long been used to trace flows of metals and other substances of concern (e.g., Reck et al. 2008; Reck and Graedel 2012; Graedel et al. 2002, 2013). The technique of hybrid LCA (Suh and Huppes 2000, 2005; Suh and Nakamura 2007; Suh et al. 2004) allows flows to be traced through more-complex systems documented by input-output (I-O) tables (IOTs). To trace global flows of embodied coltan, we used a hybrid LCA approach based on a high-resolution global MRIO model.

Social Life Cycle Assessment

Social LCA (SLCA) has become a popular tool for understanding the social impacts of production for a particular product or service. Particularly when combined with MRIO analysis, MRIO-SLCA analysis can provide a bottom-up/top-down method for assessment. Guidelines for the SLCA of products were released in 2009 (Benoit and Mazijn 2009) and the methodological sheets for the subcategories of SLCA in 2013 (Benoit-Norris et al. 2011, 2013). The strengths of SLCA (as opposed to other forms of social assessment) are the ability to focus on a product and the ability to encompass a broad range of social impacts ranging from producer behavior to socioeconomic well-being (Zamagni et al. 2011). However, as they also identify, weaknesses in this methodology also exist. The focus on an individual product (or functional unit) can draw the production boundary line too narrowly, thus missing social impacts, such as child labor, hidden elsewhere in the supply chain. Another issue raised is the relevance of the geographical and cultural context of production. The example provided is of a car manufacturer producing the same make of car in several different countries—although the product is the same, the social impacts may not be. Achieving a balance between impacts on the whole of society versus the social impacts along a company supply chain can also be difficult (Zamagni et al. 2011).

SLCA studies to date range from products as varied as a laptop computer (Ekener-Petersen and Finnveden 2013) to strawberry yogurt (Benoit et al. 2011). For the SLCA of a laptop computer, the full supply chain of a laptop computer had to be simplified to enable a hotspot assessment. When considering resource extraction, the study found that a generic laptop was made up of more than 50 materials, and because of the complexity, the study focused on only seven components. It should be noted that the study did identify the DRC as a country with "severe impacts"; however, because the weight of material sourced for the production of a laptop was relatively low, the issue of ongoing conflict in the DRC linked with resource extraction was not strongly captured (Ekener-Petersen and Finnveden 2013). This study also highlighted some methodological shortcomings in SLCA—the inability to measure real social impact, the difficulty in finding real data, and the need for simplification. In a study of the sustainability assessment of how new technology can both contribute to sustainable development and take away from it, the researchers found that the lack of data available using the SLCA approach for developing countries was a significant problem; lack of indicators was also problematic and the methodology not yet feasible for the given case study (Lehmann et al. 2013). Jørgensen and colleagues considered the impact pathways in relation to the "area of protection" (Jørgensen et al. 2010) using SLCA, with particular reference to child labor and well-being. This study found difficulty in getting relevant data and boundary-setting issues. The difficulty in highlighting a pathway between an objective social indicator and subjective well-being was also raised. They state that "The inclusion of subjective indicators necessitates an assessment of the experience of the actually impacted stakeholder" (Jørgensen et al. 2010 , 8). Although highlighted as a difficulty in their study, our study does use a social indicator that provides an assessment of direct experience of the stakeholder. Lack of data and the use of proxy indicators can be a shortcoming for both SLCA and MRIO analysis. However, where MRIO analysis can work well with SLCA is to overcome issues with boundaries, whether they be product or country specific. Used together, LCA and MRIO analysis can provide both depth and breadth to the analysis of social impacts of production. Examples of this are beginning to emerge, such as the Social Hotspot Database, which combines SLCA with MRIO analysis provided by the GTAP database (Benoit-Norris et al. 2012).

Data and Methods

We used I-O analysis (IOA) (Leontief 1986) and structural path analysis (SPA) (Suh and Heijungs 2007) to trace coltan flows from the DRC through international trade routes in order to map coltan's global supply-chain network, as well as calculate a "coltan footprint" (not to be confused with the chemical tagging technique called coltan fingerprinting) for various consumer products. We sourced data from the aforementioned UN reports, research by Nest (2011), and other sources and integrated it into a global MRIO database using a hybrid life cycle approach. The complete global coltan trade network can be systematically documented, and trade routes can be traced not just to buyers and refiners, but also through multiple trade and transformation steps to final consumers. In this study, we describe how we organized existing data on coltan in an I-O structure and used Leontief footprints and SPA to trace coltan to final consumers. IOA has traditionally been of limited use in studying social issues, so our work represents a new contribution not only to the literature on coltan, but also to the nascent field of SLCA.

We used a hybrid approach combining LCA with a MRIO database (Suh 2004; Wiedmann et al. 2011; Bullard et al. 1978; Suh and Nakamura 2007; Heijungs et al. 2006). Hybrid LCA does not refer to any single technique, but rather refers to any study that attempts to marry LCA-based inventories with IO-based accounts, either by extending an LCA analysis using I-O accounts to provide information about background systems or by augmenting an I-O using superior disaggregated data, as has been done in this study. In this method, superior data on coltan-related transactions is used to split existing mining and metals processing sectors in the MRIO into coltan and non-coltan-related subsectors. We will first discuss the coltan-related data that we collected and then explain the MRIO disaggregation procedure.

Data

A number of assumptions were made during the disaggregation process. First, we made an assumption about the spot-market price of coltan. In 2000, the spot price for tantalum ranged from US$30/lb to over US$300/lb (USGS 2001a). Unlike typical long-term mining supply contracts, this spot-market price can vary widely, and because tantalum is not traded on a metals exchange, there exists no definitive price record. Further, the price paid for ore will vary between points along the long supply chain leading from the artisanal diggers through various transporters, traders, and exporters to the refiners. Finally, the conflict coltan in question was sold at informal markets where prices doubtless differ from those published in the weekly metals bulletins. The U.S. Geological Survey (USGS) quotes an average price of US$219/lb for the calendar year 2000 (USGS 2000, 2001b), though prices varied, as noted above. A price of US$220/lb was assumed unless better data could be found. Variations in the price per kilogram (kg) between locations, ore grades, and short-term fluctuations make it difficult to accurately convert between physical and monetary units.

The UN Security Council reports that coltan mined in the DRC in 2000 was exported both directly to refiners and transported across the porous borders through neighboring Rwanda and Uganda. Nest estimates that half of Rwandan coltan exports in 2000 were actually mined in the DRC. Rwanda is not a traditional producer, but it has accessible surface deposits similar to the DRC. However, because artisanal mining in Rwanda (and, to a lesser degree, in neighboring Burundi and Uganda) is less ethically worrisome than DRC artisanal mining, this study focused exclusively on DRC-originated coltan. The Rwandan transportation sector appears in some of the results, but this is solely a transportation stage; only DRC-sourced coltan is being traced.

The United States, Germany, and China are home to major refiners (e.g., Kemet, AB Singher, and Nixon). These companies were implicated in the UN reports as buyers of smuggled coltan. In our analysis, in addition to assuming coltan was sent to these countries, it was also assumed that the processing plant in Kazakhstan was a major buyer of DRC coltan in 2000, buying US$5.5 million of the US$33.9 exported from DRC that year. The UN reports identified Kazakhstan as a recipient of coltan mined in DRC in 2000, an allegation the Kazakh government has neither confirmed nor denied (UNSC 2001, §22). The Ulba manufacturing plant of national processor Kazatomprom began selling capacitor-grade tantalum in 2001 (Kazatomprom Ulba Metallurgical Plant 2012), and, based on our research, we believe it is unlikely the plant was fully supplied by long-term contracts at that time. Tantalum imports into Kazakhstan in 2000 were estimated based on data from UN Comtrade (UNSD 2007). Specific data were not available for 2000 on tantalum, so the value for niobium/tantalum imports into Kazakhstan in 2002 was used as a proxy. Of the US$5,548,500 assumed imported to Kazakhstan in 2000, 40% was assumed to arrive directly from DRC and 40% indirectly through Rwanda.

The USGS Tantalum Niobium Commodity Report (USGS 2000) was used to determine trade flows between DRC, Rwanda, Kazakhstan, and the United States. One limitation of our study is that some refining or value-added production using coltan could potentially be unreported or conducted by black market actors. Such activities would not be recorded in the MRIO table, because MRIO tables do not typically record black market or unreported transactions (except in very rare instances where they have been specifically estimated by the relevant national statistical agency). However, coltan refining and processing requires relatively sophisticated technology and there is no reported evidence of black market refining or processing, so it may be assumed that the omission of the black market in refining is not a major shortcoming in this study.

Table 1 Sector disaggregation: new subsectors will contain coltan-specific transactions

Country	*Remaining original sector and new subsector*
DRC	Mining and quarrying Coltan mining
Rwanda	Mining and quarrying Coltan transportation
Kazakhstan	Nonferrous ores Coltan processing
USA	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing Coltan processing
Germany	Other metallic ores Coltan processing

Note: DRC = Democratic Republic of Congo.

Methods

Based on the data and assumptions outlined above, information from Nest (2011), and the UN Security Council reports, a trade network was quantified linking the DRC with Rwanda, Kazakhstan, Germany, China, and the United States. We employed hybrid LCA to insert transactions data representing this network into a global MRIO table from the Eora database. The Eora MRIO table (Lenzen et al. 2012) used in this study covers 187 countries with 26 to 500 sectors per country. The original MRIO sectors containing the coltan-related sectors were disaggregated (split) into new coltan-related subsectors and the remaining original sector, so that coltan flows could be traced separately (see table 1; compare with the technique used by Liu et al. [2012]).

As with many LCA and I-O studies, this method is attended by some systematic sources of uncertainty, including from the use of a monetary model to trace physical flows (and the subsequent uncertainty resulting from fluctuating prices), and the constant need for more data and resolution with which to more accurately trace which particular products flow through which particular sectors. In this study, our aim is merely to make an initial estimate of the coltan footprint. We do not assert that, with the limited data available for this study, the findings are ready for any policy application. With more data on transactions, and more confidence in these data, we would be able to further improve the reliability of the findings.

The MRIO is augmented by using data on coltan transactions. Data points on coltan transactions were inserted into the new sectors based on data collected on coltan exports from DRC and Rwanda, tantalum imports and exports into and out of Kazakhstan, and tantalum imports and exports into and out of the United States. Figure 1 describes coltan transactions in an I-O format. Origin sectors are listed row-wise and destinations sectors column-wise; for example, the Kazakh processing sector buys US$2.2 million worth of coltan ore from both the DRC and Rwanda and sells US$0.9, US$2.6, and US$0.9 to the American capacitors industry, Chinese electronics industry, and other sectors, respectively. The only input (read figure 1 column-wise) to the DRC coltan mining sector is raw ore (primary inputs), which it exports (read figure 1 row-wise) to transportation and processing sectors. The US$33.9 million of coltan originating in the DRC flows both directly and indirectly, by Rwandan transporters, to processing industries in Germany, Kazakhstan, and the United States. These processing sectors then sell products to electronics sectors and all other sectors. In this table, unsigned values are inserted directly, (+) signed values are added to the pre-existing transactions from the original MRIO, and (–) signed values are subtracted from the pre-existing transaction in the MRIO. Further data on coltan flows could be added in the same manner to further improve the accuracy of the model. The "all other sectors" row and column actually condense the other ≈15,000 individual sectors in the Eora MRIO table. The adjustments in those columns are prorated out among those ≈15,000 sectors using either the original sales mix of the source sector (for positive adjustments) or the input recipe of the destination sectors (for negative adjustments). A total

	DRC Mining	Rwanda Transportation	Kazakhstan Processing	Germany Processing	Germany Electronics	USA Processing	USA Capacitors	China Electronics	Rest of World
DRC Mining		17.0	2.2	10.2		3.4			**+1.2**
Rwanda Transportation			2.2	8.5		5.9			**+0.3**
Kazakhstan Processing							+0.9	+2.6	**+0.9**
Germany Processing					+13.1				+5.6
Germany Electronics									
USA Processing							+9.3		+0
USA Capacitors									
China Electronics									
All other inputs					-13.1		-10.2	-2.6	-34
Primary Inputs	+33.9								

Figure 1 Augmenting the MRIO table with coltan transactions. New sectors are italicized. Unsigned values are inserted into the MRIO table, (+) signed values are added to the pre-existing transaction value, and (–) signed values are subtracted from the pre-existing transaction. Value changes to "all other sectors" (deonted in bold font) are distributed on a pro-rata basis. Blank cells are not zero, but are taken from the source MRIO; this table merely highlights the augmentations to the base MRIO. MRIO = multiregion input-output; DRC = Democratic Republic of Congo.

of US\$33.9 million in coltan inputs are added and a total of US\$33.9 million of other normal inputs are subtracted so the modified IOT remains balanced; that is, the column sum of each sector (the sum of its inputs) equals its row sum (the sum of its sales).

Using the Leontief inverse calculus, it is possible to link demand for coltan to final consumers. Using the $S \times S$ Eora MRIO table $\mathbf{T}$ containing transactions between $S = 14787$ sectors, the coltan footprint $\mathbf{F}$ $(1 \times S)$ in terms of mineral mined in the DRC, resulting directly and indirectly from spending $\mathbf{y}$ $(S \times 1)$ of final consumers, is $\mathbf{F} = \mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y}$, where $\mathbf{x}$ $(S \times 1)$ denotes sectoral gross output, the ^ operator denotes diagonalization, $\mathbf{I}$ is an $S \times S$ identity matrix, and $\mathbf{Q}$ $(1 \times S)$ is an environmental satellite account containing the value of coltan used as input in that sector. In this case, $\mathbf{Q}$ contains only a single nonzero element, which is US\$33 million in the DRC coltan mining sector. Note, that in environmentally extended IOA, the satellite account may contain nonmonetary units, so the same method could be used to calculate the coltan footprint not in \$ of coltan but in kg or, potentially, number of conflict-induced deaths associated with coltan production. The term $\mathbf{Q}\hat{\mathbf{x}}^{-1}$ contains the coltan content of each sector's production, in terms of US\$ coltan per US\$ gross output, for each sector. The term $(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$ is the classic Leontief inverse. All analysis was conducted in terms of producers' prices.

Findings

The results indicate Germany, the United States, China, the UK, and Japan ultimately consumed a total of 58% of the coltan mined in the DRC in 2000 (table 2). The results of the hybrid LCA method are immediately apparent: Even though the UK, Japan, France, and other countries do not directly import or process any coltan, consumers in those countries use a substantial amount of coltan embodied in products. Here, we shall use the term "embodied" in a slightly nonstandard manner. Typically, the term refers exclusively to indirect use; for example, if tungsten carbide tools are used to produce a car, that car is said to include embodied tungsten even if the vehicle itself contains no actual tungsten. Coltan is used in products both indirectly (e.g., in cutting tools used to produce cars) and also directly (e.g., in capacitors in an engine control computer). Here, we use the term "embodied" to refer both to the indirect and direct coltan used by a product. The analysis is conducted

Table 2 Consumers of DRC-sourced coltan in 2000, as share of total global coltan footprint

Country	*Percentage of total coltan consumed in 2000*
Germany	18
USA	14
China	14
UK	7
Japan	6
France	4
Italy	4
Canada	3
Spain	2
Netherlands	2
All others	26

Table 3 Top ten supply flows of coltan from the DRC to final consumers, and estimated magnitudes in terms of value ($US million)

Path value (m USD)	*Path*
$2.0	DRC → Germany processing → Final consumption in Germany of communication and electronic equipment products
$1.7	DRC → Rwanda → Germany processing → Final consumption in Germany of communication and electronic equipment products
$1.0	DRC → Germany processing → Final consumption in Germany of office equipment products
$0.9	DRC → Rwanda → USA processing → Final consumption in USA of electronic capacitor, resistor, coil, transformer, and other inductor manufacturing products
$0.8	DRC → Rwanda → Germany processing → Final consumption in Germany of office equipment products
$0.5	DRC → USA processing → Final consumption in USA of electronic capacitor, resistor, coil, transformer, and other inductor manufacturing products
$0.4	DRC → Kazakhstan processing → Final consumption in China of electronic computer products
$0.4	DRC → Rwanda → Kazakhstan processing → Final consumption in China of electronic computer products
$0.3	DRC → Kazakhstan Processing → Final consumption in China of communication equipment products
$0.3	DRC → Rwanda → Kazakhstan processing → Final consumption in China of communication equipment products

Note: A path value of $2 million indicates that $2 million worth of embodied Coltan from DRC through the specified path to reach the specified final demand sector.
DRC = Democratic Republic of Congo; m USD = million U.S. dollars.

in monetary, not physical, units, and because the price of coltan varies widely, rather than attempting to convert the monetary flows to physical units, we report flows in monetary units.

In the scenario as modeled, we find that Germany is a disproportionately heavy user of embodied coltan. This is because German (and, to a lesser degree, U.S.) plants were primary buyers of implicated coltan. Kazakhstan was also a buyer; however, final consumption of electronics and implicated products in Kazakhstan is much lower—much of these are exported—meaning that Kazakhstan is essentially a middleman, not end user, of implicated coltan. Because German processing firms likely used coltan, German electronics have higher loads of embodied coltan.

Using SPA (Suh and Heijungs 2007; Treloar 1997; Lenzen 2002), it is possible to identify important international supply routes through which coltan flows from the DRC coltan mining sector out to final consumers. Many of these flow through the Rwandan transportation sector. The top such paths are shown in table 3. If enumerated completely, this list of paths would be mutually exclusive and collectively exhaustive, but given that the value of smaller paths approaches zero, it is not computationally efficient to trace more than the top 100,000 or so (Lenzen 2006).

Coltan is famously used in mobile phone batteries. One representative path is "DRC → Rwanda → USA processing → USA electronic capacitor, resistor, coil, transformer, and other inductor manufacturing products → Final demand in South Korea in the radio, television, and communications equipment sector" showing ≈US$75,000 worth of coltan (0.22% of coltan mined in 2000), embodied in what are most likely electronics within game consoles and mobile phones purchased by Koreans.

More-obscure paths can also be traced. For example the path "DRC → Rwanda USA processing → USA electronic capacitor, resistor, coil, transformer, and other inductor manufacturing products → Mexico manufacture of transport equipment industry → Final demand in Mexico in the manufacture of transport equipment sector" shows ≈US$57,000 worth of coltan flowing out of DRC through Rwanda to U.S. processors and then into vehicle components for vehicles bought by Mexican consumers. This embodied coltan could be used in cutting tools used in factories, in corrosion-resistant bolts in the vehicles, or directly in the vehicle electronics, including in the airbag system, ignition system, motor control module, global positioning system, or antilock brake system. This particular path contains ≈US$57,000 worth of coltan. A similar path, but through German processors into Spanish vehicle manufacturing, contains ≈US$12,000 worth of coltan implicated.

Yet another path shows ≈US$40,000 worth of coltan (0.12% of year 2000 production), flowing from "DRC → Rwanda → Germany processing → Germany communication and electronic equipment products → Final demand in Germany in the medical, scientific, optical equipment, and watches sector." This embodied coltan could be embodied in hearing aids, pacemakers, suture clips, coated on medical implants, used to produce X-ray film, or included in trace amounts in camera optics or in the electronics in a digital camera.

Coltan is also used in aerospace applications as an alloy in high-temperature steels. This is a smaller use than in electronics, but still a notable one. The flows "DRC → Germany processing → Final demand in Germany in the air transport sector" and "DRC → Rwanda → USA processing → USA electronic capacitor, resistor, coil, transformer, and other inductor manufacturing products → USA general federal defense government services industry → Final demand in USA in the general federal defense government services sector" include coltan embodied in alloys used for jet engines, rocket engines, and chemical process equipment.

Conclusions

Our basic motivation for this study was to highlight the utility of hybrid LCA as a method for tracking social indicators in general, and a method for tracing global coltan flows in particular. Though there is general agreement that conflict-source coltan should be illegal, there has been comparatively little work done to try and identify the major flows of coltan. This is where tools from IE can be brought to bear. Research into trace, critical, and major flows of materials has been one of the core objectives of IE since the outset.

Tracing the supply chains using coltan reveals that the mineral is widely used. Hybrid LCA is a powerful tool for elucidating the global supply chains connecting producers to consumers. The method both provides a consistent framework in which various data sources can be organized and also enumerates the global supply chains connecting consumers to local problems.

There exist many approaches to tracing substances of interest, including material flow accounting, in which physical inventories are traced, and bottom-up LCA methods. The former is highly accurate, yet difficult to implement, and can usually only be applied once a system is in place, not retrospectively to substances of interest. Bottom-up LCA approaches can be used to estimate either physical flows or embodied flows and can be based on mixed economic and physical data. However, LCA approaches are quite reliant on data availability, and also the bottom-up approach can allow analysis to miss flows that would be indicated by a top-down analysis. The hybrid MRIO method is admittedly less accurate than either of these two approaches; however, a study can be executed quickly and retrospectively. The choice of which tool to use to study a flow of interest depends highly on the level and detail of data available and how much time is available to execute the study. As a next step for studying embodied flows of coltan, the major flows from this top-down analysis could be used as the starting point for bottom-up LCA studies that start by investigating those flows. One outcome of the Dodd-Frank ruling could be that major tantalum users start to audit their tantalum supply chain, thus effectively implementing a mass flow analysis.

Policy responses to address the problem of conflict coltan have had mixed success. The conclusions of the UN reports on coltan were frank and disheartening: "[T]he exploitation of natural resources that does not benefit the majority of the Congolese people is not a new phenomenon . . . In the absence of a strong, central and democratically elected Government that is in control of its territory, illegal exploitation will continue . . . " (UNSC 2003, §48). Various initiatives to constrict the trade in conflict coltan have been put forth. These have included UN Security Council resolutions, a certification program from the German ministry of economic development, the Durban Process (modeled on the Kimberly process for conflict diamonds), Section 1502 of the Dodd-Frank Act (US SEC 2012), and a number of nongovernmental organization–led efforts addressed both to supply-chain partners and consumers. Yet, for the most part, these measures have been too little too late. These controls were only erected years after the problem was first identified. Additionally, the more-stringent certification requirements have been criticized both for enacting a de facto ban on Congolese coltan production that hurts workers more than militias and for not addressing the true problem of weak government (Dizolele 2012; Aronson 2012).

Because coltan is valuable and easily mined, ethical concerns over artisanal scale mining (as opposed to mining by accountable larger corporations) are likely to persist wherever small coltan surface deposits are worked. China has recently expressed interest in Colombia's substantial surface reserves (Walsh 2012a), and Colombia has stepped up regulation against illegal mining (Molinski 2012). Coltan mining is also illegal in neighboring Venezuela, but surface deposits lying along the Colombia/Venezuela border are already worked by small-claim miners (Diaz-Struc and Poliszuk 2012) and have reportedly drawn the interest of FARC rebels (Fox 2012; Walsh 2012b). Together, these factors set the stage for increased illegal mining activity in this region, with the specter of associated violence.

The problem of conflict minerals is unlikely to disappear. Violent contests will persist wherever there are valuable resources and weak governments. The public and private sectors have been slow to respond to the issue of conflict coltan. We believe this is, in large part, a result of lack of transparency. Shortly after the problem flared up in 2000, good information became available on the scope and structure of the problem (from the UN and other sources), but efforts to trace coltan were not able to follow the mineral beyond the major processing firms. Using estimation techniques, as has been done here, to trace these flows fully out to consumers could have provided first-order estimates of the major flows, implicated products, and biggest consumers. Such information could have been used to accelerate policy response, corporate transparency, and certifications of coltan-free supply chains. The focus on getting major consumer-facing electronics companies (e.g., Apple), rather than intermediate suppliers or individual products, to become completely "coltan free" seems a good strategy. Fully accountable traces using physical methods, such as chemical fingerprinting (Melcher et al. 2008) or the Kimberley Process, to control conflict diamonds may be overkill as well as slow to implement. The chemical fingerprinting technique took 8 years to develop, and the Dodd-Frank formal disclosure rules took 12 years to enact. Hybrid LCA techniques could provide improved transparency into global coltan flows with much less time and effort.

Both the domestic situation and controls on conflict coltan from DRC have improved since 2000. Our aim in this initial study has not been to inform policy regarding this particular conflict mineral, but rather to highlight how hybrid LCA methods, in conjunction with high-resolution MRIO tables, can provide a useful tool for tracing global flows of substances of social concern.

References

Aronson, D. 2012. How congress devastated Congo. *The New York Times*, 7 August, section Opinion.

Benoit-Norris, C., D. A. Cavan, and G. Norris. 2012. Identifying social impacts in product supply chains: Overview and application of the social hotspot database. *Sustainability* 4(9): 1946–1965.

Benoit-Norris, C., G. Vickery-Niederman, S. Valdivia, J. Franze, M. Traverso, A. Ciroth, and B. Mazijn. 2011. Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. *International Journal of Life Cycle Assessment* 16(7): 682–690.

Benoit, C., D. Aulisio, C. Hallisey-Kepka, N. Tamblyn, and G. Norris. 2011. *Social scoping prototype, report product category 7: Strawberry yogurt*. Tempe, AZ, USA/Boston, MA, USA: The Sustainability Consortium/New Earth.

Benoit, C. and B. Mazijn. 2009. *Guidelines for social life cycle assessment of products*. Druk in de weer, Belgium: UNEP/SETAC Life Cycle Initiative.

Benoit-Norris, C., M. Traverso, S. Valdivia, G. Vickery-Niederman, J. Franze, L. Azuero, A. Ciroth, B. Mazijn, and D. Aulisio. 2013. *The methodological sheets for subcategories in social life cycle assessment (S-LCA)*. Paris: United Nations Environment Programme and SETAC.

Bullard, C. W., P. S. Penner, and D. A. Pilati. 1978. Net energy analysis—Handbook for combining process and input-output analysis. *Resources and Energy* 1(3): 267–313.

Coghlan, B., R. J. Brennan, P. Ngoy, D. Dofara, B. Otto, M. Clements, and T. Stewart. 2006. Mortality in the Democratic Republic of Congo: A nationwide survey. *The Lancet* 367(9504): 44–51.

Diaz-Struc, E. and J. Poliszuk. 2012. *Venezuela emerges as new source of 'conflict' minerals*. Washington, DC: The Center for Public Integrity.

Dizolele, M. 2012. Conflict minerals in the Congo: Let's be frank about Dodd-Frank. *The Huffington Post*, 22 August, section Opinion.

Ekener-Petersen, E. and G. Finnveden. 2013. Potential hotspots identified by social LCA—Part 1: A case study of a laptop computer. *The International Journal of Life Cycle Assessment* 18(1): 127–143.

Fox, E. 2012. FARC set to exploit Venezuela 'conflict mineral': InSight: Organized crime in the Americas. www.insightcrime.org. Accessed October 2013.

Graedel, T. E. and B. R. Allenby. 1995. *Industrial ecology*. Englewood Cliffs, NJ, USA: AT&T-Prentice Hall.

Graedel, T. E., E. M. Harper, N. T. Nassar, and B. K. Reck. 2013. On the materials basis of modern society. *Proceedings of the National Academy of Science*. Published online ahead of print. DOI: 10.1073/pnas.1312752110.

Graedel, T. E., M. Bertram, K. Fuse, R. B. Gordon, R. Lifset, H. Rechbergera, and S. Spataria. 2002. The contemporary European copper cycle: The characterization of technological copper cycles. *Ecological Economics* 42(1–2): 9–26.

Hayes, K. and R. Burge. 2003. *Coltan mining in the Democratic Republic of Congo: How tantalum-using industries can commit to the reconstruction of the DRC*. Cambridge, UK: Flora & Fauna International.

Heijungs, R., A. de Koning, S. Suh, and G. Huppes. 2006. Toward an information tool for integrated product policy: Requirements for data and computation. *Journal of Industrial Ecology* 10(3): 147–158.

Jørgensen, A., L. C. H. Lai, and M. Z. Hauschild. 2010. Assessing the validity of impact pathways for child labour and well-being in social life cycle assessment. *The International Journal of Life Cycle Assessment* 15(1): 5–16.

Kazatomprom Ulba Metallurgical Plant. 2012. Tantalum history. www.ulba.kz/en/company3.htm. Accessed 5 September 2012.

Lehmann, A., E. Zschieschang, M. Traverso, M. Finkbeiner, and L. Schebek. 2013. Social aspects for sustainability assessment of technologies—Challenges for social life cycle assessment (SLCA). *The International Journal of Life Cycle Assessment* 18(8): 1581–1592.

Lenzen, M. 2002. A guide for compiling inventories in hybrid LCA: Some Australian results. *Journal of Cleaner Production* 10(6): 545–572.

Lenzen, M. 2006. Structural path analysis of ecosystem networks. *Ecological Modelling* 200(3): 334–342.

Lenzen, M., K. Kanemoto, D. Moran, and A. Geschke. 2012. Mapping the structure of the world economy. *Environmental Science & Technology* 46(15): 8374–8381.

Leontief, W. 1986. Input-output analysis. In *Input-output economics*. New York: Oxford University Press.

Liu, C.-H., M. Lenzen, and J. Murray. 2012. A disaggregated emissions inventory for Taiwan with uses in hybrid input-output life cycle analysis (IO-LCA). *Natural Resources Forum* 36(2): 123–141.

Melcher, F., M. Sitnikova, T. Graupner, N. Martin, T. Oberthür, F. Henjes-Kunst, E. Gäbler, et al. 2008. Fingerprinting of conflict minerals: Columbite-tantalite ("coltan") ores. *SGA (Society for Geology Applied to Mineral Deposits) News* 23(1): 7–13.

Molinski, D. 2012. Columbia to wage battle against illegal coltan mining. *Wall Street Journal*, 12 March 2012. http://goo.gl/K8XXb. Accessed October 2013.

Nest, M. 2011. *Coltan*. Cambridge, UK: Polity Press.

Reck, B. K. and T. E. Graedel. 2012. Challenges in metal recycling. *Science* 337(6095): 690–695.

Reck, B. K., D. B. Müller, K. Rostkowski, and T. E. Graedel. 2008. The anthropogenic nickel cycle: Insights into use, trade, and recycling. *Environmental Science & Technology* 42(9): 3394–3400.

Roberts, L., C. Hale, F. Belyakdoumi, L. Cobey, R. Ondeko, M. Despines, I. D. Bukavu/Kisangani, and J. Keys. 2001. *Mortality in eastern Democratic Republic of Congo: Results from eleven mortality surveys*. New York: International Rescue Committee.

Suh, S. 2004. Functions, commodities and environmental impacts in an ecological-economic model. *Ecological Economics* 48(4): 451–467.

Suh, S. and G. Huppes. 2000. *Gearing input-output model to LCA—Part I: General framework for hybrid approach*. Leiden, the Netherlands: CML, Leiden University.

Suh, S. and G. Huppes. 2005. Methods in life cycle inventory (LCI) of a product. *Journal of Cleaner Production* 13(7): 687–697.

Suh, S. and R. Heijungs. 2007. Power series expansion and structural analysis for life cycle assessment. *International Journal of Life Cycle Assessment* 12(6): 381–390.

Suh, S. and S. Nakamura. 2007. Five years in the area of input-output and hybrid LCA. *International Journal of Life Cycle Assessment* 12(6): 351–352.

Suh, S., M. Lenzen, G. J. Treloar, H. Hondo, A. Horvath, G. Huppes, O. Jolliet, et al. 2004. System boundary selection in life-cycle inventories. *Environmental Science & Technology* 38(3): 657–664.

Tantalum-Niobium International Study Center. 2012. Applications for tantalum. http://tanb.org/tantalum. Accessed 24 August 2012.

Treloar, G. J. 1997. Extracting embodied energy paths from input-output tables: Towards an input-output-based hybrid energy analysis method. *Economic Systems Research* 9(4): 375–391.

UN High Commissioner on Human Rights. 2010. *Report of the mapping exercise documenting the most serious violations of human rights and international humanitarian law committed within the territory of the Democratic Republic of the Congo between March 1993 and June 2003*. Geneva: Office of the United Nations High Commissioner for Human Rights (OHCHR).

UNSC (United Nations Security Council. 2001. *Report of the panel of experts on the illegal exploitation of natural resources and other forms of wealth of the Democratic Republic of the Congo*. New York: United Nations Security Council.

UNSC (United Nations Security Council. 2002. *Final report of the panel of experts on the illegal exploitation of natural resources and other forms of wealth of the Democratic Republic of the Congo*. New York: United Nations Security Council.

UNSC (United Nations Security Council. 2003. *Follow-up to the report of the panel of experts on the illegal exploitation of natural resources and other forms of wealth of the Democratic Republic of the Congo*. New York: United Nations Security Council.

UNSC (United Nations Security Council). 2008. *Final report of the group of experts on the Democratic Republic of the Congo*. New York: United Nations Security Council.

UNSD (United Nations Statistics Division). 2007. *UN Comtrade—United Nations Commodity Trade Statistics Database*. New York: United Nations Statistics Division. http://comtrade.un.org/. Accessed October 2013.

USGS (U.S. Geological Survey). 2000. Niobium (columbium) and tantalum statistics and information 2000. http://minerals.usgs.gov/minerals/pubs/commodity/niobium. Accessed October 2013.

USGS (U.S. Geological Survey). 2001a. *Minerals yearbook: Columbium (niobium) and tantalum*. Reston, VA, USA: U.S. Geological Survey.

USGS (U.S. Geological Survey). 2001b. Tantalum mineral commodity summary 2001. http://minerals.usgs.gov/minerals/pubs/commodity/niobium/231301.pdf. Accessed October 2013.

USGS (U.S. Geological Survey). 2002. *Mineral yearbook*. Reston, VA, USA: U.S. Geological Survey.

US SEC (U.S. Securities and Exchange Commission). 2012. SEC adopts rule for disclosing use of conflict minerals. http://sec.gov/news/press/2012/2012-163.htm. Accessed 24 August 2012.

Usanov, A., M. de Ridder, and W. Auping. 2013. *Coltan, Congo, and conflict*. The Hague: The Hague Center for Strategic Studies.

Walsh, H. 2012a. China may accelerate mining for coltan in Eastern Colombia. *Bloomberg* http://goo.gl/DCuJx.

Walsh, H. 2012b. Colombia Seizes Record Amount of Coltan From Rebel Smugglers. *Bloomberg*, 13 September 2012. http://goo.gl/qouA4. Accessed October 2013.

Wiedmann, T. O., S. Suh, K. Feng, M. Lenzen, A. Acquaye, K. Scott, and J. R. Barrett. 2011. Application of hybrid life cycle approaches to emerging energy technologies—The case of wind power in the UK. *Environmental Science & Technology* 45(13): 5900–5907.

Zamagni, A., O. Amerighi, and P. Buttol. 2011. Strengths or bias in social LCA? *The International Journal of Life Cycle Assessment* 16(7): 596–598.

About the Authors

Daniel Moran, **Darian McBain**, **Keiichiro Kanemoto**, and **Arne Geschke** were all Ph.D. students at the Center for Integrated Sustainability Analysis (ISA) at the University of Sydney, Sydney, Australia, at the time this article was written. **Daniel Moran** is now a researcher at the Programme for Industrial Ecology at Norwegian University of Science and Technology in Trondheim, Norway. **Keiichiro Kanemto** is currently an assistant professor at the Institute of Decision Science for a Sustainable Society at Kyushu University in Fukuoka, Japan. Arne Geschke and Darian McBain remain affiliated with ISA. **Manfred Lenzen** is chair of sustainability and head of ISA at the University of Sydney.