Substance Flow Analysis of Tantalum:
Tracking the Conflict-Free Path

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Tantalum is a critical material used in specialized industrial manufacturing processes and end-use applications ranging from aerospace to high performance electronics. In Central Africa severe human rights violations are associated with illicit mining and conflicts in regions where tantalum is extracted. Considerable efforts from industry, government and non-profit organizations have gone into conflict-free sourcing programs using mechanisms such as due diligence and chain-of-custody. However, a paucity of quantitative information exists on the global sources and amounts of metal, and this impedes decisions towards potential solutions. The purpose of this research was to quantify global flows of tantalum production and characterize patterns of conflict-free production. This study employed substance flow analysis (SFA) to characterize tantalum mass flows for 48 processing facilities located in 12 countries. A novel facility-level bottom-up method to SFA was employed on smelting and metal refining activities to aggregate information on global flows of metal. Results estimate the mass flows of global tantalum production and present an ostensible pattern of tantalum production. Global tantalum production in 2014 was estimated at 2800 tonnes, with a global average recycled content of about 35%, and 46 conflict-free tantalum processing facilities accounted for processing over 95% of global tantalum mineral concentrates. The emergence of conflict-free tantalum mineral sourcing from 2010 to 2014 is quantified. This research advances the SFA approach for metal flows accounting with greater facility-level detail and geographic information. The descriptive view of tantalum flows informs discussions on conflict-free programs and supports metal certification of sustainable supply chains of metals.

Key words: Tantalum, substance flow analysis, conflict-free, metal, responsible sourcing, metal production, sustainable supply chain management.

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Chapter 1

Introduction

1.1 Context for Research

Nature gives today's industrial economies with a rich spectrum of raw materials. In practice, minerals constitute the largest set of these resources providing over 60 elements for diverse industrial applications ranging from machinery, energy, transportation, building and construction to information technology, and appliances (Strothmann, 2013; UNEP-IWP,2010, 2011, 2013). As a crucial material in industrial systems, metals are essential to the global economic value chain and societal development (Graedel & Erdmann, 2012; Guss, 2014). Additionally, of the many resources bestowed to human society, minerals are uniquely valuable to modern technologies and have become increasingly important to trade (Graedel et al, 2010). However, given the growing rate of exploitation of metals, complexities in metals and minerals trading, and the sporadic imbalance between metals demand and supply witnessed in recent times, concerns have been raised on the sustainability risks associated with the supply chain of minerals and metals (Bloodworth, 2014a; Herrington, 2013). Among these are the issues of 'conflict minerals' concerning practices in mineral trade and production in the Democratic Republic of the Congo (DRC).

The conflict minerals are mineral ores of tantalum, tin, tungsten and gold (3TG) - columbite-tantalite (known as coltan in DRC), cassiterite, wolframite and gold - illegally exploited and traded, and financing unstaunched civil conflicts in the Democratic Republic of the Congo (DRC) (US Securities and Exchange Commission, 2012). The conflicts in the DRC are highly violent, most critical traits are high rates of human rights and sexual abuses (Enough Project, 2009; Kalisya, et al., 2011; Nelson, 2014; Global Witness, 2015). Aside from human mortality, environmental and biodiversity problems are also repercussions of civil conflicts, exhaustive and illegal mineral mining activities in the DRC. The conflict minerals problem presents a social issue and geopolitical risk in the supply chain of minerals and metals (Bleischwitz & Guesnet, 2012; Chirico & Malpeli, 2014; Hofmann, Schleper, & Blome, 2015; Janus, 2012; Klassen & Vereecke, 2012). Illicit trade of minerals is propagated by the ease of moving pillages though neighboring countries in the Great Lake Region of Africa (Bleischwitz, Dittrich, & Pierdicca, 2012; Pact, 2015). The conflict minerals problem reflects a resource curse (Janus, 2012; Lalji, 2007) reality wherein many actors benefit from concessions as pillages and illegally traded minerals enter into formal channels (United Nations, 2001; Bannon & Collier, 2003; United Nations

Security Council, 2009; Garrett & Mitchell, 2009). Indeed, there is little interest from these characters to break mineral-conflict links (Bleischwitz et al., 2012). As a widespread practice for sourcing high-value resources, some activists assert that "illegal and often unethical mining has been effectively condoned by the marketplace for the sake of access to rare and high-value commodities" (Herrington, 2013, pg. 13).

Effective in 2012, the US government moved to curb the trade of conflict minerals by mandating all publicly traded US corporations to disclose the origins of 3TG metals used for their products by ensuring a "reasonable country of origin inquiry" (US Securities and Exchange Commission, 2012). Several reviews of conflict mineral reports (CRM) filed by US corporations in 2013 and 2014 suggest that the conflict mineral reports provide limited insights about the country of origin of 3TG minerals in their products (Arriaga, Jurewicz, & Brophy, 2015; DavisPolk, 2014; KPMG, 2015; Sankara, Lindberg, & Razaki, 2016; Schwarts, 2015). US corporations claimed that collecting relevant information from suppliers is difficult (Gianopoulos, 2015). While the first two years are considered a learning and transition period (KPMG, 2015; PWC, 2014), skepticism is rife on the effect of the US conflict minerals law to ameliorate conflict minerals supply and its impacts (Arriaga et al., 2015; Hofmann et al., 2015). The economic cost of implementing the provisions of this law implies substantial costs for corporations (Griffin, Lont, & Sun, 2014) and the incentive to source minerals from the DRC has greatly decreased (Bleischwitz & Guesnet, 2012). And yet other jurisdictions including Europe are considering conflict minerals legislation (Manhart & Schleicher, 2013). Consequently, there is a growing movement towards responsible sourcing of minerals and management of metals supply chains (Fleury & Davies, 2012; Sarfaty, 2015; Young, Dias, & Zhe, 2013).

Responsible sourcing efforts developed by industry and other stakeholders for conflict minerals are evolving; a broad range of initiatives adopt due diligence requirements, chain of custody, compliance and certification mechanisms to trace the origins of materials, manage risks in the supply chain of 3TG metals and increase legal trade of conflict-free minerals from the DRC (Guo, Lee, & Swinney, 2015; OECD, 2011; Yawar & Stefan, 2015; Young, Fonseca, & Dias, 2010; Young, Dias, & Zhe, 2014; Young, 2015). Initiatives for conflict minerals certification and conflict-free sourcing of 3TG metals are to a large extent voluntary. Although substantial progress has been reported for corporations' performance in country of origin inquiry and due diligence (Gianopoulos, 2015; Pact, 2015); growing participation in conflict-free sourcing programs (Young, 2015) and increased records of verified conflict-free audits (Sankara et al., 2016); alongside increasing records of documentation trails of mineral production confirmed from conflict-free source (Pact, 2015). For example, the Conflict-free Smelters Program (CFSP) claims that 95% tantalum producers sourced conflict-free minerals in 2014 (Butler, Holeman, & Rohwer, 2016). However, there is limited knowledge on how much of the 3TG metals are produced from conflict-free minerals. A complex supply chain and information gaps result in greater difficulty to understand the effectiveness and potentials of conflict-free sourcing of minerals and metals (Bleiwas, Papp, & Yager, 2015; Young et al., 2013; Young, 2015).

The subject of this thesis is the metal tantalum. Concerns about supply risk of tantalum have been raised coupled with its role in financing conflicts (Bafilemba, Mueller, & Lezhnev, 2014; Bleischwitz et al., 2012; Polinares, 2013). Tantalum is an economically important metal widely identified as critical, given its limited production; supply risk arising from metal and mineral production due to highly concentrated production and/or governance issues with the producers; and significance in specialized industrial manufacturing processes and end-use applications ranging from aerospace to high performance electronics (Guss, 2014; Matthais Buchert, Schüler, & Bleher, 2009; Moss, Tzimas, Willis, Arendorf, & Tercero Espinoza, 2013; Peiró, Méndez, & Ayres, 2011; USNRC, 2008). Tantalum is particularly important to the electronics industry for fabrication of high performance capacitors widely used in modern electronics devices (Mackay & Simandl, 2014; Miller, 2007; Nikishina, Drobot, & Lebedeva, 2014). About 60% of global tantalum production is for the electronics industry, and capacitors have become the single largest end-use market (Bleiwas et al., 2015; USGS, 2005). Tantalum powder sintered into a pellet is able to form a thin insulating oxide layer on its surface when submerged in an electrolyte; thus, a single pellet can serve as the anode and dielectric of a capacitor, distinguishing tantalum capacitors as having high volumetric capacitance and lower weight (Reynolds, 2008). These characteristics make tantalum capacitors ideal for small high performance electronic devices such as mobile phones and laptops (Espinoza, 2012; Nikishina et al., 2014; Polinares, 2012). Tantalum is useful for many components of digital devices (Agulyonski, 2004; Yager, Bleiwas, & Papp, 2015) surgical implants replacements (Liu, Bao, Wismeijer, & Wu, 2015; Matsuno, Yokoyama, Watari, Uo, & Kawasaki, 2001; Patil, Lee, & Goodman, 2009; Wauthle et al., 2015), cutting tools and super alloy industrial components (Bayarjargal, Winkler, Friedrich, & Juarez-Arellano, 2014). Although the DRC is not a major producer of tin, tungsten and gold, the country is a major contributor to global production of tantalum primary concentrates (Anderson, 2015; Bermudez-lugo, 2014; George, 2015; U.S Geological Survey, 2014). In 2014, tantalum mineral production from only three countries in the Great Lake Region (Rwanda, DRC, Burundi) accounted for about 70% of the global mine production of tantalum(Papp, 2015). The inherent risk associated with conflict minerals may present a potential short-term supply risk of tantalum mineral concentrates to the global supply of tantalum (Polinares, 2013; Green, 2014). Demand for the 3TG metals (like other metals) is soaring. Fitzpatrick et al., (2014) project demand increases of 50%, 66%, 44% and 40% - for tungsten, tin, tantalum, and gold respectively within the next 5 years. Consequently, the issues have revealed growing metals supply chain issues to worldwide affairs and deracinated old fears of metals scarcity to global concern.

Growing awareness of problems in metals supply chains have stimulated the need to develop sustainable strategies to guide business practices in many parts of the world. However, the business and physical barriers in metals supply chains present a number of challenges (Atherton, 2011; Nilsson-Lindén, Baumann, Rosén, & Diedrich, 2014; Young et al., 2013; Young & Dias, 2011). The mixing of material sources in metals production chains is a physical challenge to tracing materials flows through supply chains, moreover tantalum production stems from an opaque tantalum market (Bleiwas et al., 2015). Thus, as a baseline for managing metals supply, one must understand the material pathways in the supply chain of metals. Limited data availability hinder the ability to measure and manage the impacts of strategies for supply chain sustainability (Atherton, 2011); Young et al. (2013) suggest that quantification of material flows at the facility level is required to discuss possibilities of supply chain sustainability certification for 3TG metals. Moreover, there is a growing call to track metal flows across supply chains in order to effectively adopt approaches to shape a sustainable supply chain of metals that promote ethical sourcing and secure supply (Bloodworth, 2014a).

In view of this, this research seeks to quantify the flows of tantalum along the production chain using substance flow analysis - a tool of industrial ecology. Substance flow analysis has been an effective tool to identify the scale of physical activity, the pathways of materials across economic sectors for different purposes, and to identify changes, relationships or inefficiencies in production systems or in consumption contexts (Ayres & Ayres, 2002; Brunner & Rechberger, 2004b; Kral, Brunner, Chen, & Chen, 2014; Mendez, Peiro, & Wegener, 2014). However, within the discourse of substance flow analysis (SFA) studies of metals, there is a paucity of knowledge on the flows of tantalum and a lack of a relevant material account for the global tantalum production system (Chen & Graedel, 2012a; Wäger, Lang, Wittmer, Bleischwitz, & Hagelüken, 2012). It is essential to identify the pathways of tantalum global flows and quantify production, in order to understand the efficacy and potentials of conflict-free tantalum production. Thus, the goal of this research is to characterize tantalum global flows and identify the extent and magnitude of conflict-free production of tantalum.

1.2 Research Focus

The conflict mineral narrative embraces all manner of digressions of issues and solutions, however sustainable metals management is key to understand supply chain of 3TG metals and resolve the conflict minerals problem. To effectively implement and develop strategies for securing metals supply and managing risks, tracking metal flows is central to address data gaps and mitigate issues with lack of transparency in supply chains. Three main areas have been identified to be addressed by the present study:

i) Market participation in conflict-free sourcing has reached appreciable levels, but the mass of material sourced from conflict-free sources in comparison to the total material supply in the global market has not been quantified.

ii) Analysis of tantalum flows at a global level is lacking in the SFA literature. The application of substance flow analysis to tantalum is novel and can give knowledge about global flows related to production and sourcing practices;

iii) An approach for the assessment of global metal production at a facility level is required to meet the needs in studying trends for material accounts.

1.3 Thesis Structure

Chapter 2 reviews the relevant background topics under the categories of conflict minerals and metals supply chains (Section 2.1), the socio-economic importance of tantalum and the tantalum production chain (Section 2.2). Chapter 3 reviews the literature on substance flow analysis of metals and presents the research objectives and rationale. The research method, based on the SFA approach, is described in Chapter 4 wherein the bottom-up method was developed and applied. The results of the research are presented in Chapter 5, wherein tantalum mass flows characterization and system descriptive statistics are presented for global tantalum production and regional tantalum processing practices. Chapter 6 discusses the results in relation to the study objectives and provides conclusions.

Chapter 2

Conflict Minerals and Tantalum Supply Chain

Current practices in minerals and metals production already present both social and environmental problems (MMSD, 2002), yet under the business as usual scenario, resource use and demand for metals are set to double by 2050 (Bloodworth & Gunn, 2012). The use of metals in product chains has increased by 4 to 15 times over the past 50 years (Allwood & Cullen; 2012). While it is unlikely that we will run out of mineral resources in the near future, accessing economically viable ores will become increasing difficult and the associated supply risk presents bigger challenges for sustainable development (Guss, 2014). For industrialized nations, perhaps one of the most unsettling consequences of resource scarcity and constraint is the uncertainty they create. Consequently, "tracking and tracing"[1] of metals has become increasingly important to understand and manage metals supply (Bloodworth, 2014b; Young, 2015). To clearly articulate the research problem and focus of the present study, the background section 2.1 provides an overview of the socio-geopolitical risks growing from the dynamics of conflict minerals trade in the DRC and complex global supply chain of metals. Specifically, it provides a brief introduction to the conflict minerals problem, the efforts for conflict-free mineral sourcing, and a synthesis of the discussion on "conflict-free" minerals and 3TG metals supply chains. Section 2.2 provides an overview of the ostensible supply chain of tantalum.

2.1 Conflict Minerals and Metals Supply

2.1.1 Introduction

Natural resources have often been linked to civil wars, particularly in low-income countries where primary commodities with high economic benefits are produced by rural communities. Although natural resources are not the sole driver of conflict, the revenue from the exploitation and the illicit trade of primary commodities in conflict zones is known for financing war lords and rebel groups, thereby exacerbating the risk of conflict (Bannon & Collier, 2003). Within the broader discourse of links between natural resources and conflict, the 'conflict minerals' narrative is concerned with the link between exploitation and trade of mineral commodities and on-going civil conflict in the Central

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[1] Tracking and Tracing are two concepts of sourcing introduced by Young (2008)

African region, particularly the mineral-rich Democratic Republic of the Congo (DRC) (Bleischwitz & Guesnet, 2012).

Awareness of the link between natural resources and conflict in the DRC started in the early 2000s and has risen in the past decades. The first study investigating illegal exploitation of natural resources and other forms of wealth in the DRC concluded that "the illegal exploration of mineral and forest resources of the DRC is taking place at an alarming rate" (United Nations, 2001). Major international interest in the conflict minerals issue arose in 2004 when the UN Group of Experts on the Democratic Republic of Congo wrote to the UN Security Council, declaring illegal mineral exploitation as a major source of revenue for rebels and Congolese armed groups, and thus a key economic driver of conflict in the DRC (United Nations Security Council, 2004). There was a call for transparency in mineral production and ethical responsibility in trade and supply chains of minerals from the DRC (United Nations Security Council, 2009). The DRC is richly endowed with alluvial deposits of mineralized pegmatites easily recovered with simple tools like a shovel and pan to produce valuable mineral ores and concentrates, therefore mineral production is largely through informal artisanal activities (Milesi et al., 2006; Mustapha, Mbuzukongira, & Mangala, 2007). Although the artisanal mining (ASM) activities are small scale, larger revenue is collectively generated, which makes up a complex informal economy entangled in a blurred sphere of illegal and legal trade networks (Chirico & Malpeli, 2014). The United Nations (UN) reports accused the neighboring countries (Rwanda, Uganda and Zambia), a number of individuals, as well as corporations in America and Europe of systematically exploiting the minerals and generating several million dollars for armed groups through the criminal structure and informal networks in minerals trade (United Nations, 2001; United Nations Security Council, 2004; 2009). Aside from armed groups or militia controlling many artisanal mining sites, there is evidence that the DRC national army is heavily involved in mining activities, illegal taxation and looting minerals (Bleischwitz & Guesnet, 2012). Complex 'ecologies of violence'(Laudati, 2013) coalesced the grassroots activities in the DRC, particularly artisanal mining (Chirico & Malpeli, 2014). The situation is pervasive and entrenched in such a war economy where continuous violence and insecurity is shaping the livelihood of belligerents (Reyntjens, 2009).

The DRC has been drenched in a series of political crises and mass violence since the early 1990s, which culminated to a disastrous civil war in 1996 and the second Congo war in 1998 (Stearn, 2012a). These violent conflicts involved governments, militias and armed groups from the DRC and the neighboring countries Rwanda, Uganda and Burundi (see figure 2.1) and lasted for over four years in what was described as “Africa’s World War’ (Reyntjens, 2009). The impacts of these prolonged conflicts in the DRC encompass high rates of atrocities such as sexual and gender-based violence, and reaching peak death counts in war mortality threshold (Martin, Salumu, Baabo, Singh, & Lenglet, 2014). Sexual violence and human rights abuses are disproportionately inflicted on children and youths (Kalisya, et al., 2011). Even though the second Congo war was officially ended when all parties involved in conflict signed the so-called “Global and All-inclusive Agreement” in 2002, the tension and civil conflicts within the eastern provinces, especially Kivu, were not resolved by the peace agreement (Davis & Hayner, 2009; Stearn, 2012b). Crude mortality rates remain elevated even years after the war officially ended (Perouse de Montclos, 2016). Coghlan, et al. (2007; 2009) estimate an excess death toll of 5.6 million Congolese for the period between 1998 and 2007, and claimed 4.6 million deaths occurred in five eastern provinces of the DRC within the same period. Aside from the human slaughter, wildlife habitats are endangered (Fa, Currie, & Meeuwig, 2003), forest cover and reserves are lost—mainly owing to the exhaustive mining activities (Potapov et al., 2012). The environmental repercussions of civil conflicts and mineral exploration in the great lake region are an important risk to sustainable development (Levin et al., 2012). Civil society groups have highlighted austere conditions and fatal humanitarian crises in the DRC still plunging the eastern provinces long after the official end of civil war (Coghlan, et al., 2009; Enough Project, 2009; Global Witness, 2015).

Figure 2.1 Map of the Democratic Republic of the Congo (Source: Google map (2016))

Conflicts in the DRC are not entirely due to exploitation of natural resources: manifold issues are extensively discussed by Jason Stearn in his books (2012a; 2012b), and these are potentially rooted back to indigenous crises in colonial eras, genocide in the neighboring country of Rwanda and the weakness of the Congolese government. Conflict minerals[2] subsumes a variety of factors but typically refers to the illicit mining and commerce of cassiterite, niobium-tantalite (coltan in DRC), wolframite and gold funding the rebels and Congolese militias who propagate widespread violence, human rights abuses and other social problems and risks in the eastern provinces of the DRC. The situation analysis by conflict researchers concludes that illegal commerce of natural resources in conflict zones is an important factor that triggers and prolongs human conflict (Bannon & Collier, 2003; Billon, 2013). The conflict minerals problem presents a geopolitical reality in which many actors benefit from concessions including pillages and illegally traded minerals that may subsequently enter into formal channels (Garrett & Mitchell, 2009; Bleischwitz et al., 2012).

As widely acknowledged in the growing literature on illicit trade, the vast majority of mineral commodities trade which sustains and fuels civil wars depends on access to the global economy (Janus, 2012). Illicit commerce is infiltrating economic activities across the globe (Naim, 2005) and gaps in official trade data depict patterns of smuggling activities (Berger & Nitsch, 2012). Illegal taxes charged at mines and transport routes can generate as much as $500 million per year, specifically $9,200 per week in the region (Koning, 2011). Blieschwitz et al (2012) estimates illicit trade of coltan accounts for 20% of the tantalum world market, and the inconsistent trade statistics in the tantalum supply chain indicate that $27 million annually is likely lost to illicit trade of coltan from the DRC. Another study suggests that armed groups generated $11.8 million from illegal trade of coltan in 2008 (Nest, 2011, p.94). The risks abound amid geopolitics and challenges to economic growth, sustainable development and global security (World Economic Forum, 2012).

As early as 2001 corporations in America and Europe were accused of supporting the war economy in DRC by facilitating mineral exploitation, illicit commercial and material benefits for war lords (United Nations, 2001; IPIS, 2002). Around 2007, non-governmental organizations (NGOs) launched campaigns that vociferated the conflict minerals problem, calling on the corporations and original equipment manufacturers (OEMs), particularly American and European brands, to take responsibility for the human rights issues associated with the supply chain of conflict minerals for their products (Young et al., 2010; Koning & Enough Project, 2013). Some advocacy groups prepared reports linking

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[2] Conflict minerals is open to include other minerals like cobalt which in 2016 raised issues of human rights and conflict in DRC. The definition put forward in this study is in line with the US Dodd Frank Conflict Mineral Act.

electronics products to conflict in the DRC, while others employed campaigns likend to the campaign against blood diamonds (Koning & Enough Project, 2013; Global Witness, 2015).

2.1.2 Efforts for "Conflict-Free" Minerals and Metals

The conflict minerals problem illustrates a complex interconnectedness created by globalization in trade, communication, product manufacturing and consumption. There is a strong focus on identifying effective means to breaking the link between mineral trade flows and conflict in the DRC (Koning, 2011).

Initial responses stem from the UNGoE call for due diligence (United Nations Security Council, 2009), an approach formally established in the *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas* (OECD, 2011). The OECD Due Diligence Guidance provides a five step framework for companies operating in conflict-affected areas to ensure that they respect human rights and do not directly or indirectly contribute to financing conflict through supply and/or use of minerals and metals. Mineral extraction for tin, tantalum, tungsten and gold in Central Africa are identified as such high-risk areas (OECD, 2011). The OECD guidance encourages transparency in mineral supply chains and sustainable corporate engagement through the risk-based due diligence[3]. In 2010, a mandatory due diligence requirement was passed into law in the United Stated of America (USA) (U.S. Securities and Exchange Commission, 2010) even before the OECD published the first version of its due diligence guidance. In passing section 1502 of the Dodd Frank Act, the US Congress felt the conflict minerals problem was a matter of life and death (Nelson, 2014). The law addresses corporate disclosure on the use of "conflict minerals" in products manufactured by public companies traded in the USA: firms that are regulated by the US Securities and Exchange Commission (SEC). The provisions of section 1502 instructed the SEC to promulgate and adopt rules that require corporations to report the use of conflict minerals – specifically actions taken by these corporations "to exercise due diligence on the source and chain of custody of minerals" originating from the DRC or the nine adjoining countries (see figure 2.1). This provision requires that reports from each listed corporation include a description of the products manufactured that are not "DRC conflict-free", the auditor that certified the products, the facilities used to process conflict minerals, the country of origin of conflict minerals, and efforts to determine the mine or location of

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[3] According to the OECD guideline, risk-based due diligence refer to steps a company should take to address "potential adverse impacts of a company's operations, which results from company's own activities or relationships with third parties, including suppliers and other entities in the supply chain"(OECD, 2011)

origin. Nine countries in the Central African region are defined as "covered countries" by this provision, as they are possible routes for illicit trade of conflict minerals – Angola, Burundi, Central African Republic, Congo Republic, Rwanda, Sudan, Tanzania, Uganda and Zambia. In 2012, the SEC final rule became effective, with the first corporate reports in May 31, 2014. The rule requires all "issuers"[4] trading under the US SEC jurisdiction to comply with the due diligence provision, including US traded foreign corporations whose head offices are not located in the United States (US Securities and Exchange Commission, 2012). According to the SEC, although the DRC accounted for only 20% of the world's tantalum supply, 75% of the 5,994 issuers are affected and these corporations will need to submit an audited Conflict Minerals Report (CRM). The policies brought the conflict minerals problem to the fore inter alia and added to other pressures on corporations and OEMs, in turn elevating interest in ethical sourcing of minerals and management of metals supply chains (Young et al., 2013). These interventions entreated a shift in supply chain management with stipulations that extend producers' responsibility to issues of upstream minerals and metals production chains.

In parallel efforts, various non-governmental initiatives and tools emerged to manage and disconnect minerals supply from illicit trade of minerals funding armed groups in the DRC. Industry-led efforts were mainly in response to the due diligence requirement for tracing the origins of minerals and developing a responsible supply chain of minerals and metals. A variety of industry-lead responsible sourcing initiatives have adopted chain of custody, certification and/or compliance mechanisms to manage the supply chain of metals and promote conflict-free sourcing of minerals. While initiatives like the Certified Trade Chains Initiative (CTC) focus on certification of artisanal mines and in-region supply chains (Franken et al., 2012), other initiatives such as the ITRI[5] Tin Supply Chain Initiative iTSCI bag and tag system focus on maintaining a secured chain of custody of "clean" material exiting non-conflict mine regions (iTSCi, 2015a, 2015b). The Conflict-Free Smelters Program (CFSP) focuses on smelters and refiners as the "pinch point" in global metals supply chains (Young & Dias, 2012). The CFSP is a program under a broader industry initiative, the Conflict-Free Sourcing Initiative (CFSI) that uses information resulting from tracking and tracing of materials to identify processing facilities which

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[4] An issuer is a legal entity that develops, registers and sells securities for the purpose of financing its operations. Issuers may be domestic or foreign governments, corporations or investment trusts. Issuers are legally responsible for the obligations of the issue and for reporting financial conditions, material developments and any other operational activities as required by the regulations of their jurisdictions. (Source: Issuer Definition | Investopedia http://www.investopedia.com/terms/i/issuer.asp#ixzz43WVd4yGC)

[5] Industrial Technology Research Institute (ITRI) is a not for profit industry organization which represents the tin industry and is supported by tin producers and smelters.

are audited to establish assurance for conflict-free 3TG metals sourcing. Parallel programs include the London Bullion Market Association's (LBMA) Responsible Gold Guidance that focuses on implementing due diligence by certifying gold refiners (Young, Zhe, & Dias, 2014a). Fairtrade and Fairmined Gold, and the Chain-of-Custody (CoC) Certification by the Responsible Jewellery Council (RJC) focus on the supply chain of gold and adopt multiple sustainability and responsibility criteria (Manhart & Schleicher, 2013). Other approaches include the "closed pipeline" supply chain responsible sourcing project by Kemet Corporation, a full scale project led by a manufacturer of electronic components. This practice ensures tight management of coltan from the mine site to the processing facility and manufacturer of electronic components (see Appendix C). The Solutions for Hope Program, Conflict-Free Gold and Conflict-Free Tin Initiative adopt a similar approach and focus on supply chains for different 3TG metals (Pact, 2015). A broad range of tools and initiatives are evolving to mitigate the conflict minerals issues, support compliance with the Dodd Frank Act and due diligence requirements, and/or manage metals supply chain risks. These efforts for "conflict free" minerals and metals sourcing have been the subject for considerable analysis (Koning, 2011; Manhart & Schleicher, 2013; Schwarts, 2015; Young, 2015). The challenges and potentials of conflict-free mineral sourcing are widely deliberated in the literature, and briefly reviewed in this study section 2.1.3.

2.1.3 "Conflict-Free" Mineral Sourcing and Metal Supply chain

In addressing conflict minerals problem, many potential solutions emerged even without a clear understanding of the effects of interventions. While the OECD guideline and other industry-led initiatives implored voluntary due diligence through responsible sourcing supply chain of minerals, the US Dodd-Frank Act is a legally binding supply chain responsibility law for publicly traded US corporations (Manhart & Schleicher, 2013). Producers' responsibility is extended to social issues related to business practices of producers multiple tiers upstream of the end product - in this case, the supply chain of conflict minerals and metals. These interventions epitomized a significant shift in supply chain management that confers both challenges and potential for sustainability management of 3TG metals and their supply chains; a subject area gaining traction in research.

In the first year of implementation of the due diligence guidance, the OECD reported that challenges to engaging economic actors in responsible supply chain management included a lack of transparency and commercial confidentiality in minerals supply chains (OECD, 2012). The OECD attributes the progressive shift towards engagement at the end of the one year pilot implementation to the Dodd-

Frank Act and requirements set in programs by downstream and upstream[6] industries such as those contained in the CFSP and iTSCI programs (OECD, 2013). Skepticism is rife about the impacts of the Dodd-Frank conflict minerals law. The economic cost of implementing the provisions of this law implies substantial costs for corporations (Griffin, Lont, & Sun, 2014) and the incentive to source minerals from the DRC has greatly decreased (Bleischwitz & Guesnet, 2012). Opponents suggest that the Dodd-Frank Act created a *de facto* embargo and has adversely impacted the socio-economic wellbeing of over 2 million miners and families dependent on artisanal mining in the region (Cuvelier, Van Bockstaal, Vlassenroot, & Iguma, 2014; Seay, 2012; Woody, 2012). Views from a management perspective emphasize that issues related to management chains of metals present major challenges to implementing the conflict minerals law. Young & Dias (2011) argue that the law is flawed as it underestimates the complex nature of metals supply chains and overlooks physical aspects of metals supply that make it difficult to track and trace metals through tiers. The confidentiality of commercial information is one challenge to the management of supply chains (Young et al., 2008) that is further complicated when the number of supply chain tiers increases to as many as five or more (Resolve, 2010), and even more complex given the fragmented characters of suppliers dispersed globally (Young et al., 2013). The physical properties and transformation of metals make it difficult to trace these materials back to their origin. The production processes of metals breaks the chain as different raw materials (including primary mineral concentrate and scrap) sourced from different parts of the world can be processed at one smelting or refining facility to produce refined metals used in products and product components, thus the known provenance of raw materials become obscured at this pinch point (figure 2.2) (Resolve, 2010; Young et al., 2008). As a baseline for life cycle management (LCM) of product chains, a basic understanding of the physical chains and pathways of material flows is required for effective management of the supply chain of 3TG metals (Young & Dias, 2011).

Discussions from the legal profession maintain that using US domestic law to regulate global supply chains of minerals and metals has the potential to encourage responsible corporate behavior, and the existing challenges of due diligence could be overcome by more effective global regulatory responsible sourcing initiatives like the Kimberley Process Certification Scheme (Woody, 2012). Corporations should improve compliance with conflict-free initiatives and promote an internal culture of sustainable

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[6] OECD defines the downstream industry of the mineral supply chain as companies engaged in economics activities from the smelter and refiners up to the product manufacturers such as the electronic OEMs, while the upstream industry includes miners (both ASM and LSM), traders and other parties up to the smelters and refiners.

supply chain management (Schwarts, 2015; Sarfaty, 2015). As an innovative sustainability certification mechanism for metals and minerals, the Kimberley Process Certification Scheme was developed with an inter-state import/export regulation as a global resource governance initiative for responsible sourcing of diamonds in response to the observed link between diamond production and conflict. In their study, Manhart & Schleicher (2013) drew a widely held conclusion by proponents of the section 1502 of the Dodd Frank Act that aside from stimulating international attention to the war economy and policy decisions concerning conflict minerals in the DRC, there are significant impacts on natural resource governance and the involvement of armed groups in exploitation and trade of the 3TG minerals from the DRC. Although these proponents concur with the perceptible challenges of implementing due diligence requirements, they suggest that strategies and initiatives aiming to strengthen responsible sourcing of minerals from the DRC are important for any policy goal and should be supported. A recent investigation of the due diligence disclosures filed by US corporations in 2014, known as the Conflict Mineral Reports (CRM), claims that substantial progress has been made by US corporations towards country of origin inquiry and due diligence. On the other hand, some have argued that the CRM reports provided limited information about the country of origin of conflict minerals used (Gianopoulos, 2015; Pact, 2015).

Sustainability certification and standards are progressively popular in the agricultural, food, forest, fish and tourism industries (Alvarez & Von Hagen, 2012), but the interest in certification mechanisms for sustainable metals management has only recently increased as stakeholder pressure mounts on corporations to improve their scrutiny of their supply chains and take responsibility for the risks (Fleury & Davies, 2012; Young, Dias, & Zhe, 2013; Young, Dias, & Zhe, 2014). The responsible sourcing approach of conflict-free sourcing initiatives has adopted various responsible supply chain actions to social issues by communication, compliance and supply-development strategies (Yawar & Stefan, 2015). With regard to implementation of due diligence requirements, the mixing of streams in metals supply chains presents a physical barrier to sustainability certification of metals (Young et al., 2013). The CFSI focuses on the "pinch point" in the 3TG metals supply chain - metallurgical processing facilities where raw inputs from multiple sources, including mineral ores and scrap from manufacturing companies and postconsumer waste, are transformed into metal commodities (Manhart & Schleicher, 2013; Young, 2015). Conflict-free mineral programs have been criticized for having a narrow focus on a single sustainability issue (Levin et al., 2012) and many lack a formal accreditation mechanism. Albeit Young (2015) argues that the narrow focus creates simple criteria that makes operation of the program more effective. Young, et al. (2014) suggest that programs such as the CSFP could be expanded to manage supply chains of other metals and address a broad set of sustainability criteria. Notwithstanding to understand the effectiveness of this approach, a gap in the empirical aspects of responsible sourcing of conflict minerals exists as none of the programs have actually quantified material flows in terms of the scale of certified material in relation to the overall volume in the global supply chain (Young et al., 2013; Young, 2015).

Amongst the programs for responsible sourcing of conflict-free minerals and metals, the largest and most comprehensive is the Conflict-Free Smelters Program (CFSP) – a part of the collaborative-industry Conflict-Free Sourcing Initiative (CFSI) led by the Electronics Industry Citizenship Coalition (EICC) and Global e-Sustainability Initiative (GeSI). The CFSP focuses on the "pinch point" in the minerals and metals supply chain (Young & Dias, 2012) as the "gate" where material flows converge and thus can be observed and controlled (see figure 2.2) (Young, et al., 2014). The program does not certify metal products but confirms the compliance of metallurgical processing facilities over a period defined in its protocol in reference to each of the 3TG metals (Young & Dias, 2012). The CFSI has devised an array of tools that help corporations meet their disclosure and due diligence requirements (see figure 2.1). For example, the CFSI developed the Conflict Minerals Reporting Template (CMRT) to gather information on suppliers of 3TG from OEMs and component manufacturers down to smelters and refiners. The CMRT is a standardized template that helps downstream companies identify different sub-sets of suppliers up the supply chain, thereby supporting efforts to trace metals back to smelters and refiners.

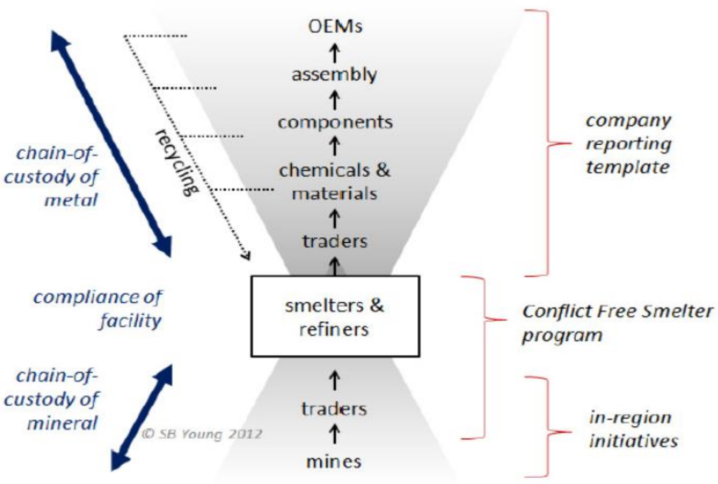

Figure 2.2 CFSP targets metallurgical processors (smelters and refiners) in the supply chain of the 3TG metals (source Young et al., 2014)

In light of complementing metals management approaches, a high level of collaboration already exists amongst the array of initiatives and tools for conflict-free minerals and metals supply. The CFSP collaborates with in-region sourcing initiatives such as iTSCi to coordinate and verify documents during the audit process for 3TG smelters and refiners (Young & Dias, 2012). There has been increased records of documentation trails of mineral production confirmed to be from conflict-free sources. iTSCi publishes the quantity of confirmed conflict-free materials from a number of mine sites in the DRC, Uganda and Burundi (iTSCi, 2015a, 2015b). Pact (2015) claims that the iTSCi program, amongst others, has helped to safeguard the livelihoods of over 80,000 miners and their dependents, but the program has faced many challenges including missing or illegible information. The OECD (2013) reported that such standardized tools as the CMRT have been impactful in the progressive engagement of business actors in minerals supply chains. The CFSP uses a third party audit process that certifies smelters and refiners as being compliant to the CFSP protocol and assures buyers of the origin and source[7] of the material (see figure 2.3 below).

Figure 2.3 The audit focus for CFSP compliance (source: CFSI, 2014)

The CFSI has established close contact with smelters and refiners engaged and compliant to the CFSP. Another laudable tool driven from the program is the Reasonable Country of Origin Inquiry (RCOI) data, which provides country-level information on sources of minerals and metals processed by 3TG smelters and refiners. Specifically, the RCOI data compiles the metal and mineral sourcing

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[7] These concepts are used in the present study in accordance with the definition by Young (2015): “Source refers to the processes by which a material is produced; metal sources include mining, recycling, historical sources (such as government stockpiles), and intermediate by-products from processing other metals (such as gold by-product from copper refining). Origin is a deeper concept and refers to the geographic location from which a resource is originally extracted or created.”

choices based on the risk level of the country of origin of the minerals and considers secondary sources form scrap. In the first 5 years of operation, the CFSP has engaged over 300 3TG smelters and refiners, and estimates that over 95% of global tantalum production is from compliant facilities (Young, 2015; Butler, Holeman, & Rohwer, 2016). This achievement reflects that compliance with the CFSP has grown rapidly among tantalum producers, but to better discuss the efficacy of conflict-free sourcing programs and potentials for any sustainability certification program, substantial participation of 3TG supply chains in responsible sourcing programs is required (Fitzpatrick, Olivetti, Miller, Roth, & Kirchain, 2015) alongside material flow accounts of production data (Bleischwitz et al., 2012) including a breakdown of material certified as conflict-free and material alleged to have unknown or conflict origin (Young et al., 2013).

2.2 Tantalum

2.2.1 Introduction

Tantalum is a uniquely valuable technology metal whose intrinsic properties are required to fulfill essential functions in specialized applications and crucial global products. Tantalum is characterized by excellent electrical conductivity and corrosion resistance; it has high density, dielectric strength, melting and boiling points (3,020 °C and 5,457 °C respectively); it is biocompatible, very strong yet ductile, which allows for ease of fabrication (Agulyonski, 2004; Lanbert, 2007). As a transition metal, tantalum has similar physical and chemical properties to niobium and other d-block elements of group 5 and typically both metals are hosted by the same mineral oxides (USGS, 2014). However, tantalum is a preferred metal for many products particularly due to electrostatic properties that allow a very small quantity of tantalum to store and release high amounts of energy, making it suitable for high-performance capacitors in miniature products (Nest, 2011, p.9; USGS, 2014).

These characteristics make tantalum indispensable to hi-tech industries. Tantalum is important to the electronics industry for fabrication of high performance capacitors widely used in modern electronic devices (Mackay & Simandl, 2014; Miller, 2007; Nikishina et al., 2014). About 60% of tantalum production is used in the electronics industry and capacitors have become its single largest end use market (Bleiwas et al., 2015; USGS, 2005). Tantalum powder sintered into a pellet is able to form a thin insulating oxide layer on its surface when submerged in an electrolyte; thus a single pellet can serve as the anode and dielectric of a capacitor, distinguishing tantalum capacitors as having high volumetric capacitance and lower weight (Reynolds, 2008). These properties make tantalum capacitors ideal for high performance electronic devices such as mobile phones and laptops. Tantalum is useful for other components of digital devices such as sputtering targets, surface acoustic wave filter, X-ray films, ink jet printers, and lenses for digital cameras (Yager et al., 2015). The electronics industry also uses tantalum as a barrier between two incompatible elements – copper and silicon – for production of computer chips and storage devices (Agulyonski, 2004). Tantalum has also become a valuable component of 'super alloys' used for aerospace applications and land-based gas turbines in the metallurgical industry, which accounts for 20% of tantalum consumption (Mackay & Simandl, 2014). As a valued surgical material in the medical industry, tantalum disks and plates are used for implants in dental, knee, joint, skull and hip replacements (Liu et al., 2015; Matsuno et al., 2001; Patil et al., 2009; Wauthle et al., 2015). In the chemical and metallurgical industries, tantalum is used for coatings and is incorporated into pipes, tanks, vessels and other equipment (Espinoza, 2012). Tantalum metal powder sintered onto composite metals forms cemented carbide used in cutting tools for machining and other engineering applications (Bayarjargal et al., 2014). Other uses include manufacturing of semi-finished and finished products such as heat exchangers, reaction vessels, blade heaters, and radiation shields (Bleiwas et al., 2015). The functionality of these applications and products are sought to meet economic and/or security needs of many nations today (Bleiwas et al., 2015; Espinoza, 2012; Nikishina et al., 2014).

Tantalum metal does not occur naturally; rather, it is extracted after processing its mineral concentrates, which are recovered from tantalum-bearing mineral ores, as a by-product of tin production, or from scrap materials recycled from industrial processes and/or post-consumer scrap (Linnen, Trueman, & Burt, 2014; Mackay & Simandl, 2014; Nikishina et al., 2014). In the earlier years of tantalum production, a significant portion of tantalum production was associated with tin mining and smelting particularly from south-east Asia, but diversification of tantalum supply increased as demand grew for tantalum capacitors in the early 1970s (Crockett & Sutphin, 1993). A number of factors, including the fall of tin prices, contributed to increased tantalum mineral production and growing industrial requirements for high purity metals resulted in less demand of tin slag and increased investment in tantalum production from conventional sources. Tantalum mining is economically viable in only a few parts of the world. The minerals of most economic interest are tantalite, tantalite-columbite, microlite, wodginite, struverite (Burt, 2016; Mackay & Simandl, 2014). Although tantalum-bearing mineral deposits have been identified in almost every continent (Adabanija & Oladunjoye, 2014; Dewaele et al., 2011; Dill, 2015; Hark et al., 2012; Kuster, 2009; Mackay & Simandl, 2015; Melcher et al., 2015; Milesi et al., 2006), fewer than 20 countries account for global mineral production

(U.S Geological Survey, 2015). The geology of mineral deposits impacts the cost of exploration and mining. The hard rock carbonatites in Canada, pegmatites in Australia, and alkaline-granites in Brazil are mined through large scale mining (LSM) operations that require substantial investment to maintain production. Whereas in the DRC, Rwanda, Nigeria and other nations, recovery of tantalum concentrates is less cost intensive, as simple artisanal mining (ASM) tools can easily extract minerals from placer pegmatite deposits that occur at or near the surface (Burt, 2016; Shaw & Goodenough, 2011).

Australia, Brazil and Canada were the leading producers of tantalum mineral concentrates in the early 2000s. In past five years, the Central African countries are leading mine production. By 2014, Rwanda accounted for 50% and the Central African region, including the DRC, accounted for almost 80% of world mine production. A recent publication from United States Geological Survey (USGS) graphically mapped some factors and effects on the changes in mine production for the period 2000 to 2014 (figure 2.4).

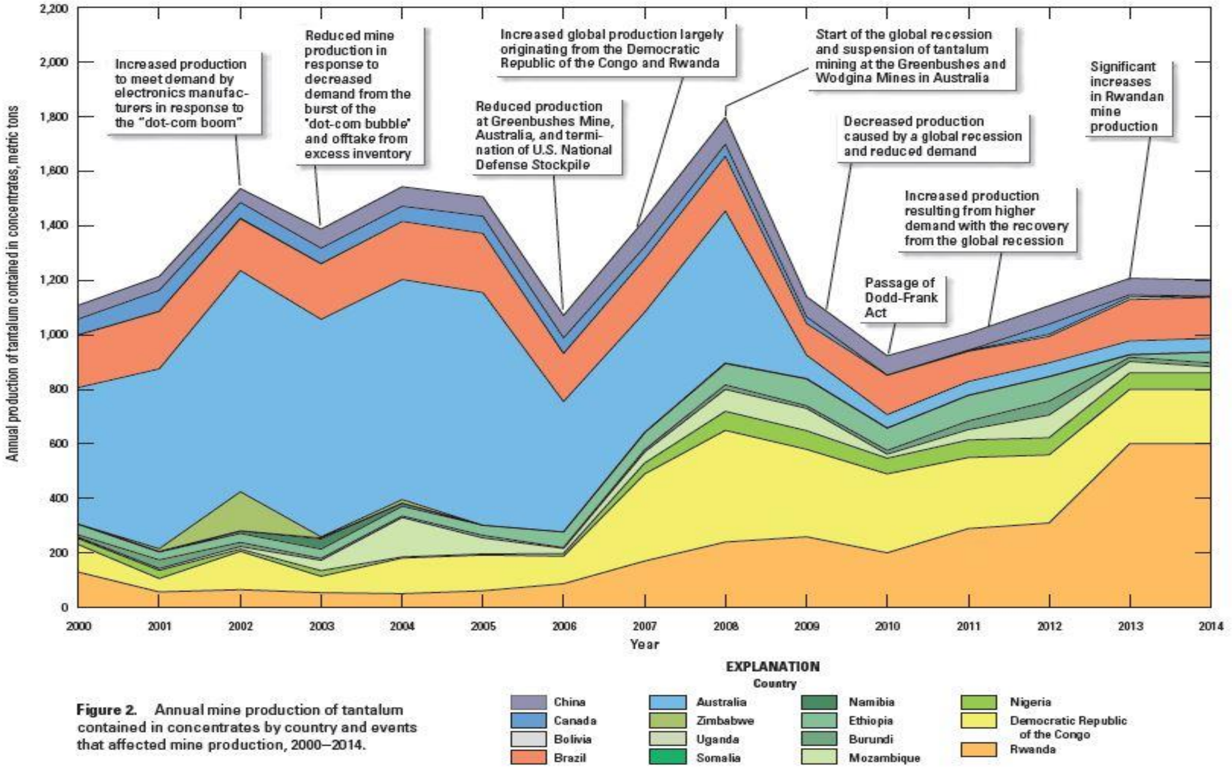


Figure 2. Annual mine production of tantalum contained in concentrates by country and events that affected mine production, 2000–2014.

Figure 2.4 Recent changes in the supply of tantalum minerals (source: USGS report by Bleiwas et al., (2015))

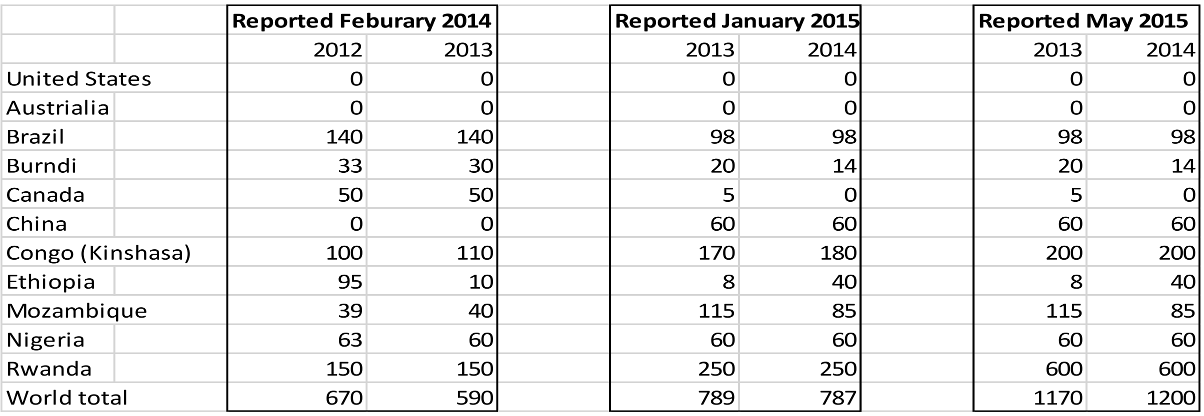
Naturally, geological restrictions and economic viability dictate minerals production, but the actual availability of minerals and metals is influenced by many other factors including social constraints, politics, legislation, environmental regulations, capacity, capabilities and capital (Herrington, 2013). The apparent diversification in tantalum mine production in the recent past reflects the role these factors play in metals and minerals supply. Of concern is that the largest producers, in the Central African region, are known to be connected with conflict minerals practices (as discussed in section 2.1). The shift to DRC and Rwanda has been linked to many intertwined factors, including the closure of tantalum mines in Australia due to financial issues, the increasing supply of cheap artisanal mined minerals from central African countries, and the falling prices of tantalum minerals to the impact of the Dodd-Frank (Bafilemba et al., 2014; Bleiwas et al., 2015; Polinares, 2013). Common to mineral commodities, the effects of demand and supply are reflected in price (Andrews-Speed et al., 2012). The price of tantalum minerals rose 50% between 2010 to 2013 (McLeod, 2015). Tantalum is one technology metal whose mineral market has experienced very unstable short term price oscillations with very steep short-lived price spikes (Yager et al., 2015). The steep prices in the early 1980s are conceivably connected to the increasing demand of tantalum capacitors in the use of computers (Crockett & Sutphin, 1993), while the price spike in the 2000s is alleged to have resulted from overly optimistic demand forecasts for tantalum capacitors based on a sharp rise in demand for new technologies (especially laptops), and advancements in digital technologies including mobile phones and gaming devices (Nest, 2011). Tantalum minerals are not traded on commodity exchanges; rather, the price is set privately between the buyer and seller (Espinoza, 2012). Most trade is achieved by long-term contracts between the processing company and the mining corporation (Mackay & Simandl, 2014; Nikishina et al., 2014). In cases of artisanal miners, for example the DRC which holds easily accessible surface alluvial deposits, mineral trade is more complicated for minerals recovered largely through artisanal mining activities (Koning, 2011). Coltan from mine sites in the DRC usually goes through multiple tiers of traders (called negociants/buyers/comptoirs) then exported through neighboring countries (Bleischwitz & Guesnet, 2012; Ma, 2009). Bleischwitz et al. (2012) claim that the neighboring countries, especially Rwanda, are gateways for illicit trade of coltan from the DRC propagating conflict and environmental problems (as discussed in section 2.1). This argument is based on the inconsistency of trade data between Rwanda and importing countries such as China (Ma, 2009; Moran, McBain, Kanemoto, Lenzen, & Geschke, 2014; Sutherland, 2011; Polinares, 2013).

2.2.2 Tantalum Production Chain

Sporadic imbalances in demand and supply are typical for tantalum; for example, the United States is a leading consumer of tantalum and tantalum products but has not produced tantalum minerals since 1959 (Bleiwas et al., 2015). As the global economy increasingly depends on huge influxes of resources to build and grow, the increasing demand for materials witnessed in recent times is also ascribed to tantalum. Tantalum demand increased relatively steadily per year at 6% in the 1990s (Ma, 2009), but the growing demand for hi-tech products has resulted to increased tantalum production over 50% in the past decade (Mackay & Simandl, 2014). According to the Tantalum-Niobium International Study Centre (TIC) tantalum product shipments increased by 9% in the period of 2013 to 2014, while specific products such as tantalum chemicals, tantalum capacitors and tantalum carbide rose by 25%, 17% and 35% respectively (Schwela, 2014, 2016). Demand for tantalum products is soaring alongside technological advances and economic growth, such that diverse industry sectors continue to leverage the properties of tantalum to enable product functionality. A recent market report projects a 41% increase in global shipment of mobile phones. Such growing demand, combined with limited production and geopolitical risks, is akin to the group of metals known as “critical metals” (Guss, 2014) to the development of the global economy.

The growing concern about critical metals is not based on a shortage in mineral reserves, but rather the complexities and the risks associated with their supply chains that impact the availability and accessbility of these resources (Ayres & Peiró, 2013; Bloodworth & Gunn, 2012; Peiró, Méndez, & Ayres, 2011; Guss, 2014). Coupled with low recycling rates (Graedel et al., 2011; Graedel, 2011; Reck & Graedel, 2012; UNEP-IWP, 2011), the supply risks of critical metals has gained interest in many nations. Tantalum production is limited and its supply chain is very complex (Linnen, Trueman, & Burt, 2014). For some applications like capacitors, substitution is challenging due to cost and performance penalties, yet demand is increasing (Ayres & Peiró, 2013; Peiró, Méndez, & Ayres, 2013; Strothmann, 2013). A recent study predicts a 44% increase in tantalum demand for Information and Communication Technology (ICT) only in 5 years (Fitzpatrick et al., 2015), while another study predicted a steady 15% increase for all tantalum products used for industrial and consumer products (Startton, 2013). Tantalum is critical for the development of sustainable energy technologies economic growth and national security in the United States (Bleiwas et al., 2015). In Europe, tantalum is identified as one of the “critical metals in the path towards the decarbonization of the EU energy sector” (Moss et al., 2013). Studies on how to mitigate supply risks of critical metals and foster a secure, sustainable supply of these metals, suggest many strategies including material efficiency, reuse, recycling, product redesign, encouraging improved waste collection, investment in substitution and life cycle management of products (Matthais Buchert et al., 2009; European Commission, 2014; USNRC, 2008). However, the development and implementation of these strategies is highly dependent on reliable quantitative data (Chancerel et al., 2013) and a clear understanding of the industrial activities and markets for these metals. Key challenges pertaining to critical metals are that information on their mineral occurrence, metal flows and processes is limited and their supply chains are non-transparent (Bloodworth, 2014a; Guss, 2014). Information on tantalum production is limited and in most case available data are not reliable. For example from the widely sort data source, the United States Geological Survey (USGS) database, tantalum mine production estimates have been difficult and were repeatedly updated, resulting in changes in estimates reported in these official mineral commodity summaries (Table 2.1). TIC has criticized the inconsistency in data reported by USGS.

Table 2.1 USGS Tantalum Mineral Commodity Summary Reported Between 2014 and 2015 (adapted from U.S Geological Survey , 2014, 2015a, 2015b)



	Reported Feburary 2014		**Reported January 2015**		**Reported May 2015**	
	2012	2013	2013	2014	2013	2014
United States	0	0	0	0	0	0
Austrialia	0	0	0	0	0	0
Brazil	140	140	98	98	98	98
Burndi	33	30	20	14	20	14
Canada	50	50	5	0	5	0
China	0	0	60	60	60	60
Congo (Kinshasa)	100	110	170	180	200	200
Ethiopia	95	10	8	40	8	40
Mozambique	39	40	115	85	115	85
Nigeria	63	60	60	60	60	60
Rwanda	150	150	250	250	600	600
World total	670	590	789	787	1170	1200

In supply chain theory, supply chains are comprised of "nodes" and material/information flow paths that deliver valuable products and services for consumers; nodes can be facilities that process goods linked by material flow paths (Min & Zhou, 2002). As mapped by Soto-Viruet et al. (2013), the supply chain of tantalum begins with raw materials recovery from the lithosphere (tantalum mineral concentrates), tin processing residue (tin slag) and anthropogenic sources (products and process scrap) and ends with tantalum in products. The supply chain of tantalum begins with a series of upstream processes that includes mining, metallurgical processing (chemical processing and metal refining) and extends downstream to fabricating and manufacturing of component parts and complex products. Many efforts have been made to close the knowledge gap in tantalum mineralogical and geochemical data, but knowledge of the production chain is limited – particularly with regard to the material flows with the tantalum industry (Bleischwitz et al., 2012; Polinares, 2013).

Although the metallurgical processing of tantalum is generally done by two broad alternative methods depending on the composition of the tantalum resources processed, figure 2.6 illustrates the traditional, predominant method (Linnen, Trueman, & Burt, 2014). The tantalum metallurgical production system becomes very complex, when the six or more sub-processes which can be completely done at one facility and company or partly at different processing facilities and by a large number of companies, depending on the processing method applied at the production facility and the tantalum product category that is produced. Apparently, the challenge in examining the tantalum industry is intensified to include understanding the market and discerning the roles of different players and layers in the sector. Moreover, the tantalum industry is highly opaque, as the industry is known for being secretive (USGS, 2013). Bloodworth and Gunn (2012) suggest that an understanding of the material flows in the minerals and metals sector is important to plan for future demand of critical metals. This knowledge gap for tantalum is demonstrated in a recent study of data needs for raw material flow analysis and assessment of material value chains for 21 strategic materials in Europe (RPA, 2012).

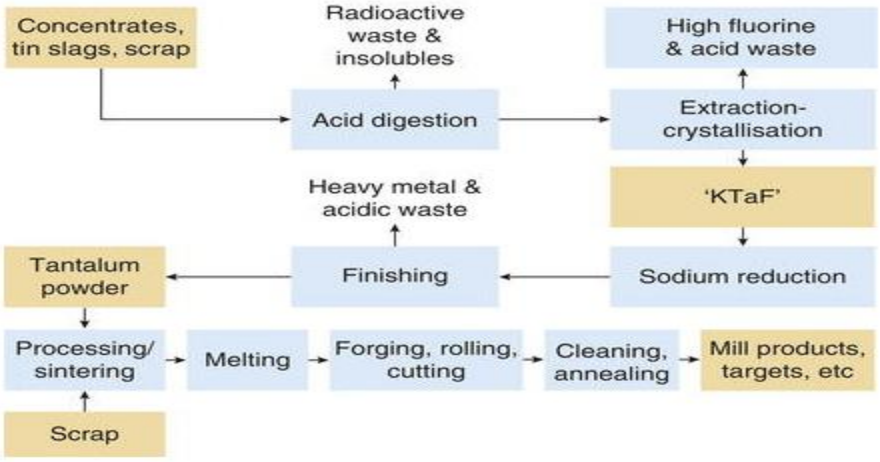


Figure 2.5 Simplified Process-flow sheet of the method for tantalum production from tantalum resources – tantalum mineral concentrates, tin slag and scrap (source: Linnen, Trueman, & Burt, 2014)

A limited number of academic studies have identified and/or quantified tantalum flows. Available studies have focused on a region or nation (for example the United States by Sibley, 2004), select product groups (Chancerel, Marwede, Nissen, & Lang, 2015; Fitzpatrick et al., 2015), tantalum minerals from the DRC and largely depended on trade statistics (Nest, 2011; Bleischwitz et al., 2012), in some cases using information for niobium to fill data gaps (Moran et al., 2014). The USGS publishes annual mineral production statistics for tantalum mineral concentrates (U.S Geological Survey, 2014, 2015a, 2015b), and has done extensive work in quantifying tantalum flows in the United States while reporting measures for resource management such as recycling efficiency (Sibley, 2004). The tantalum industry association TIC, has produced yearly statistics on tantalum production from raw material sources to the first use tantalum product categories such as capacitor powder, tantalum carbide, tantalum mill products, tantalum chemicals and tantalum refined metals in the form of ingots and powder (Schwela, 2014, 2016). However, these industry reports only represent data from members registered with the TIC and largely excludes the small individual miners in central Africa and the traders from the region. So over 40% of the mineral trade is outside the data reported by the industry (Burt, 2016). The industry claims it uses the receipts and shipment records of its members to adjust for missing data (Schwela, 2016). The records may be more aligned further up the supply chain as many of those producers and traders are subscribed to this association compared to the number of participants upstream (Schwela, 2014). Market research companies such as Roskill provide detailed reports on the apparent demand and supply of tantalum metal products and raw materials (PRNewswire, 2012; Startton, 2013). The retrospective study by Moran et al. (2014) used a hybrid life cycle assessment (LCA) method to trace flows of tantalum mineral concentrates from the DRC. Although the LCA study revealed a likely path of coltan from the DRC to products and industries in the global north, it reflects the weaknesses of LCA tools for quantifying material flows in the minerals and metals sector, and assessing supply chain sustainability already identified in literature (Atherton, 2011). The limitations of LCA include continued dependence on industry–average upstream data sets and product-oriented analysis which flouts system analysis at material level; unresolved debates with respect to allocation procedures, and spatial and temporal dimensions (Yellishetty, Haque, & Dubreuil, 2012; Yellishetty, Ranjith, Tharumarajah, & Bhosale, 2009). The USGS has carried out studies to map the supply chain of tantalum, and characterized some components of tantalum flows from mineral extraction to first tier in-use products, and identified 30 tantalum processing facilities, but did not provide any information about the sources of material processed at the facilities nor the quantity of tantalum produced (Papp, 2014a; Soto-Viruet et al., 2013). There is a limited knowledge on global tantalum production from conflict-free sources and much of the supply chain is still very opaque.

Chapter 3

An Industrial Ecology Tool – Substance Flow Analysis

3.1 Background

As a system embedded in the biosphere, human society depends on the natural environment for its subsistence which is enabled by an interrelated process of material and energy transformation (Brunner & Rechberger, 2004; Van der Voet et al., 2013). An analogous notion of biological metabolism emerged in the field of socioenvironmental research to understand society's transformation in relation to natural environment (Fischer-Kowalski, 1998). The application of metabolism to human society expanded from the catabolism and anabolism metabolic concept to a core analytical concept for understanding material and energy exchange of society with their natural environment (Ayres & Kneese, 1969; Fischer-Kowalski, 1998; Frosch & Gallopoulos, 1989). Although the application of the term metabolism to society can be traced to classic social science research as far back in 1860s, the awareness of anthropogenic environmental changes links with the prevailing trajectory of society's use of natural resources characterized by unsustainable production and consumption driven by rapid global population and economic growth, expansion of industrial civilization revived the interest in society's metabolism (Ayres & Ayres, 2002; Brunner & Rechberger, 2004; Fischer-Kowalski, 1998). Abel Wolman (1965) and Robert Ayres & Allen Kneese (1969) made the earlier attempts to developing conceptual framework for analyzing the impacts of human-induced activities on environmental relations. Two broad overlapping field of study have increasingly strengthen the concept of society's metabolism in contemporary socioenvironmental research. One is the social metabolism, is more general and conceptualize the interaction between the natural environment and the society that covers industrial system and nonindustrial modes of human livelihood (Fisher-Kowalski, 1998). Ayres and Kneese (1969) coined the notion of industrial metabolism and described it as the process of material and energy flows through industrial systems in a thermodynamics framework that operates based on the law of conservation of mass. Ayres and Kneese (1969) argue that industrial transformation processes in the anthroposphere ought to model biological systems in the ecosphere to ameliorate the adverse effect of industrial activities. Their first material flow analysis for the United States between 1963 and 1965 conceived the metabolism of industrial society as an input problem that can be solved through efficient use of material resources (Ayres and Kneese, 1969). Wolman (1965) in his case study of the metabolism of cities in United States, concluded that "the metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard" (Wolman 1965 p.179). Comprehensive literature review papers by Fischer-Kowalski (1998) and Fischer-Kowalski & Hüttler (1999) provides detailed information on history and the development of the society's metabolism concept.

Industrial ecology (IE) emerged as field of study with a goal to understand the structure and operationalize the industrial metabolism (Lifset & Graedel, 2002). As widely acknowledged in various IE literatures, sustainability problems arise from unsustainable material resource production and consumption which is primarily driven by global industrial expansion in the pursuit of economic growth and development (Allen et al., 2009; Ayres & Ayres, 2002; Ciacci, Reck, Nassar, & Graedel, 2015; Graedel, 2011; Harper, Johnson, & Graedel, 2006; Korhonen, 2004; Sendra, Gabarrell, & Vicent, 2007). The sustainable use of resources requires an understanding of the flow of resources from the time of sourcing, through processing, manufacturing or fabrication into other products, use and final destination as waste or reusable resource (National Research Council of the National Academies, 2004). The broader concept for such analysis is called material flow analysis (MFA), a technique used in the field of IE to characterize the flows of a material (for example substances, biotic and abiotic materials, products) through a system or stage of the material life cycle (including extraction, production, transformation, consumption, recycling and disposal) defined in space and time (Ayres, 1994; Ayres & Ayres, 1998; Brunner & Rechberger, 2004; Eurostat, 2012).

Material Flow Analysis (MFA) generally encompasses both substance flow analysis (SFA) and the economic-wide MFA. Both are upheld as representative of the MFA approach (Bringezu et al., 1997; Kleijn et al., 1999; Daniel & Moore, 2002) SFA is a specific brand of MFA that focuses on substance while Economy-wide MFA focuses on flows of 'bulk' material throughput through firms, sectors and geographical areas (M. Fischer-Kowalski et al., 2011). MFA is guided by the law of conservation of matter and uses mass units for quantifying physical material stocks and flows (Brunner & Rechberger, 2004) MFA has led to various insights into connections of material origins, pathways, and intermediary and final disposal in a system, and the identification of inefficiencies within a system (Graedel, 2010; Strothmann, 2013). As an important tool for quantifying the magnitude of material flows in the global economy, economic-wide MFA and SFA studies have informed strategies for sustainable materials management (Allen et al., 2009; Allen, Halloran, Leith, & Lindsay, 2009) including agricultural nutrient management (Qiao, Zheng, & Zhu, 2011), waste and waste treatment (Liu, Tanaka, & Matsui, 2006; Nakamura & Nakajima, 2005; Rotter, Kost, Winkler, & Bilitewski, 2004), process control (Chancerel, Meskers, Hagelüken, & Rotter, 2009), resources production and consumption (Graedel, 2010), recovery and recycling performance (Graedel & et al., 2011; Sibley, 2011), and resource efficiency and dematerialization (Lifset, Eckelman, Harper, Hausfather, & Urbina, 2012; Schandl & West, 2010).The Economy-wide MFA framework is based on socio-economic metabolism, an established approach and has a methodological guideline linking MFA accounts to official statistics (Eurostat, 2012) and assesses the flows and stock of bulk materials (Hinterberger, Giljum, & Hammer, 2003; Fischer-Kowalski & Weisz, 2005; Fischer-Kowalski, et al., 2011).

Compared to the multi-material aggregated in economy-wide MFA, substance flow analysis (SFA) accounts for specific chemically defined substances, commonly elements and chemical compounds (Ayres & Ayres, 2002; Brunner & Rechberger, 2004b). SFA is certainly not a new method of analysis; as presented in pioneering studies, for example to address the metabolism of cities (Wolman, 1965), industries (Ayres & Kneese, 1969; Ayres, 1989) and regional basins (Huntzicker et al. 1972). SFA, as a tool for industrial ecology (IE), informs strategies to operationalize industrial metabolisms. It reflects a systems approach, and in most cases, a life cycle perspective, to trace flows of one substance or group of substances into and out of a system. Thus it illuminates the behaviors of substance flows and stocks that emerge within the system (Harper et al., 2006). Substance flow analysis (SFA) is a quantitative approach to track flows of metals (Chen & Graedel, 2012b), nutrients (Qiao, Zheng, & Zhu, 2011), and complex chemicals (European Environment Agency, 2007) usually originating from biophysical systems (biosphere or geosphere) through the transformation in societal (anthroposphere) metabolism and to the final sink in the biophysical systems (biosphere or geosphere) (Brunner & Rechberger, 2004b).

The next three sub-sections provide a review of SFA and its application to tracking flows of metals. The goal of this literature review is to identify a framework on which to base further research, namely to help characterize the supply chain of tantalum and understand the magnitude and pathways of tantalum flows. Specifically, this review examines the quantitative characterization of metal flows and draws upon salient aspects of SFA, namely the systems perspective and the anthropogenic cycle of metals. Section 2.3.2 provides an overview of the substance flow analysis framework, while identifying methodological differences and knowledge gaps. This section ends with a discussion of the strengths and weaknesses of both SFA and MFA.

3.2 Substance Flow Analysis of Metals

For managing metals and minerals supply chains, understanding the material flow patterns has been widely identified as a baseline to inform strategies (Allen et al., 2009; Alonso, Gregory, Field, & Kirchain, 2007; Bloodworth & Gunn, 2012; Bloodworth, 2014b; Harper et al., 2006; Young & Dias, 2011). Substance flow analysis (SFA) is an important tool for quantifying metal flows. SFA is described as an analytical tool that “aims to provide relevant information for an overall management strategy with regards to a specific substance or a limited group of substances” (Ayres & Ayres, 2002, p. 91). SFA is often driven by different yet complementing research themes from environmental pollution to resource scarcity, availability and utilization, and the goal is to inform the subject matter by analyzing and understanding the flows and stocks of a substance or group of substances within a system (Binder, Van Der Voet, & Rosselot, 2009; Wagner, 2002). Whereas the key principles of SFA are simple, the practical procedure is seldom so, thus there is still no standardized methodology for SFA (Binder et al., 2009; Huang, Vause, Ma, & Yu, 2012).

As a branch of the broader concept of MFA, the methodological foundation of SFA is based on the mass balance principle. Conversely, SFA tends to check substance stocks and flows balance as a basis to understand changes regarding societal or industrial metabolism. Although substance flow analysis has been applied since the early 1970s to trace substance flows through the physical processes in society (Brunner & Rechberger, 2004b), the diversity of SFA studies infers no standardized consensus on a methodological framework (Binder et al., 2009). A methodological framework for SFA was first proposed by Udo de Haes, Voet, and Kleijn (1997) to initiate, foster and structure information exchange between researchers in MFA (Stefan; Bringezu et al., 1997). Therein, Udo de Haes et al. prosed a three-step SFA framework inspired by the technical framework of Life Cycle Assessment (LCA) (ISO 14040, 2006). As recommended by Udo de Haes et al. (1997) and reiterated in the “Handbook of Industrial Ecology” (Ayres & Ayres, 2002), the following steps should guide SFA analysis:

1. Goal and systems definition: includes formulation of target questions (which flow will be accounted for in order to quantify the volume and path of the flow, definition of the scope (defines the spatial, temporal and sometimes functional extent of the subject objects) and system boundary (defines the start and the end of the material flows). A flow chart showing the network of nodes is established in this step which provides the basis for the next step. For SFA, it is crucial to define the scale and level at spatial and functional boundary, time horizon and the materials to be studied.

2. Inventory and modelling: quantification of the network including collecting the relevant data and modelling. Based on data requirements and potential for policy support, one of these modelling approaches - bookkeeping, static and dynamic modelling can be applied. Results of an SFA study can be presented as a quantified descriptive analysis of a system.

3. Interpretation: evaluation of the robustness of results or translation of results into policy-relevant terms are two ways of interpretation in the third step. SFA is useful for monitoring and evaluating management strategies, and for revealing the location, timing and extent of future sustainability problems linked with substances (Daniels & Moore, 2001). Interpretation of SFA results can be defined in terms of aggregate data on flows which can be expressed in terms of indicators to facilitate interpretation of results for policy makers (Udo de Haes et al. (1997).

This framework has been expanded and in some cases streamlined into other SFA approaches developed and used for SFA studies. For example, in a practical handbook on MFA, Brunner and Rechberger (2004) recommend an iterative six-step framework that reflects a partitioning of the generic three steps. In practice, Voet (2002) suggests that all three steps involve a variety of methodological choices which depend on the goal of the study and the questions to be answered. These fundamental aspects guide the decisions on what frame of reference the research will adopt, details to define the reference system and sub-systems, flows and/or stocks to include in the study, the quantification approach and finally how to interpret the results. A few studies have adapted the generic SFA framework to explore a focal stage or processes in a systematic perspective and analyzed flows within and through life cycle stages, chains of processes or stages. Bai et al. (2015) analyzed the production system of lead by adapting the three-phase SFA framework from Voet (2002) and the six-step procedure form Brunner & Rechberger (2004b). The authors translated the SFA methodology into five steps - definition of systems; identification of pathways flows and data; mass balancing of substance flow accounts; evaluation using indicators; and interpretation of results (Bai et al., 2015). The SFA framework has been expanded to a form of “hybrid” analysis to include the economic dimensions of flows related to management of supply chains – for example, in Dahlström and Ekins (2006) study that explored the value chain of steel, and Williams (2003) study of material and economic flows in the production chain for silicon.

3.2.1 System Definition: Spatial and Temporal Dimensions, Frame of Reference

The first step is to clearly describe the metabolism of the systems under study, so in system definition is to select the substance or group of substances of concern, and define the units of analysis in boundary terms of space, time and function (Udo de Haes, Voet, & Kleijn, 1997; Van der Voet, 2002). The boundaries are set at spatial scale, time horizon and functional level to analyze a particular substance or group of substances to achieve the goal of the study. The remainder of the system definition and the quantification method are largely driven by two basic views of the basic notion of the interrelations between the environment and the economy, where the relationship is interpreted distinctly or integrated (Ayres & Ayres, 2002, p. 94). The two systems define the frame of reference in SFA studies, and consequently the distinct views are reflected in the widespread SFA research approaches. A societal system (also known as the technosphere or anthroposphere) is the economy which contains material stocks and flows mainly controlled or induced by human activities. The other is the environment (biosphere, geosphere or lithosphere) that consists of natural, biologically available stocks and flows of materials.

The methodological approach defined by Baccini & Brunner (1991) assesses the anthropogenic and environmental flows in a single system. This approach is appplied to analyze material flows and fluxes in the metabolism of a region, thus has informed environmental management strategies concerning a substance or group of substances within regions (Baccini & Brunner, 2012). The flows of substances are studied with the aim of finding their sources, routes, and pathways in the society (anthropogenic) and the environment (geogenic); thus the goal of this approach to determine the material balances of the anthropogenic system and the corresponding materials balances of the environment into which the anthropogenic system is embedded (Brunner & Rechberger, 2004). An anthropogenic system is defined by "the transfer, storage and transformation of material within that system and exchange of materials with its environment" (Brunner & Rechberger, 2004). The systemic perspective focuses on the anthropogenic system to define the units of analysis for stocks and flows through the life cycle of anthropogenic substances. The substance life cycle provides a frame of reference to identify and quantify material stocks and flows of assembled reservoirs and tracked substance flows into, out of and among several reserves (Chen & Graedel, 2012; Harper, Kavlak, & Graedel, 2012). A distinction can be made between the stages of the substance life cycle, in that flows at each stage and for the whole system can be analyzed. This methodological approach is commonly referred to as cycle methodology, anthropogenic cycle of materials or elemental cycle (Klee & Graedel, 2004).

The anthropogenic metal cycle methodological framework (figure 3.1) stems from material cycle studies known to have a strong history in biogeochemistry, started with global carbon cycle then paved way for biogeochemical nitrogen, phosphorus and expanded to other elements on the periodic table such as metals (Chen & Graedel, 2012a; Harper et al., 2006). The anthropogenic cycle of metals depicts a substance life cycle approach to track metal flows through a defined system while establishing substance balances for all metal life cycle stages. The metal life cycle is a frame of reference to identify and quantify metals stocks and flows, and track metal flows into, out of and within systems (Chen & Graedel, 2012b; Harper et al., 2012).

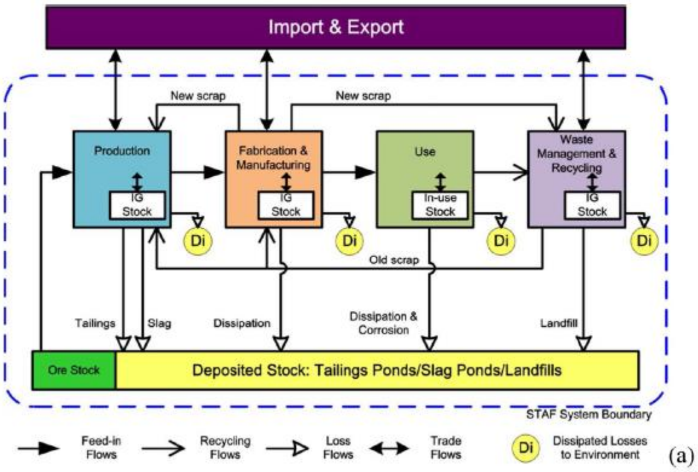


Figure 3.1 Conceptual framework of the anthropogenic metal cycle approach of SFA (source: Chen & Graedel (2012b))

The anthropogenic metal cycle has been widely adopted as the conceptual framework to quantitatively characterize the flows of metals and metalloids (Chen and Graedel, 2013). Using this framework, the stocks and flows of metals (predominantly a narrow focus on specific metals within a geographically defined region) can be quantified by balancing input and output flows, and stocks of each stage in the metal life cycle. Typically SFA allows for accounting flows and stocks at the following metal life cycle stages: raw material extraction, production processes, fabrication and manufacturing into products, use in society, final disposal or recycling at product end of life (Chen & Graedel, 2012b; Gordon, Bertram, & Graedel, 2006; Harper et al., 2006). The Stock and Flow project (STAF) group at Yale University applies the cycle method (as shown in figure 3.2) to trace flows of widely used metals and make complexities of the metal cycle more transparent, thereby informing strategies for resource sustainability (Eckelman, Reck, & Graedel, 2012; Gerst & Graedel, 2008; Graedel et al., 2004; Graedel, 2011; Harper et al., 2006; Rostkowski et al., 2007; Harper & Graedel, 2008; Reck, Müller, Rostkowski, & Graedel, 2008).

A recent review by Chen and Graedel (2012), indicates anthropogenic cycles have been constructed for 45 metals but only about a dozen of them are well characterized. The main challenges to cycle construction include the need to establish quantitative flows for each arrow (see figure 3.1) from limited or unavailable relevant data, and submerging many complex subsystems into four compound subsystems. Each of the life cycle stages in figure 3.1 have three, four or more stages submerged. For example, the production stage is a collation of processes such as mining, smelting and refining (Chen & Graedel, 2012b; Wang, Chen, & Li, 2015). Therefore, an SFA study of metal flows based on metal life cycles seems to be an overarching approach to gain a comprehensive understanding of impacts associated with metal systems including production and consumption, but may not illuminate issues in one stage such as immersed effects of a management strategy for a particular chain of stages (Williams, 2003), changes in a particular process (Bai et al., 2015), or trends in a particular production process like refined metal production (Wang et al., 2015).

A few studies have adapted the generic SFA framework to explore a focal stage or processes in a systematic perspective and analyzed flows within and through life cycle stages, chains of processes or stages. Bai et al. (2015) characterized mass flows of lead and focused on a specific lead smelting processing to define scope and system boundaries for the study(see figure 3.2). The flows of precious metals during the processing of electronic equipment waste was analyzed by Chancerel et al. (2009), while the flows of toxic waste in similar processes were the focus of a recent study by Oguchi, Sakanakura and Terazono (2013). The functional dimension of SFA system and resource efficiency of a particular substance in the system were paramount objectives of most of these studies. Such studies have illustrated that certain problems or changes could be hidden by a macroscopic perspective of the metal life cycle, thus it is vital to reference a practicable frame to enable SFA analysis to manage data availability constraints and still provide the required understanding of substance flows and stocks.

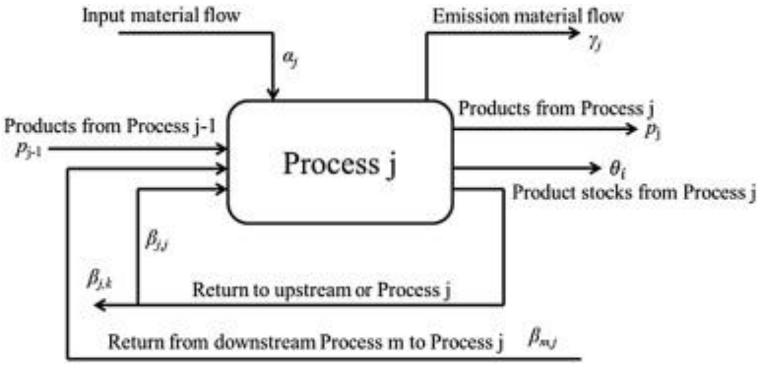


Figure 3.2 Substance flow chart for SFA of lead smelting process (source: Bai et al. (2015))

Anthropogenic cycles have been constructed at multiple levels to understand the interplay of anthropogenic flows and stocks within defined boundaries. The spatial boundaries include a micro-level of a city to a macro level of global scale analysis. Over the last years, a number of studies have characterized flows and stocks of widely used metals, for example at global scale aluminum (Liu & Müller, 2013), copper (Wang et al., 2015), lithium (Peiró, Méndez, & Ayres, 2013); regional scale as well as national scale for example silicon (Williams, 2003), iron (Davis et al., 2007), indium, niobium and nickel (Leal-Ayala, Allwood, Bloodworth, Cilliers, & Moore, 2014); to analysis of flows with a defined municipal boundary (Oguchi et al., 2013); and a processing facility (Bai et al., 2015). Multilevel analysis also exists, for example copper (Graedel et al., 2004), cobalt (Harper et al., 2012), and nickel (Reck et al, 2008; Eckelman et al., 2012). Chen and Graedel (2012) estimate that a total of 1,074 individual metal cycle analyses have characterized the flows of about 45 metals.

However, limited research has focused on flows of metals produced from conflict minerals. A recent study quantified the global mass flows of tungsten to determine the material efficiency of the mass flows of tungsten across supply chains and inform strategies for supply security (Leal-Ayala, Allwood, Petavratzi, Brown, & Gunn, 2015). A global cycle of tin has also been analyzed at national levels and a global scale in a similar sense to address resource efficiency (Chen & Graedel, 2012b). Tantalum flows, on the other hand, have been quantified for only two nations and a recent study only quantified tantalum use in select products such as electronic devices (Chancerel et al., 2015; Fitzpatrick et al., 2015). Therefore, the present study aims to characterize tantalum flows with a granular data level not previously undertaken for a global scale. While a city, national or regional scale analysis of a metal can inform strategies for managing flows within that geographical boundary, a review of the literature has demonstrated that the lack of understanding of metals mass flows in a global scale inhibits the evaluation of long-term resource sustainability strategies (Chen & Graedel, 2012b).

3.2.2 Quantification of metal flows

The methodological foundation of SFA as part of MFA is the mass balance principle. Accordingly, SFA tends to check the balance of substance stocks and flows as a basis to understand changes regarding systems metabolism. SFA approaches to anthropogenic flow and stock analysis estimate the balance of inputs and outputs of the whole system, and at each stage of the system (Mendez et al., 2014). Anthropogenic material stocks and flows arise from human activities of production, use, and disposal of products. Quantifying flows and stocks of metals cycle stages, identifies the relationship production among metals. Some metals are not sourced on their own, but instead depend on other metal ores; this is the case for many rare earth elements (Ayres & Peiró, 2013; Peiró et al., 2011). Another relevant effect is on policy goals. For example, phasing out cadmium may affect production of its primary metal (Mansson, Bergback, & Sorme, 2009), and to inform decision makers which processes increase waste attributes and dissipation to the environment. In general, SFA studies have mapped the sources of specific substances to find the main use with a focus on inflows and the build-up of stocks (Lifset, Eckelman, Harper, Hausfather, & Urbina, 2012; Nakamura et al., 2014; Schandl & West, 2010; Peiró et al., 2013).

To model anthropogenic cycles of a metal, the mass balancing is observed at each life cycle stage, thus the substance input flows must equal output flows after considerations have been made for any substance accumulation or storage (i.e. stocks) for that stage (Harper et al., 2006). By balancing input and output flows of each stage in the material life cycle, depletion or accumulation of material stocks as well as flows of waste and environmental loadings are revealed, and their sources are identified early enough to take measures or to promote further buildup and future utilization (Mendez et al., 2014; Peiró et al., 2013). Information on mass flows is usually taken from databases or measured directly or indirectly on site, and for solid material flows (Brunner & Rechberger, 2004a).

Depending on the data available and explicit or implicit requirements of the study, various researchers employed the stock-based techniques - either a top-down and/or a bottom-up approach to estimate in-use stocks at use stage of the metal life cycle (Gerst & Graedel, 2008; Graedel, 2010). A top-down approach uses information from historical databases regarding flows and infers in-use stock by the cumulative difference between inflows and outflows in a system or stage. In contrast, the bottom-up approach uses information on stocks to estimate in-use stock and infer the behaviour of flows is desired. Both approaches are geopolitically constrained, and the trade-off is dependent on the unit of analysis selected and the study goal (Gerst & Graedel, 2008). Bottom-up studies can be used to precisely disaggregate stocks among the principal uses and in-stock use information depicts the basis for material discard management (Rostkowski et al., 2007). To date such granular analyses have not been developed for quantifying mass flows. Consequently to quantify production flows on a global or regional scale; data is aggregated from national data or industry-average. The present study employs a bottom-up method to enhance the conventional SFA approach for quantifying mass flows.

SFA modelling approaches typically compute flows and stocks for a given year, which means that flows and stocks reflect the annual temporal scale of the analysis. There are three main modeling approaches - accounting, static modelling and dynamic modelling (Udo de Haes, Voet, & Kleijn, 1997).

These modelling approaches can be used to inform new resource management regimes (Bloodworth, 2014b; Strothmann, 2013), track the flows of critical metals (Müller, Hilty, Widmer, Schluep, & Faulstich, 2014; Nansai et al., 2014), analyze origin or source of particular flows (Nakajima et al., 2013; UNEP-IWP, 2013) and locate where metals may be available for future recycling (Eckelman et al., 2012; Reck & Graedel, 2012; UNEP-IWP, 2011).

The accounting approach is a bookkeeping type of modelling that mainly serves as a step to develop a flowchart for a given system and error checks to find missing data. This approach provides a descriptive statistic in an overview of flows for a system (Ayres & Ayres, 2002). Such information is vital for understanding a particular system and analysis into the relationships in changes of flows, stocks and the processes that influence changes, for example, the SFA of metals and organic compounds by Månsson (2009). The majority of SFA studies for metals use a static model, one-year snapshot wherein all flows are characterized in one time period (Harper et al., 2006). Static material flow analysis models have been well addressed for bulk metals such as steel, iron, copper, zinc and aluminium at both global and national level, but metals like tantalum have only three static models at a national level from the USA and Japan (Chen & Graedel, 2012b)

Dynamic modelling, though very few studies exist compared to static models, is preferred because it provides information about the behaviour of a system or reservoir (primary and secondary) of stocks based on information extrapolated from stocks and flows over a given time period (Harper et al., 2006). A recent review of 60 dynamic modelling studies of material flow analysis (Müller et al., 2014), reveals that the modelling principles applied are similar but extrapolation methods for stocks and flows are varied based on socioeconomic variables considered and the goal of the study. As illustrated in two studies of tungsten, Harper & Graedel (2008) used the traditional end-user sector model to determine tungsten use over time and final product model to determine the pattern of end-use products in the United States, while another study by the same authors (Harper et al. 2008) produced a more detailed product-level analysis based on the finished products entering the United States and how long the product stays in use in turn provides an indicator of when the product is expected to enter the waste stream. Quantitative data on end-use and lifetimes of metals in products expresses the metals products content that enter use, eventually reach their end-of-life and are either recycled or discarded. Dynamic material flow analysis exists for most metals including complex metalloids such as magnets (Habib, Schibye, Vestbø, Dall, & Wenzel, 2014), but literature for tantalum, indium and rare-earth metals is scarce (Ayres & Peiró, 2013; Glöser, Soulier, & Tercero Espinoza, 2013; Müller et al., 2014; Peiró et al., 2011; Wang, Mao, Johnson, Reck, & Graedel, 2008).

Quantification of technology metal cycles also illuminates metals use levels and opportunities for recycling and reuse, along with the effects of growing consumption (Lifset et al., 2012; Nakamura et al., 2014; Peiró et al., 2013; Peiró et al., 2013). It is therefore imperative to characterize the flows of critical metals in order to mitigate possible future supply risks (United Nations Environment Programme, 2013; Van der Voet et al., 2013). Characterizing stocks and flows have revealed sourcing dependency of some metals on other metal ores; for example, rare-earth elements are dependent on zinc and iron ores, for tantalum and niobium possibly mined from individual ores, also depend on tin ores for production to meet the metal demand (Graedel & Erdmann, 2012; Peiró et al., 2013). The impacts of policy goals on cadmium was reveal to affect zinc production by characterizing the metal cycle (Mansson, Bergback, & Sorme, 2009).

3.2.3 Interpreting SFA Results: SFA sustainability indicators

The release of substances to the environment is of primary interest in SFA. SFA is useful for monitoring and evaluating management strategies, and for revealing the location, timing and extent of future sustainability problems linked with substances. Interpretation of SFA results are defined in terms of aggregate data on flows and accumulation of the material under study, thus expressed as indicators of relevance to policy makers (Udo de Haes et *al.*,1997). Amongst the many sustainability indicators, two are often adapted to SFA studies: resource efficiency and recycling efficiency.

Resource efficiency enables strategic planning for efficient sourcing, production, manufacturing, use and disposal of anthropogenic stocks and flows. MFA estimates are measured against standards prevalent to the spatial region and to the material to determine the efficiency of each process and stage sustainability concerns ascertained in those standards and accepted practice (Bringezu, Schütz, Steger, & Baudisch, 2004). Metrics may evaluated demand increase, production, or consumption and disposal of metals increase dissipation to the environment.

SFA methodology can also provide the information necessary for key recycling efficiency rates (Sibley, 2011; UNEP-IWP, 2011). Recycling aims to restrain the consumption of natural resources and reduce environmental loads. In the field of industrial ecology, recycling is a strategy for closing the material cycle loop, simply “loop closing” or “supply loop” and mining from society’s in-use product at end-of life “urban mining” (Rebitzer, Fullana, Weidema, & Jolliet, 2003; Tercero Espinoza, 2012).

High recycling efficiency at production implies that scrap obtained from end-of-life products sufficiently displaces the need for primary resources such as minerals that are extracted from the environment. Recycled content (RC) and old scrap ratio (OSR) are metrics for assessing recycling efficiency at the production stage of metals (Dubreuil, Young, Atherton, & Gloria, 2010; Graedel & et al., 2011).

Recycling rates can influence policy goals for material efficiency, for example, the EU directive on end-of-life vehicles (ELV). Considering the goal of using MFA to characterize the life cycle of production, consumption, recovery and recycling is to close various levels of value-added and under various circumstances, minimize environmental issues caused at both the back and front end of linear production and consumption systems and sustain economic value of resources (Ayres & Peiró, 2013; Buchert, Schuler, & Bleher, 2009; Glöser et al., 2013; Geyer & Jackson, 2004; Zimmermann et al., 2014), it is crucial to have information on how to close supply chain loops.

3.3 Strengths and Weaknesses SFA Method

SFA in industrial ecology provides information on resource sustainability. Examining the growing concern of material criticality (Leal-Ayala et al., 2014), especially of minor metals, provides another justification for studying the way materials are used in the global economy. The challenge is that implementation of SFA results in decision making is driven by the fact that the results of SFA studies are dependent on the scale and level under which the study is undertaken. The barriers to implementation at the global, regional and intermediate level are intensified by the number of stakeholders, uncertainty of data, and not clearly defined goals of materials management (Binder, 2007). SFA results using sustainability indicators such as recycling rates (Graedel et al., 2011) and material use levels can direct policy goals and strategies for achieving those goals, addressing what can be sustained or changed to influence resource flows through society and the environment (Binder et al., 2009; Brunner, 2002).

As a tool for analyzing industrial and society’s metabolism, the most criticized drawback of SFA is the inability to link mass-based MFA indicators to environmental impacts (Hinterberger et al., 2003; Spangenberg, Hinterberger, Moll, & Schutz, 1999). Sendra et al. (2007) argue that material use indicators can be used to analyze industrial use of resources and their efficiency. SFA studies, in combination with other methods such as input-output analysis (Nakamura & Nakajima, 2005), life cycle assessment (Rochat, Binder, Diaz, & Jolliet, 2013) and statistical models (Eckelman & Daigo, 2008; Eckelman et al., 2012) can solicit a more robust evaluation and interpretation of SFA results that decision makers can use for strategic policy goals. An example is the global multi-regional SFA-based Markov chain model that can illuminate and account for changes related to different patterns in production, end-use sectors and recycling systems. Any of these models can be applied to management strategies for crucial technology metals (Bloodworth, 2014a) to assess the technology lifetime of metals in a product, and for better planning resource efficiency and recycling performance (Leal-Ayala et al., 2014), the number of times the metal is reused and recycled in an economy or sector as a key metric for resource efficiency (Chen & Graedel, 2012; Graedel et al., 2011).

3.4 Research Objective and Rationale

This study aims to understand the pathways of materials in the production chain of tantalum, and from this basis determine the quantity of tantalum production that is produced from conflict-free sources. The specific objectives are:

1. Explore an approach to quantify global scale of tantalum production and flows at facility-level
2. Quantify global tantalum production including characterization of different production mass flows
3. Estimate the magnitude and progression of tantalum produced from conflict-free sources from 2010 to 2014.

The global tantalum analysis will illuminate tantalum supply chain complexities; describe sources of metal, total amount of metal production, sourcing patterns by region including mineral sourcing choices; estimate production into end-use component categories and recycling efficiency; identify opportunities and risk areas associated with current global tantalum sourcing practice and production trends; indicate areas to improve efficiencies, help manage ethical commodity supplies, and support secure material access. The results of this research help inform discussions on conflict minerals and critical materials and, more broadly, support public and corporate strategies towards development of sustainable metal management.

This work contributes to the SFA literature empirically and methodologically. It is the first effort to complete a substance flow analysis of tantalum at a global scale. In order to quantify tantalum production and conduct a global scale analysis of tantalum material flows, a bottom-up method is used in this study. The bottom-up method complements the conventional SFA methodology with an approach to quantify global metal production system with a facility-level sampling and quantification of metal flows.

Chapter 4

Methodology

The approach used in this study is consistent with the general principles of substance flow analysis (SFA) described in chapter 3. Various researchers have looked at metal flows from a production or consumption perspective depending on the objectives of the study. They have adopted substance life cycle or efficiency-oriented approaches aimed at improving material, processes and recovery efficiency across metal life cycle stages, or changing consumption behaviors (Chen & Graedel, 2012b). Given the objectives and potential applications, this thesis adopted a production-oriented approach with a focus on the upstream end of the supply chain of tantalum. In order to quantify tantalum production and conduct a global scale analysis of tantalum material flows, a new bottom-up method is used in this study as an extension of the accounting approach of conventional SFA methodology. SFA of metals can consider multiple spatial scales and time horizons, sections 4.1 through 4.4 provide details on the methodology and data adopted in this study.

4.1 Substance Flow Analysis Methodology

This research adopts a substance flow analysis (SFA) approach to analyze materials flows in the supply chain of tantalum. The goal of the study is to provide an overview of global tantalum production and mass flows through the supply chain to determine the quantity of tantalum production that is from compliant conflict-free sources. This study examines global flows in 2014 as a baseline.

As discussed in chapter 3, although no standardized methodology for SFA exists, several frameworks have been put forward and adopted to look at metal flows across a system or systems. The goal and scope of a study set the term for choices regarding both system definition and the method for SFA modelling of substance flows association with a process or a system. The definition of the research goal and scope directs the methodological decisions, determines the boundaries of analysis and indicators to be evaluated, and guides further data collection.

Given the goal and the available dataset, the present SFA study on tantalum flows adopted the methodological framework for SFA proposed by Udo de Haes et al (1997) and Voet (2002). However, this thesis further used an original bottom-up method to enhance the SFA framework. Generally, the SFA framework presents a quantitative research methodology that includes definition of the system to be analyzed in terms of substance of interests, geographical boundaries, time and functional dimensions. This is followed by a quantification of the system's substance flows; and interpretation of the results for policy decision makers. The three basic steps of SFA framework (system definition, quantification and interpretation of results) can be conducted in many ways, the methodology as adopted in this study is shown in figure 4.1. This study enhances the second step by developing and using the bottom-up method.

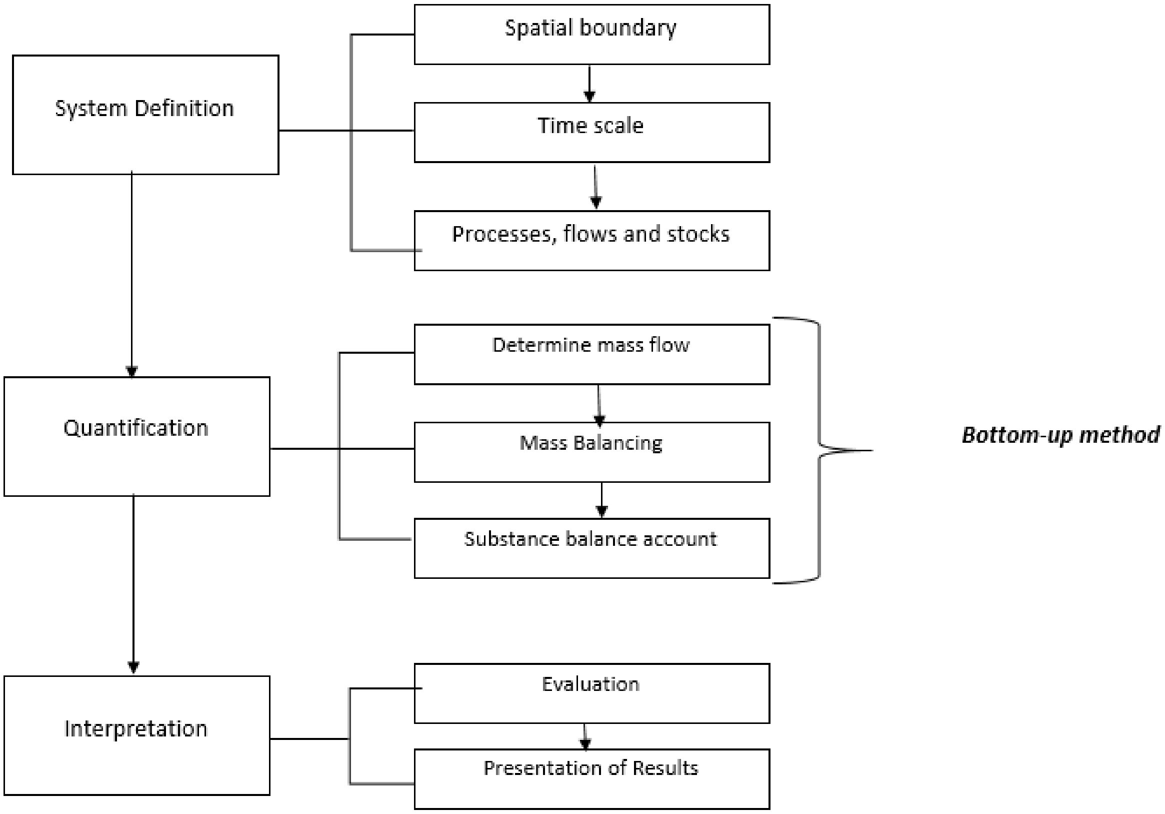


Figure 4.1 General methodological framework of SFA, indicating how in this study the quantification step has employed a novel bottom-up method

4.2 System Definition

The system definition of the substance flow analysis is articulated in the units of analysis and the approach that allow quantitative expression of available data. Units of analysis are defined on spatial and temporal scales (Gerst & Graedel, 2008). Taking the prevalent substance lifecycle view seems to be an overarching approach by which a researcher can gain understanding of the substance pathways that both production and consumption of the substance entails (figure 4.2). Given the production-oriented approach and goal of this study, the scope of analysis is limited to the upstream part of the supply chain. The upstream boundaries were drawn where the substances enter the metallurgical processes as metal feedstocks. The downstream boundaries were drawn at the point through which the substance exits as metal commodities for first-use in fabrication and manufacturing. Thus, the scope of this analysis is limited to the upstream metal production stage of the supply chain focusing on metallurgical production of tantalum (see figure 4.2 and 4.3).

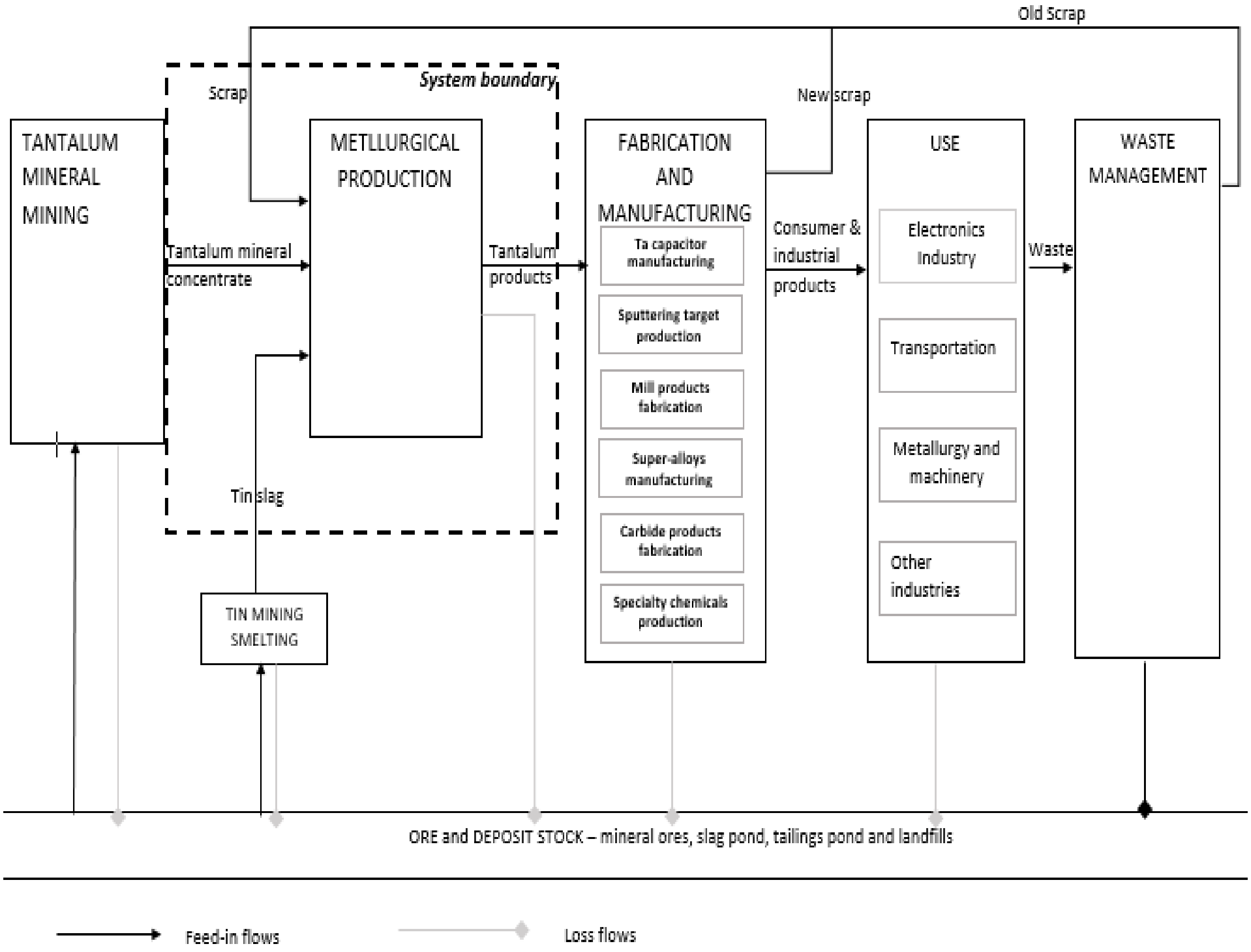


Figure 4.2 Simplified flow diagram for tantalum, based on global anthropogenic metal cycle approach. Dashed line indicates life-cycle boundaries used in this study.

4.2.1 Spatial and Time Boundaries

The geographical boundary of the SFA is global, as the production of tantalum occurs around the world. The baseline year for the SFA is 2014. This scope allows for a comprehensive accounting of all tantalum material flows using the most recent practicable dataset available. A number of industry and government sources correspond to 2014, which are employed. Additionally, to address study objective #3, the current study considers a retrospective analysis of tantalum production for the period 2010 – 2014. This provides an estimate of the scale and progression tantalum produced as conflict-free sources were introduced.

4.2.2 Definition of System Processes, Stock and Flows

The tantalum flow diagram (figure 4.2) outlines pathways of metal flows and breakdowns the essential stages of the supply chain of tantalum. The system boundary delineates the metallurgical production processing stages which consist of the relevant flows and processes considered in the current study. As described in chapter 2, tantalum resources undergo a series of chemical processes along with metallurgical reduction and refining to produce pure metal. The feedstock (tantalum resources) include tantalum mineral concentrate from tantalum-specific mining of tantalum-bearing mineral ores, tin slag that contains in the order of 2-10% tantalum after tin metal production, and tantalum-bearing scrap materials that are recovered from post-industrial and post-consumer wastes (TIC, 2016; Linnen, Trueman, & Burt, 2014). The tantalum metallurgical processing is a multi-process stage consisting of six or more sub-processes to produce tantalum chemicals and/or metals (Linnen, Trueman, & Burt, 2014). These processes can be completed at one facility or may be divided amongst different processing facilities. Consequently production from concentrate to metal may be done by as few as one or by a large number of companies, depending on the facilities involved and the tantalum products produced (TIC, 2016). There are two main industrial methods of producing intermediate tantalum chemicals, which consists of multiple sub-processes and dependent on the type of tantalum resource processed at a facility. Tantalum chemicals are further reduced and refined to tantalum metal products by a range of reduction processes, the selection of reduction method is driven by the tantalum product category a processor aims to produce.

In the SFA study, these sub-processes were simplified and grouped into two sub-stages (figure 4.3). First is the smelting process which includes chemical processes that transform tantalum feedstocks (tantalum mineral concentrate, tin slag and scrap) into tantalum chemicals. The next stage is the refining process which includes reduction of intermediate chemical compounds (K_2TaF_7 and Ta_2O_5) into pure tantalum metal in various product forms. Inflows to the systems are the feedstock raw materials: tantalum mineral concentrate, tin slag and scrap. The links between each stage are material flow paths of intermediate tantalum chemical compounds. Mass outflows include tantalum chemicals (oxides), tantalum metal powder, tantalum carbide, and consolidated tantalum metal and tantalum ingot.

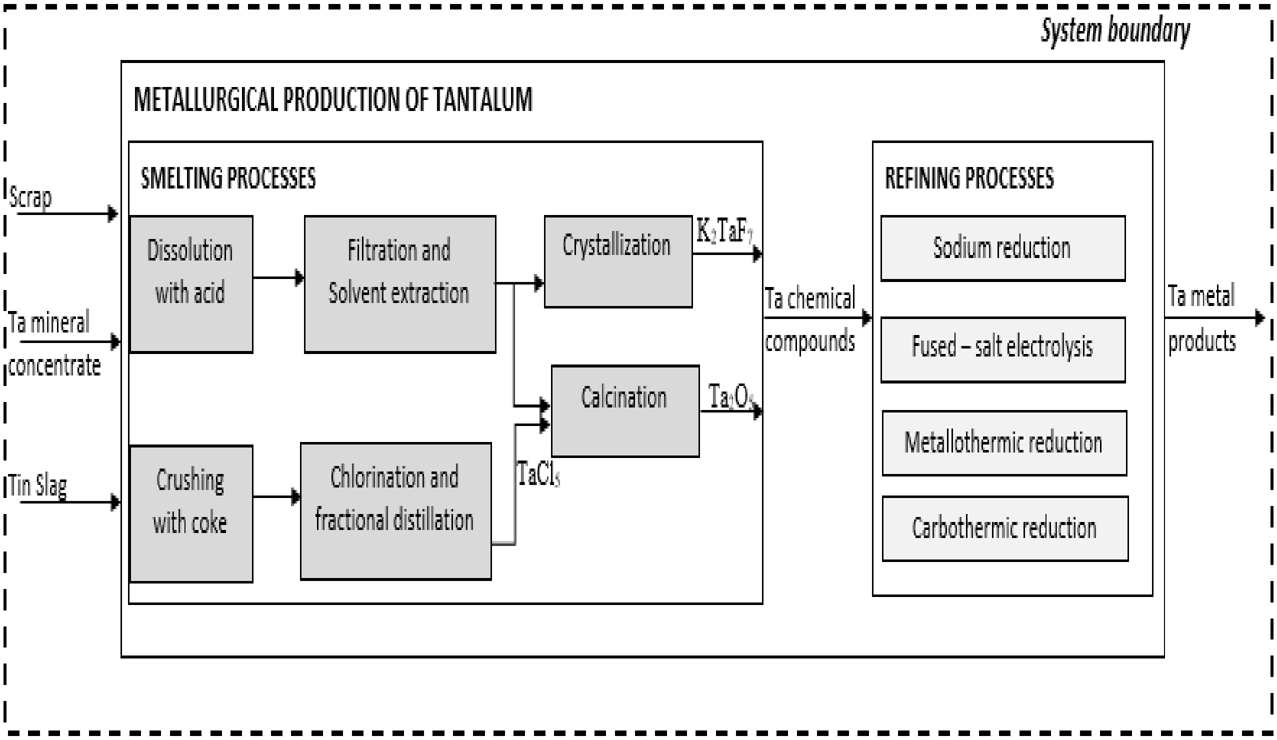


Figure 4.3 System boundary of tantalum metallurgical production stage (source: Bose & Gupta (2002), Linnen, Trueman, & Burt (2014), TIC (2016))

4.3 Quantification

The metallurgical production system of a metal is a network of processes, a web of sub-processes and pathways for materials that are transformed into metal products. These processes can be managed at just one to several processing facilities or processing companies linked by material flows to one another. A great many data are required in an SFA of this sort. Consequently, the choice and use of a quantification approach is an important consideration. An initial approach to modelling a system in SFA is to treat it as an accounting or bookkeeping system (Ayres & Ayres, 2002; vanderVoet et al., 1995). In this way, a descriptive analysis can be made by using available data on flows and applying mass balance principle to estimate missing amounts. The present study extends the conventional accounting SFA approach by applying a bottom-up method to quantify mass flows at the facility-level.

4.3.1 Bottom-up method

The bottom-up method is one novel element of this study that presents an added value to the traditional SFA framework. The approach uses facility-level data sampling and aggregation approach to quantify metal mass flows and production. The bottom-up method refers to characterizing the metal production system, estimating the amount of material used to produce metal by detailed material flow sampling and characterization based on facility-level production data and combining it with number of facilities in a given geographical boundary. The strategy of the bottom-up method here is similar to the bottom-up approach for estimating in-use stock (Gerst & Graedel, 2008). The present method takes information on flow variables at facility-level to estimate total quantity of metal produced and infer the behavior of flows for the defined boundaries of the production system. Depending on the geographical boundaries, facility-level flow estimates can be aggregated to account for defined spatial boundary.

The bottom-up method uses granular facility-level data to quantify flows at the global scale. The bottom-up method uses the geo-data of metal facilities, aggregate production statistics, collate data on content of specific substance and mass flows of material, and correlates company sourcing practices to material sources. A combination of these data builds a database on mass flow and substance flow estimates (in tonnes per year) at facility-level to analyze the defined system. Data sampling together with application of mass balance principle leads to desired overview of flows and global production from the material sources, including categorization into primary and secondary sources. The strength and weakness of the bottom-up method are discussed in chapter 5.

Variables considered were the number of different flows of tantalum (n), mass flows quantities determined for each facility (T_n), the tantalum content (M_n) of each flow, the quantity of tantalum flow ($\dot{t}n$), and the number of facilities (k). These data are then collated as shown in table 4.1, to form a data spreadsheet for determining quantities of flows at multiple facilities. Brunner and Rechberger (2004) recommend that development of a data spreadsheet is vital in the course of SFA to determine mass flows, substance concentration in mass flows and substance flows.

Table 4.1 Development of the data spreadsheet for sampling tantalum flows at facility-level

Facilities (name)	**Location (country)**	**Mass Flows (t/yr) (range of materials)**							**Substance Flows (t/yr) (range of materials)**						
F_1	L_1	T_{11}	T_{12}	*	*	*	*	T_{1n}	t_{11}	t_{12}	*	*	*	*	t_{1n}
F_2	L_2	T_{21}	T_{22}	*	*	*	*	T_{2n}	t_{21}	t_{22}	*	*	*	*	t_{2n}
F_3	L_3	T_{31}	T_{32}	*	*	*	*	T_{3n}	t_{31}	t_{32}	*	*	*	*	t_{3n}
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
F_k	L_k	T_{k1}	T_{k2}	*	*	*	*	T_{kn}	t_{k1}	t_{k2}	*	*	*	*	t_{kn}

For mathematical formation, the quantity of tantalum flow ($\dot{t}n$) can be estimated using equation (1). The bottom-up method adopts mass balancing exercise on substance inflows and outflows for the system as a whole using facility-level estimates, such that missing data can be identified and estimated based on substance balance account. The substance flows for tantalum production system can be established by aggregating flows at the facility level and scaling with the number of facilities (k) to form a description of the global tantalum flows. The substance balance account for all substance inflows and outflows for the system is shown as equation (2).

$$\dot{t}n = T_n \text{ x } M_n \qquad (1)$$

$$\sum_n^k \dot{t}\mathrm{n}\, inflows = \sum_n^k \dot{t}\mathrm{n}\, outflows \qquad (2)$$

For this study, the number of facilities (k) considered was 48 and the number of mass flows (n) characterized was 5, as this corresponds to the system definition in section 4.3. The 48 facilities analyzed in the present study is known to accurately represent the global tantalum processing facilities involved in tantalum production in 2014.

The bottom-up method was used to precisely disaggregate flows among the principal tantalum sources, such that material source information depicts the basis for sourcing scenario management or development. The bottom-up method estimates flows of material from different sources by detailed statistical aggregation and scaling of facility-level estimates to account for material flows for a county, regional and global level (as illustrated in figure 4.4). The step-wise quantitative modeling enabled a flexible data compilation to reveal overview of flows and estimates of metal production for a different selections of geographical boundaries. The method considers the variances with available data; where facility-data was unavailable or ambiguous company data was sought to fill data gap. Where facility level or company level information could not be accessed or was unavailable, country level data were used.

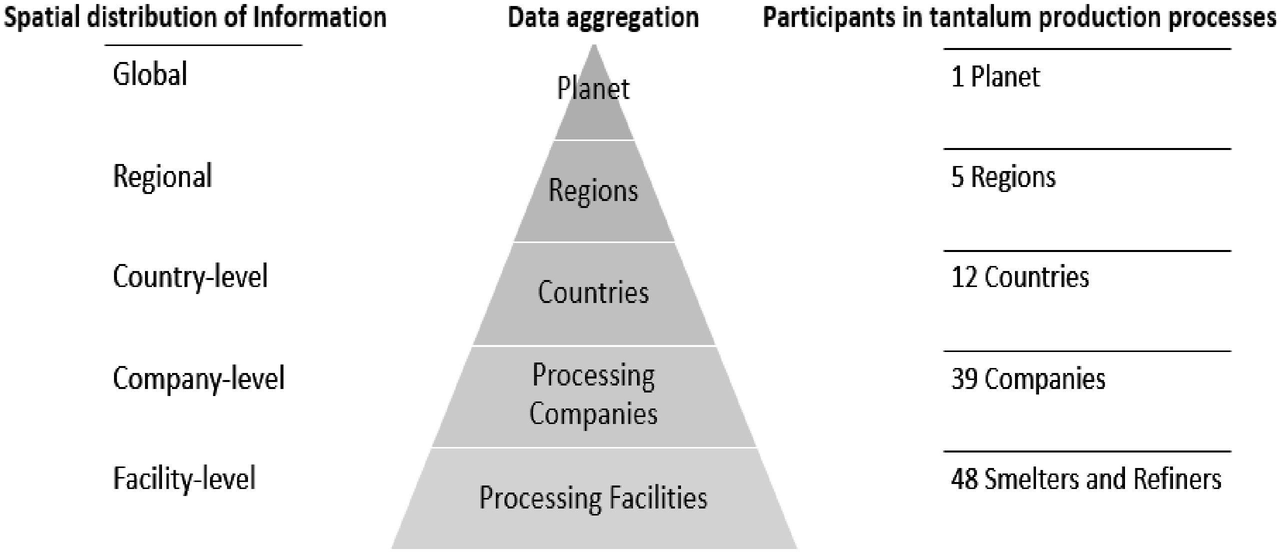


Figure 4.4 Bottom-up method for characterizing metal production. Approach for aggregating production mass flows from facility-level to account for global production.

Calculations, judgement and estimates were required to, first, characterize tantalum production mass flows from data collated, and secondly, reconcile dataset for tantalum flows account of the production system. The database developed during the course of this study, formed the basic item for organizing, handling and calculating data for facilities, processes and the production system. Data categories were specifically selected so as target mass flows sampling at facility-level. At minimum, data categories in Table 4.2 were accounted for each facility. The mass flows of tantalum were described for 48 tantalum processing facilities identified by the Conflict-Free Sourcing Initiative (CFSI) based on 2014 production and material sourcing data. Variables that were manipulated included:

- Values of tantalum mass flows in a data spreadsheet, representing mass inflows and outflows of each processing facility that indicate material sources and tantalum product categories.
- The sequence of substance flows across the tantalum production system, also representing specific values in data spreadsheet that indicate processes inflows and outflows including sources and products

Table 4.2 Database information and definitions

<table>
<tr><td><i>Facility</i></td><td colspan="2">a processing plant identified to be engaged in metallurgical extraction of tantalum. A tantalum facility may be involved in specific activities, described for transforming tantalum resources into the tantalum intermediate chemical compounds or reduction and refining of chemical compound to tantalum metal products, or can be involved in generally activities producing tantalum metal products and chemicals from tantalum resources.</td></tr>
<tr><td><i>Company</i></td><td colspan="2">name of company or company group that owns and manage activities of a tantalum facility</td></tr>
<tr><td><i>Location</i></td><td colspan="2">country where the tantalum facilities are located</td></tr>
<tr><td><i>Compliance Status</i></td><td colspan="2">the relative conflict-free sourcing standing of a facility defined by CFSP. A complaint status indicate that the facility has completed auditing process under the CFSP and verified to be sourcing only conflict-free materials. For active status, facilities have been engaged but not audited.</td></tr>
<tr><td><i>Year of Compliance</i></td><td colspan="2">the year a facility first achieved CFSP compliant status</td></tr>
<tr><td><i>Tantalum Material flows</i></td><td colspan="2">Specific mass flows records of material purchased and produced by facilities, categories of mass flows are:</td></tr>
<tr><td></td><td>Mineral concentrate</td><td>tantalum raw material produced from mining tantalum-bearing mineral ores</td></tr>
<tr><td></td><td>Tin Slag</td><td>tantalum raw material as by product of tin industrial production</td></tr>
<tr><td></td><td>Scrap</td><td>the post-industrial waste and post-consumer waste containing tantalum</td></tr>
<tr><td></td><td>Tantalum Chemicals</td><td>tantalum intermediate products from extractive metallurgy of tantalum resources, and chemical produced for specialty applications</td></tr>
<tr><td></td><td>Tantalum Metal</td><td>metal products from reduction and refining processes</td></tr>
</table>

The bottom-up approach provides a conservative estimate of global production given the wide variations across facility production practices and the significant challenges in tracking the materials purchased and produced by processing companies. Before going into details of tantalum flows analysis and assumptions, the following sub-section highlights sources of the dataset used for the present study.

4.3.2 Data Sources

The tantalum dataset was developed from a wide variety of industrial and academic sources. Central was a unique dataset from the Conflict-Free Sourcing Program (CFSP) that covers over 140 major 3TG processing (smelting and/or refining) companies with management information on about 300 facilities, including conflict-free compliance status of each facility. CFSI has endeavoured to identify all processing facilities producing 3TG metals (i.e., smelters and refineries (SOR)). This extensive dataset uses a list of all identified processing facilities producing 3TG metals, including smelters and/or refiners (SOR), through the standardized reporting template known as the Conflict Mineral Reporting Template (CMRT). The program defines a “compliant” SOR as a producer of 3TG minerals certified as “conflict-free” based on the audit protocol, whereas an “active” SOR has signed an agreement to engage in the CFSP audit process. Some SOR are not yet engaged in the program but have been identified as processing facilities (SOR). Attribute information is available for most facilities, including location, status of conflict-free sourcing practice, company policy and management system. Facility-level data were obtained from the CFSI website.

CFSP uses confidential third party audits to examine purchasing records on metal feedstocks (mineral concentrate, scrap, intermediate chemicals and metal products) processed at SOR facilities. This information is provided in a number of ways.

1. Public list on website – for tantalum this has two categories: compliant and active

2. Conflict Mineral Reporting Template (CMRT) – a public list of all identified SOR

3. A CFSI smelter database, which is a list of all SORs that CFSI provides to its members. Access to this list was provided for this research.

4. Reasonable Country of Origin Inquiry (RCOI) data, which are provided to CFSI members, but was available for this project.

Company websites and reports, national agency statistics, industry association statistics and reports from market research organizations were used to complete facility level data. Where available, information on origin of material, type of material processed and produced, production and sourcing practice were collected from these sources to corroborate CFSP data. Market report was used to estimate the tantalum outflows of production stage into the first-use fabricated products. Information for tantalum product consumption data for six first-use product categories – capacitors, super alloys, specialty chemicals, sputtering targets, mill products and carbide products were obtained from market research report collated by Roskill (Startton, 2013).

Two sources were particularly useful. First, the United States Geological Survey (USGS) database which keeps an account of mineral commodity, specifically mineral mine production for metals including tantalum. Global mine production estimates and quantities from producing countries are reported by USGS in gross mass of tantalum minerals extracted and mass of tantalum concentrate based on tantalum content in the raw material extracted (U.S Geological Survey, 2015b). Second, the industry association Tantalum-Niobium International Study Centre (TIC) which publishes tantalum statistics on the fourth bulletin of every year with detailed tantalum production and industry operations data collected from members of the association. TIC statistics reports information on tantalum production for companies associated with TIC and estimates for other firms not part of TIC. The TIC statistics provide information on tantalum raw material production (mineral concentrates and tin slag); total tantalum materials purchased (primary mineral concentrated and secondary material) by processing companies; and tantalum product categories produced by processing companies.

4.3.3 Details of Tantalum Flows Analysis and Assumptions

Assumptions and adjustments were necessary to construct the tantalum flow analysis at the level of analysis needed (see figure 4.3). Firstly, consideration had to be given to details of data collected; TIC data are reported in already aggregated detail for tantalum supply; whereas USGS data refer only to tantalum mine production and do not consider recycled sources. Generally, the system boundaries and actual data availability place limitations on breadth and depth of a substance flow analysis. Several calculations were performed at the level of process inflow and outflows in developing substance balance account. This is due to several reasons. Firstly, the objective of this research was to determine tantalum production mass flows for analysis of global tantalum flows and production. Secondly, the available dataset used here is new and the granular facility-specific information were compiled with possibility of uncertainties, for example due to time lags in reporting periods and due to gaps in the dataset. Lastly, the intension of developing the bottom-up method was to characterize mass flows with respect to variations resulting in range due to tantalum processing practiced by facilities in the industry. From the literature that was examined and data obtained, this variation was apparent. It was necessary to determine the range and importance of flow variables as they may affect results of SFA analysis of tantalum production system.

Each facility was characterized as either a smelter or refiner; the facilities that sources raw materials (tantalum mineral concentrates and tin slags) were identified as smelters, while the refiners are identified as facilities that scrap, intermediates tantalum compound and/or crude tantalum metal powder and ingot. This description is in line with industry classification of tantalum processing companies into primary processors capable of processing tantalum-bearing materials including mineral concentrates and tin slag; and the secondary processors known to have limited capability, accordingly processing mainly the intermediate tantalum chemical, scrap and tantalum metal powder or ingot (TIC, 2016). Assumptions were made around recyclers. Recyclers taking in scrap metal also accept a portion of primary ingots to supplement and purify their production. A generic number of 20% primary was assumed for most recyclers.

4.3.3.1 Quantifying Tantalum Production Flows

Data were compiled at the facility level. Gaps in data were then calculated from other data that were available. This included published information from company websites on the production capacity, annual production, types of materials purchased (e.g., recycled vs primary), and types of processing carried out at facilities. Company-level statistics were used to verify the aggregation of facility-level data. For example, USGS and other agencies identify major companies and facilities, and report mining production by nation. Industry associations also identify and rank major producers, characterize sourcing trends and provide estimates of overall metal production. A list of tantalum-bearing materials was used for consistency (Table 4.3), collated from academic papers, tantalum companies and industry reports. By industry convention, mass of tantalum material is as measured as tantalum-oxide (Ta2O5) content, which is 81.2% tantalum (Agulyonski, 2004; Lanbert, 2007). The list of tantalum processing facilities can be found in Appendix A.

Bottom-up aggregation of facility-level estimates to the global scale was conducted (see figure 4.3). The balance account of tantalum flows for system inflows and outflows were determined. The two main processes - smelting and refining, were analyzed using bottom-up estimates of global tantalum flows. The substance flow balance account determined at this point formed overview of tantalum flows for the defined production system. In effect, bottom-up quantification performed a normalization based on tantalum production mass flows requirements for facilities inflows and outflows. Composition of metal in flows needed to make assumptions on production flows at facilities added uncertainty. The contribution of each facility to the total tantalum production system was calculated; then inflows and outflow were determined for the two processes based on mass flows of facilities' contributions; and all categories were tailored across the global tantalum production system.

Table 4.3 Tantalum bearing materials

Mass flow categories	Material	Formula	Tantalum content	Data sources
Tantalum mineral concentrate	Tantalite	$(Fe, Mn)(TaNb)_2O_6$	< 40%	(Dill, 2015; Kuster, 2009; Melcher et al., 2015; Nete, Purcell, Snyders, Nel, & Beukes, 2012; Selway, Breaks, & Tindle, 2006; Shaw & Goodenough, 2011; Z.-T. Yuan, Lu, Wu, & Liu, 2015)
	Columbite-tantalite	$(Fe, Mn, Mg)(Nb, Ta)_2O_6$		
	Microlite	$(Na,Ca)_2Ta2O_6(O,OH,F)$		
	Wodginite	$(Ta,Nb,SN,Mn,Fe)O_2$		
	Ixiolite	$(Ta, Nb, SN, Mn, Fe)_4O_8$		
	Euxenrite	$(Y, Ca, Er, La, Ce, U, Th)(Nb, Ta, Ti)_2O_6$		
	Struverite	$(Ti, Ta, Fe)O_2$		
Tin slag	By-product of Tin processing	***	<10%	(Crockett & Sutphin, 1993; Subramanian, Suri, & Atomic, 1998)
Scrap	Post -industrial and post-consumer scrap	***	< 20%	(Chancerel et al., 2015; Sibley, 2011)
Tantalum Chemical	Potassium tantalum fluoride	K_2TaF_7	65%	Cottrell, 1954; Coursey et al, 2010; Emsley, 2011; Haynes, 2015
	Tantalum oxide	Ta_2O_5	82%	
	Tantalum chloride	$TaCl_5$	50%	
	Tantalum carbide	TaC	93%	
Tantalum metal products	Tantalum metal powder	Ta	99%	(Agulyonski, 2004; T.A. Theron, 2010; Linnen, Trueman, & Burt, 2014; TIC, 2016)
	Tantalum ingot	Ta	99%	
	Tantalum bar	Ta	99%	
	Tantalum powder capacitor-grade	Ta	100%	
	tantalum wires	Ta	99%	

Tantalum processing facilities were classified into two types: smelters, refineries. The selection of data to represent the mass inflows at smelting or refining process was dependent on some assumptions.

In context of this study, smelting facilities have the capability to process tantalum resources and reprocess other form of Ta materials. Refining facilities process Ta intermediates compounds and post-industrial scrap and re-melt crude/refined tantalum commodities into refined Ta metal commodities. Five categories of material flows were used to describe tantalum mass inflows and outflows of production, in relation to the 48 tantalum processing facilities: mineral concentrate, tin slag, scrap, tantalum chemicals, and tantalum metal products. Importantly, it was revealed that all five categories of material are purchased and sometimes shipped between facilities, whether managed by the same or another company (figure 4.5). Mass inflows of smelting facility typically includes of purchase of tantalum mineral concentrate and/or tin slag as these raw materials need to be chemically processed to intermediate tantalum chemicals before further processing to tantalum metal (see figure 4.5 A).

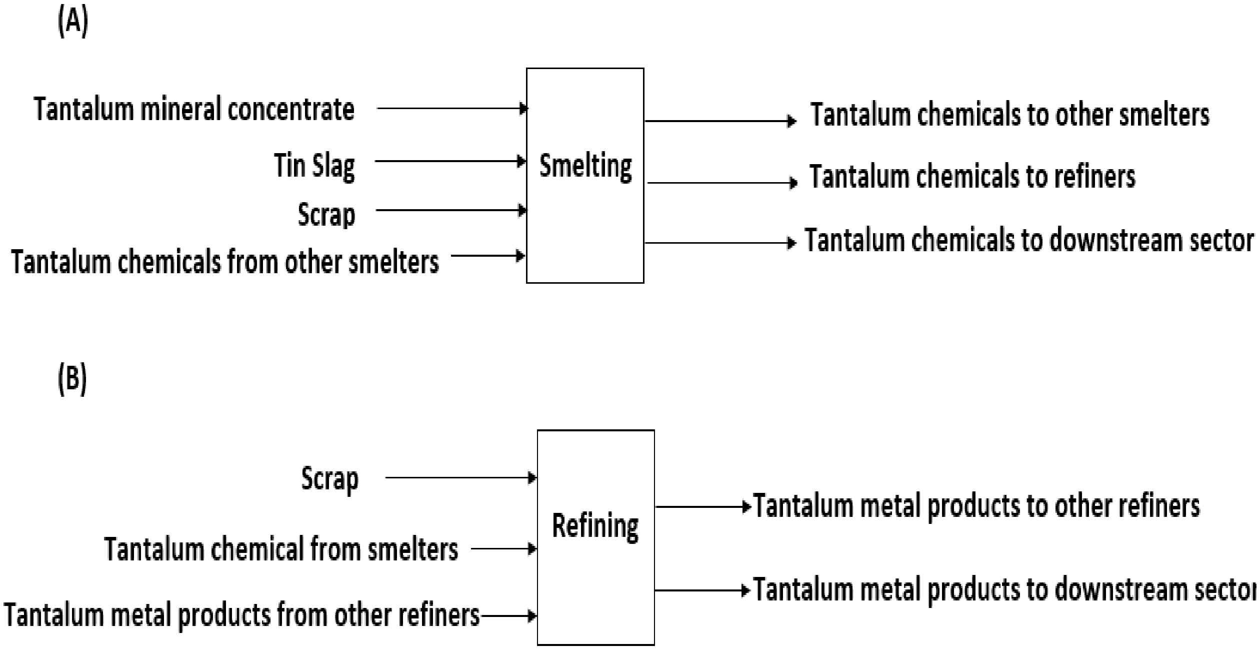


Figure 4.5 Material flows associated with a tantalum processing facility. The processing facilities are identified as smelters or refiners based on the feedstock purchased

Three main tantalum resources are important inflows to tantalum processing facilities. Tantalum mineral ores originate from tantalum mines and beneficiated from mined materials into tantalum mineral concentrate (typically about 40% Ta) before shipping to a metallurgical facility. Scrap refers to tantalum secondary materials recovered from industrial processes or end of life products waste (up to about 20% Ta). Tin slag is a minor source of tantalum that is recovered as a by-product from tin mining and smelting processes, which depending on the tin source may contain recoverable quantities of tantalum (generally < 10% Ta).Determination of mass flows at facility-level show that other categories of material such as tantalum chemicals and metal products were sourced for the production of tantalum. The mass flows from the smelting process are tantalum chemical compounds, mainly potassium tantalum fluoride (K_2TaF_7) and tantalum oxide (Ta_2O_5). Tantalum intermediate compounds mainly K_2TaF_7 (also known as K-salt) and Ta_2O_5 is commonly traded between processing companies for further processing. In addition to K_2TaF_7 and Ta_2O_5, data revealed tantalum chloride ($TaCl_5$), lithium tantalate ($LiTaO_3$) and tantalum carbide (TaC) are commonly traded chemicals in the tantalum industry. The mass inflows of refining stage are high grade post-industrial scrap and intermediate chemical compounds (K_2TaF_7 and Ta_2O_5). The mass outflows are tantalum metal product that includes tantalum metal powder, tantalum ingot, and capacitor grade tantalum metal powder (see figure 4.5 B). These tantalum metal products and tantalum chemicals such as Ta_2O_5, are inflows to the fabrication and manufacturing stage of the supply chain downstream sector. Tantalum ingot and tantalum metal powder are metal commodities also sometimes traded between processing facilities. Practice in the tantalum production industry such as materials tolling, and the reprocessing and re-melting of tantalum intermediate compounds and metallic commodity complicates description of tantalum mass flows and the material accounts at facility-level (see figure 4.6).

Double-counting of materials flows was a concern encountered using the bottom-up method. To characterize of mass flows at smelting and refining processes, the re-processing and re-melting by facilities were taken into account to quantify the reverse flows at the processing stages. Considering, some smelting facility purchased tantalum intermediate chemical products such as K_2TaF_7 which can be used for reprocessing to Ta_2O_5, and some refining facilities sourced crude tantalum metal powder which can be re-melting to achieve higher purity grade tantalum powder – an example is capacitor grade powder. Thus, some outflows such as K_2TaF_7 from smelting process serves as inflows to smelting process, same is the case of reverse flows of tantalum metal powder and ingot at the refining process. Another important case discovered in the analysis is that of tolling. This is show in figure 4.6, wherein a smelting facility (Smelter 1) take enter a service contract with another smelting facility/company (Smelter 2) to process a certain type of material which smelter 1 may not have the capacity to process.

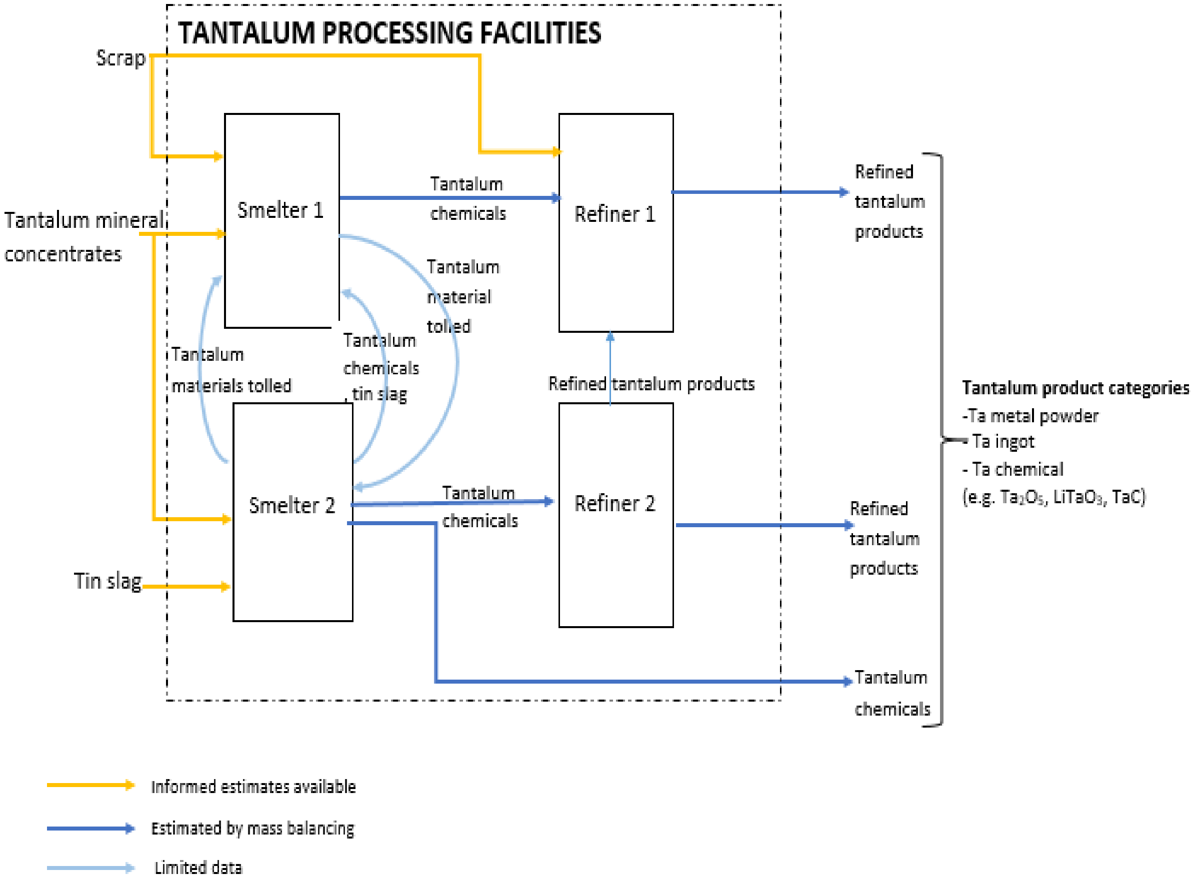


Figure 4.6 Material flows associated with tantalum processing facilities. Shows the material exchange between tantalum processing facilities – for the case of tolling and re-processing

In the case, smelter 1 ships unprocessed material to smelter 2 and record this as tolled material, which means the material only passes through the first facility (Smelter 1) and does not enter the supply chain at this point until after tolled material is processed by the receiving smelting facility (Smelter 2).

The challenges presented by material tolling, reprocessing and re-melting complicates the bottom-up SFA of tantalum. Material tolling and transfers between facilities complicated aggregation of mass flows at facility-level. Coupled with the challenges of different reporting periods of the processing facilities which were in some cases overlapping periods, it was difficult qualify the reliability of the dataset used for the bottom-up SFA of tantalum at facility-level. Some facilities report production for the period late 2013 to late 2014, while some reported production from early 2014 to early 2015. It is important to note that possibility of a time lag between the reporting periods presents uncertainty in the dataset. Due to the different time period reports, the data collected on the 48 facilities has varying production period information. Due to this inconsistency, uncertainty was introduced. Thus an adjustment by normalization became necessary. This was remedied by normalising bottom-up estimates with USGS estimates for mass of global tantalum mineral produced (Papp, 2015), and TIC estimates for total tantalum production (Schwela, 2016), which ultimately weakens the overall accuracy of the quantification, as it is constrained by the USGS or TIC statistics.

The study desire was to have an independent 2014 production total, but given uncertainties with the data available and the challenges of double-counting, time-lags and data reliability, normalization was necessary for the bottom-up facility-level production mass flows estimates. The procedure for normalization was to scale the bottom-up estimates of production mass flows for 48 facilities with respect to a reliable published industry estimate of global tantalum production. The value of 2800 tonnes for global tantalum production in 2014 (Schwela, 2016) was used, such that the aggregated mass flows of tantalum sourced and processed at 48 facilities was adjusted to equal 2800 tonnes. This means multiplying each mass flow with a scale factor defined as a ratio of industry estimates (2800 tonnes) to bottom-up estimates (3050 tonne). To highlight the normalization procedure, one example is the bottom-up mass flow of tantalum mineral concentrate estimated 1565 tonnes for 48 facilities which was normalized to 1437 tonnes by multiplying 1600 tonnes by the scale factor 0.92 (the global production ratio of 2800 tonnes to 3050 tonnes). The aggregated bottom-up estimates of 48 facilities production mass flows characterized within the study boundaries, the scale factor used and the normalized values are showing in Appendix D.

The information about smelting and refining process losses during tantalum metallurgical production were obtained from literature (Bose & Gupta, 2002; Shainyan et al., 2008; B. Yuan & Okabe, 2007), tantalum chemical process losses ranges from 15% to 5%, while the reduction processes are known to be >95% efficient. A 10% loss rate for smelting process and a 5% losses rate for the reduction process (refining) were assumed in the present analysis, then corroborated by information on known production methods (Garza, 2000). Data from industry and market report was used describe tantalum products flows into six groups “first uses” fabricated products specialty chemicals [11%], sputtering targets [13%], super-alloys [23%], mill products [10%], carbide products [9%], capacitors [34%] (Burt, 2016; Startton, 2013). This information supplemented the characterization of system outflows.

4.3.3.2 Quantifying Conflict-free Compliant Tantalum Production

The second objective of the research was to estimate the magnitude and extent of conflict free production. To achieve this objective, this analysis set out to identify how much tantalum mineral concentrated was purchased and processed by conflict-free facilities. First the year of first compliance to the CFSP requirement was used identify the number of facilities that become compliant for each year in the period 2010- 2014 (table 4.4). The CFSI tantalum smelters dataset is used to estimate annual production of conflict-free tantalum, where the representative values are the bottom-up estimates of tantalum mineral concentrate sourced by the facilities that achieved compliance in each year (2010 - 2014). Mass inflows of tantalum mineral concentrate of each facility, recorded the data spreadsheet, was aggregated with respect to the year facilities achieved CFSP conflict-free compliance status. The bottom-up estimates of tantalum mineral concentrates purchased by conflict-free facilities were normalized with respect to the tantalum mine production estimates from USGS, estimated 1200 tonnes in 2014 (U.S Geological Survey, 2015). The normalized values for mass of tantalum mineral concentrates purchased by conflict-free facilities were scaled on global tantalum mine production data collated from USGS for the period 2010 to 2014 (U.S Geological Survey, 2015).

Table 4.4 Sampling tantalum facilities compliance to CFSP requirement

Year	Number of facilities that became compliant to CFSP requirements [a]	Total number of facilities compliant to CFSP requirements
2010	9	9
2011	7	16
2012	8	24
2013	7	31
2014	13	44
2015	2	46

a – data collated for number of facility based on first year of compliance with CFSP (CFSI, 2014).

4.4 Representation and graphing of analysis

To interpret SFA results, it was important to present results in a clear and understandable way that responds to research questions and objectives. Moreover, given that some sources of data are based on confidential or commercial sources, it was necessary also to aggregate final results in a manner that does not compromise data security. Thus aggregations of results were made in a number of ways:

Types of facilities – smelting and refining

Global and regional mass flows

Location of facilities -developing verse developed countries

Sankey diagram was used in this study to visual the global mass flows of tantalum across production chain. Sankey diagrams are widely used in material flow analysis to show flow analysis and have help to clearly paint pictures of flow paths effects, efficiencies and inefficiencies alongside indicating sources, sinks and accumulation of material (Schmidt, 2008). The present research employed Sankey diagram software tool "e!sankey" to visualize tantalum flows magnitude and pathways with the width of the arrow arrows showing system inflows and outflows accounted in tonnes/year.

The geographic representation of facility data was made using five regional blocks: China, Europe, Europe, North America, Other Eurasia and South America. By summarising facility-level analysis this way, confidentiality is protected but the production practice and material sourcing patterns in the global results are revealed. More so, the regional analysis results are presented in accordance with the country categorization of the UN World Economic Situation Prospect (WESP) (United Nations, 2015), thereby presenting results for the two groups – facilities located in developing countries and those in developed countries.

Chapter 5

Results

This chapter presents the SFA study results obtained through tantalum mass flows assessment of 48 processing facilities. Quantities of tantalum flows (tonnes) for categories of mass flows were used to interpret results of SFA and conflict-free production assessment.

5.1 Tantalum Flow Analysis Results

5.1.1 Global Tantalum Production

The results of the SFA are presented as a Sankey diagram (figure 5.1) based on 2800 t of global production in 2014. The figure displays the allocation of tantalum materials across the upstream end of the supply chain by following the tantalum-bearing material sourcing, the production processes for tantalum and the points where tantalum losses occurred in the metallurgical production system. The pathways of tantalum production mass flows and the quantities are described with the arrows for aggregate production of 48 smelting and refining facilities. Although the bottom-up assessment of 48 facilities shows that 3050 t of tantalum resources were processed facilities in 2014, the estimate was normalized with respect to industry estimates for total supply of tantalum resources to processing facilities in 2014. This value from the industry association is 2800 t (TIC, 2016), and is used for mapping global tantalum production mass flows in figure 5.1. The proportions of flows do not change because of this adjustment.

Results show that tantalum mineral concentrate and scrap are the two biggest contributors to global production, estimated as 1437 t and 993 t, respectively. It is important to note that these values and other mass flows estimates shown on figure 5.1 are normalized estimates that were adjusted for the inconsistencies in the dataset. Due to data gaps, mass balance adjustments, time lags and the normalization, the uncertainty of each mass value is in the order of five percent. Mass balance accounts included estimated 12% of tantalum lost during smelting and refining process losses for each process approximately 210 t and 130 t respectively. The results show that tantalum capacitors are the largest users of tantalum produced, accounting for about 35% of global tantalum consumption in 2014. The remaining 65% is distributed at relatively equal amounts by other products/applications categories (super alloys, sputtering targets, specialty chemicals, carbides, mill products). The distribution of tantalum products - tantalum ingot, metal powder, capacitor grade powder, carbide and oxides- is shown in figure 5.1, shows consumption by the following applications/products: super-alloys [570 t], sputtering targets [320 t], capacitors [840 t], mill products [250 t], carbide products [220 t], and specialty chemicals [270 t]. The mass flows of tantalum returning to the production system at the two processing stages was quantified to show the balancing mass flows for the system. Tantalum chemicals estimated at smelting processing stages reflects a large return flow (1200 t) to the smelting process, the return flows of tantalum metals and ingots to refining process was estimated (680 t).

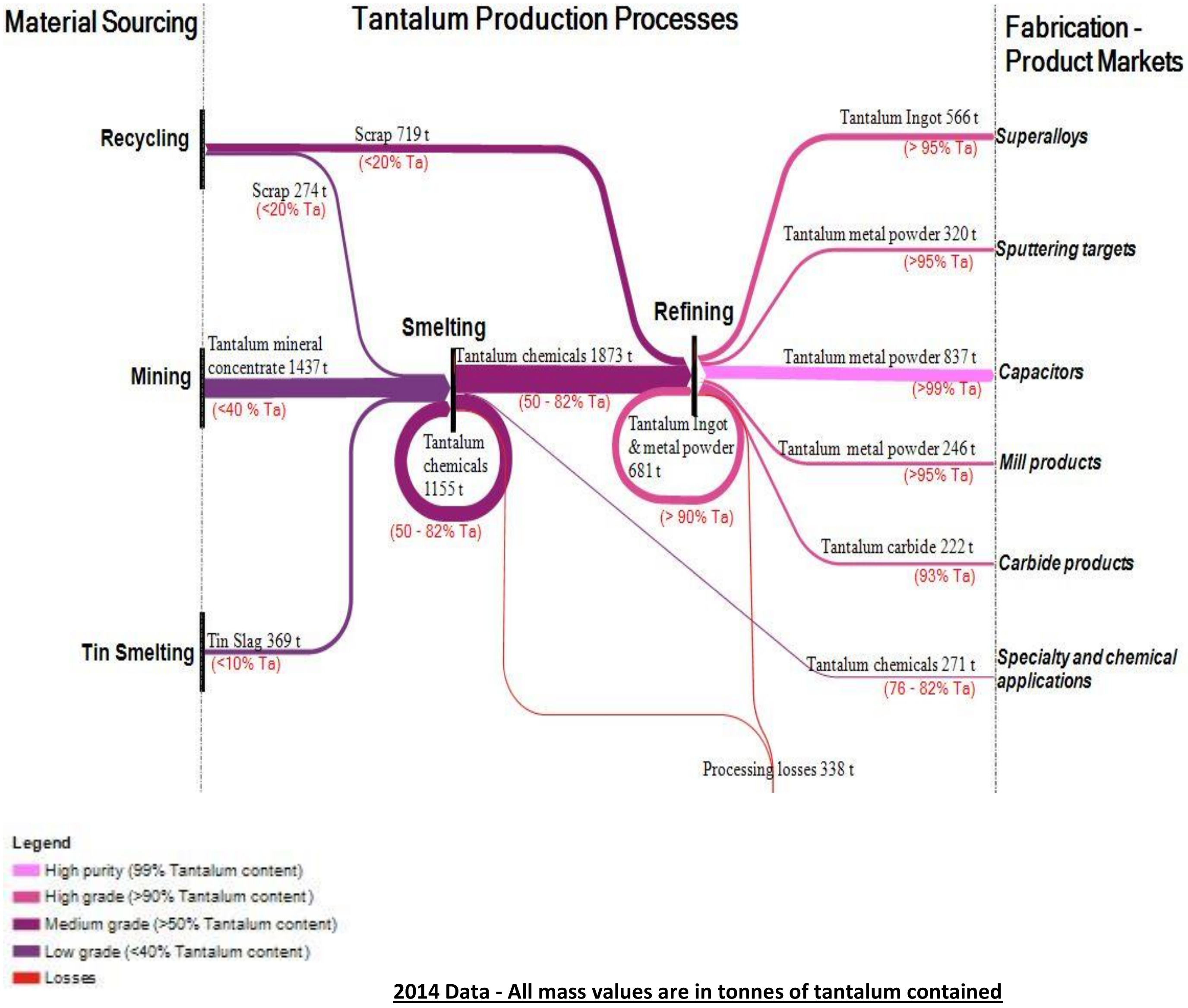


Figure 5.1 Global mass flows of tantalum in 2014. The width of arrows is proportional to quantity of flows, and the grade of each flow is represented in red.

A relatively large volume of scrap was sourced by the 48 facilitates resulting in a recycling content at 35% (figure 5.2). Findings show tin slag accounted for 14% of global tantalum production in 2014. Tantalum mineral concentrate is the major resource for tantalum processing facilities. Global estimates show that more than 50% of tantalum produced in 2014 was sourced from tantalum ores and mine production. This show a relatively high dependency on primary mineral ores for the availability and supply of tantalum for industrial uses.

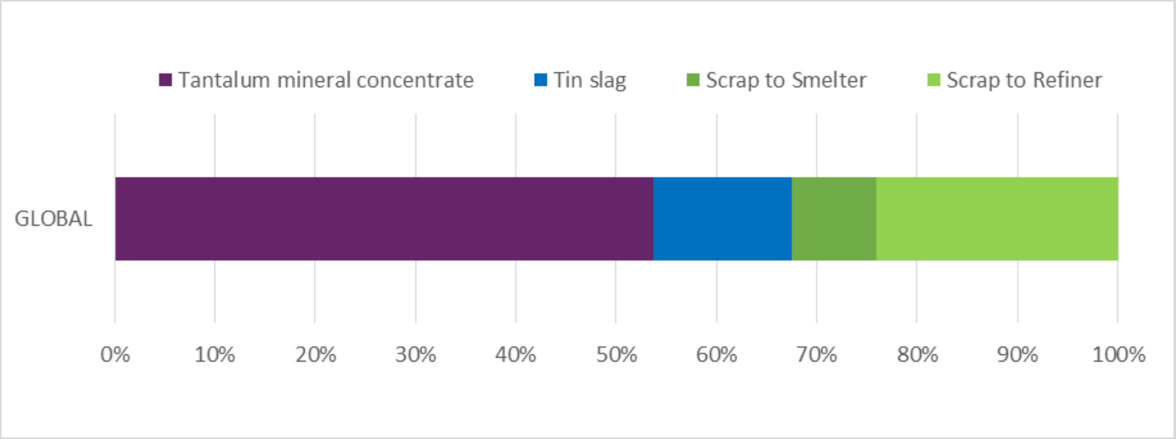


Figure 5.2 Global mass flows of tantalum resources in 2014. The recycling rate is estimated 35% for the global production of tantalum in 2014 (bottom-up estimate for 48 facilities)

5.1.2 Global Tantalum Processing Facilities - Smelting and Refining

In the present study processing facilities were classified as either smelters or refiner based on the type of material sourced by the facility. Smelting facilities have the capability to process mineral concentrate and other tantalum raw materials, while refiners can are largely limited to inputs of intermediate chemical compounds, crude metal forms and scrap material. The 48 smelting and refining facilities are unevenly distributed in functionality – smelting and refining facilities, and number of facilities in the 5 regions defined in the present study (figure 5.5 and 5.6). China alone is hosting 19 tantalum smelter and refinery facilities. The remaining 29 tantalum processing facilities are dispersed in 11 other countries. As located in other regions, Europe hosts 3 producing countries (Germany, Estonia and Austria), with 8 facilities. For North America are two producing countries (USA and Mexico) with 11 facilities. In the block of Other Eurasia, 5 countries are grouped (Japan, India, Thailand, Kazakhstan and Russia), hosting 8 facilities. The last block is South America in which there is only 1 producing country (Brazil) with 3 facilities. 46 facilities are conflict-free producers and are compliant with CFSP, while 2 facilities (located in China and the United States) are active and yet to be certified conflict-free in 2014 (figure 5.5).

Figure 5.3 Location of 48 tantalum processing facilities. Green pointers shows location of facilities compliant with the CFSP protocol, the yellow pointers show location of non-compliant facilities

Compared to other regions, China has the largest number of smelting facilities, hosting 15 smelting facilities and only 4 refining facilities (figure 5.6). North America has the largest number of refining facilities, hosting 9 refiners in United States and two smelters located in Mexico and United States. South America has the smallest number of tantalum facilities, with only two smelters and 1 refiner. For Europe, there are 4 smelters and 3 refiners located in Germany and Austria. The regional block of Other Asia has an even distribution of smelters and refiners for the region, but the 4 smelting facilities are spread in 4 countries and all 4 refiners located in Japan alone. The distribution of these 48 facilities is summarized on a table in Appendix B. Each facility attribute information including compliance status was added to the caption enabled by Google Fusion application is shown on Appendix C and a closer view of the facilities location in China is on Appendix C.

Figure 5.4 Mapping the distribution of tantalum smelting and refining facilities. The yellow pointers show the locations of smelting facilities and the green pointers show the location of refining facilities.

5.1.3 Regional Analysis

A regional view of the mass flows analysis results show varying practise of sourcing material for tantalum production by tantalum facilities assessed in the present study (figure 5.7). The feedstock purchases at facilities varied, from 100% raw materials – tantalum mineral concentrates and tin slag, to 100% scrap. As indicated in section 4.4, the regional blocks defined in this study were drawn to enable cohesive presentation of results.

15 processing facilities in one country (China alone) accounted for processing 48% of global tantalum mineral concentrate. While three regions, North America, Other Eurasia and South America accounted for processing 44% of global tantalum mineral concentrate, wherein 15%, 14% and 15% processed by each region respectively was done by only 8 processors. The remaining 9% was processed by 4 European facilities in 3 countries.

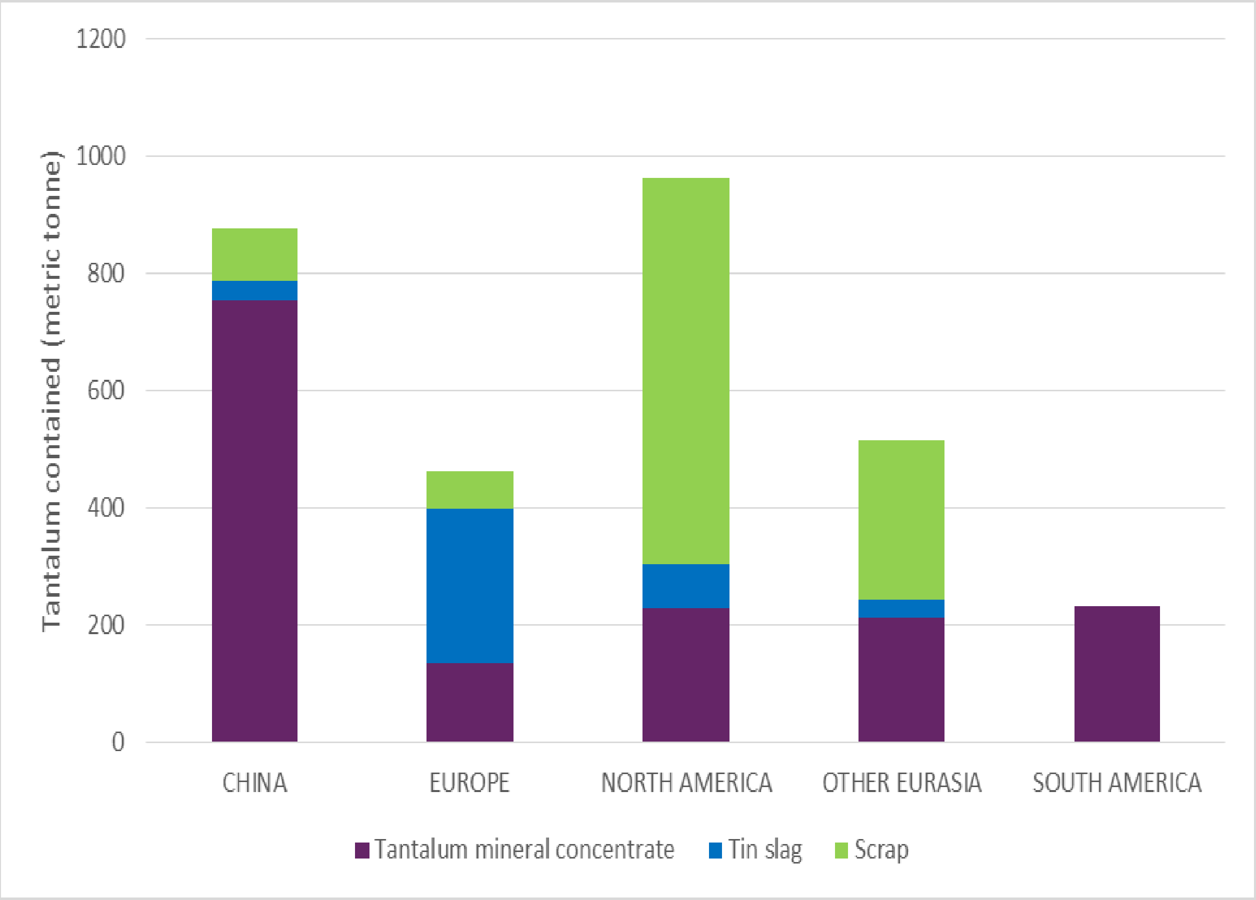


Figure 5.5 Tantalum processing by region, broken down by sources (estimate for 2014)

The distribution of scrap processing by regions is almost an inverse of the mineral processing. North America (2 countries) accounted for 61% of the scrap recycling. Results show that there was no record of scrap processing by South American processors. The remaining 39% was processed by China, Europe and Other Eurasia at 6%, 8% and 25% respectively. Conversely, Europe accounted for 66% of processing tin slag for tantalum production. China and Other Eurasia accounted for 16% shared equally. The remaining 18% of tin slag processing was by facilities North America. The result were also interpreted in terms of developing verses developed countries (figure 5.6). In accordance to the UN World Economic Situation Prospect (WESP) report in 2015; Austria, Estonia, Germany, Japan, United Stated of America (USA), United Kingdom, are among the countries listed in the developed (United Nations, 2015). While the developing countries include Brazil, China, India, Kazakhstan, Mexico, Russia and Thailand. The results show that the rate of scrap sourcing at facilities located in developing countries is very low compared to that of facilities located in developed countries, at 8% and 66% respectively.

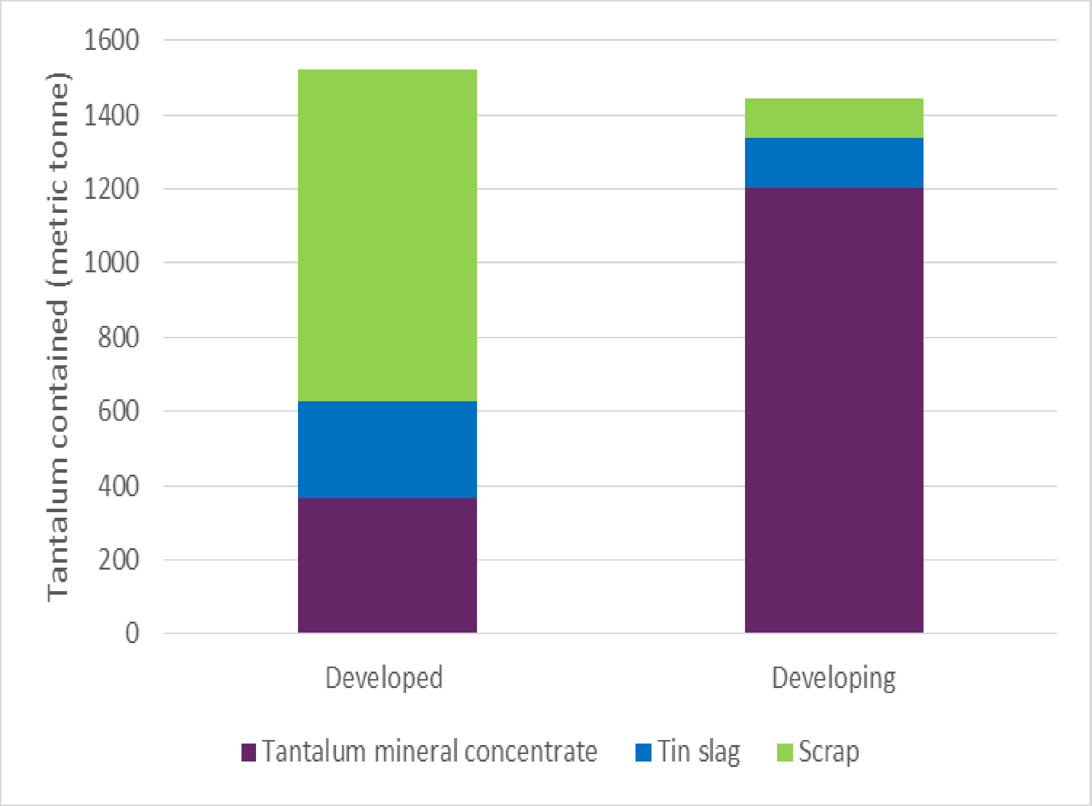


Figure 5.6 Tantalum processing by facilities located in the two categories of countries – developing vs. developed countries. This country classification is as defined by WESP, is based on industrial development, per capital income and human development index.

5.2 Quantification of Conflict-free Tantalum Mineral Sourcing

Tantalum mineral sourced by conflict-free facilities increased significantly from 2010 to 2014, from about 25% of global mine production to 99% in 5 years. After data reconciliation, as decribed in chapter 3.3.3.2, the sourcing of conflict-free tantalum mineral concentrate in 2014 is estimated as 1190 t (see figure 5.7) of the global tantalum mine production that was reported 1200 t (U.S Geological Survey, 2015). The increase can be attributed to the growth in the number of participating companies in the CFSP from 2010 to 2014 (see figure 5.8). Only 2 of the 48 facilities identified and assessed in the present study are not complaint in 2014 with the CFSP protocol for tantalum smelters and refiners both of which are small producers. The results show that a large portion of tantalum produced has been verified to be sourced ethically from DRC, neighbouring countries and other tantalum mineral producers.

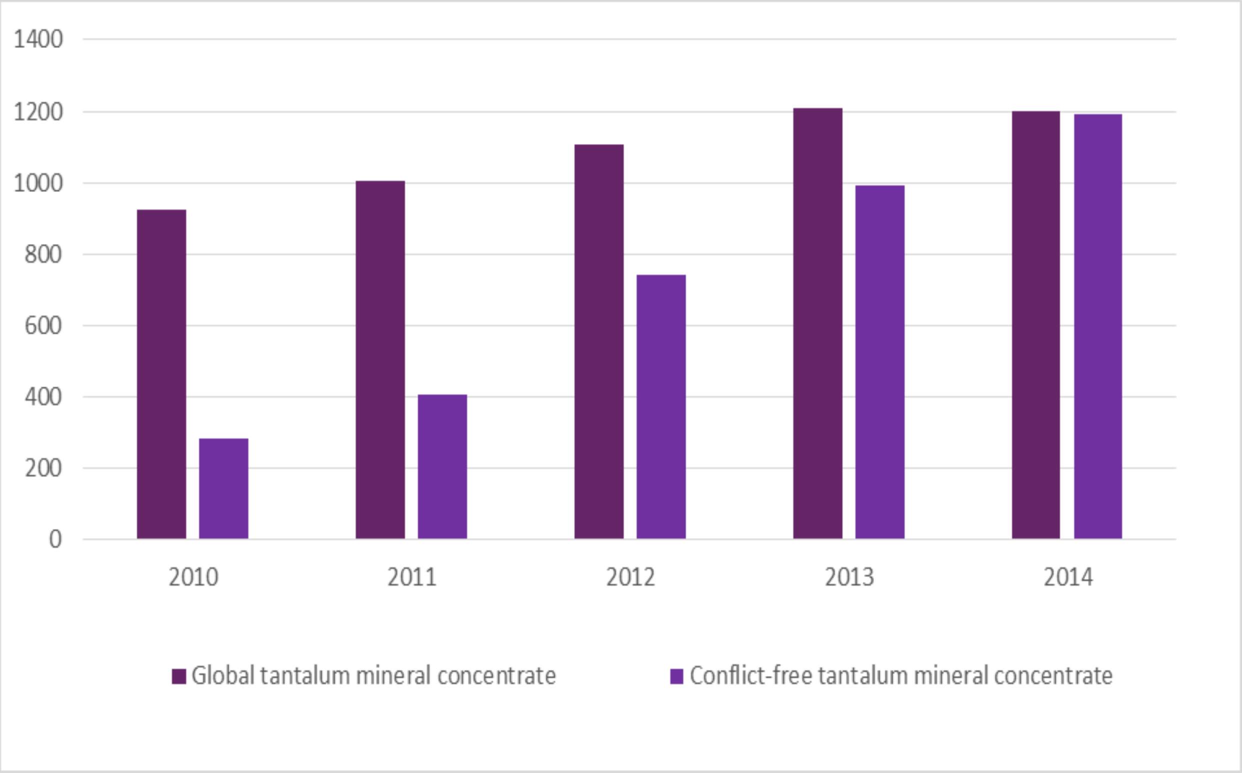


Figure 5.7 Progression of tantalum production from conflict-free sources. Estimate of conflict-free mineral sourced in 2014 is 99% of the reported tantalum mineral produced.

The presentation of the quantification of conflict-free tantalum production (figure 5.7) in the magnitude and progression of conflict-free tantalum for the first five years (2010-2014) of assuring conflict-free sourcing at processing facilities shows a progress in production of tantalum from conflict that exhibit a pastiche of the present management regime by CFSI (figure 5.8). The results show the possibilities of a managing sourcing practice mainly in related to tantalum mineral sourced by 48 facilities know to produce tantalum for the period 2010 to 2014. It should be pointed out that the results are based on obstensible mass of tantalum mine production. Consequently, the data uncertainty should guide interpretation such that avoid flaterry of actual practise. The mass of tantalum mineral concentrate sourced by conflict-free produced has increased silmulanously with the number of conflict-free processing facilities participating in the global production of tantalum (figure 5.8).

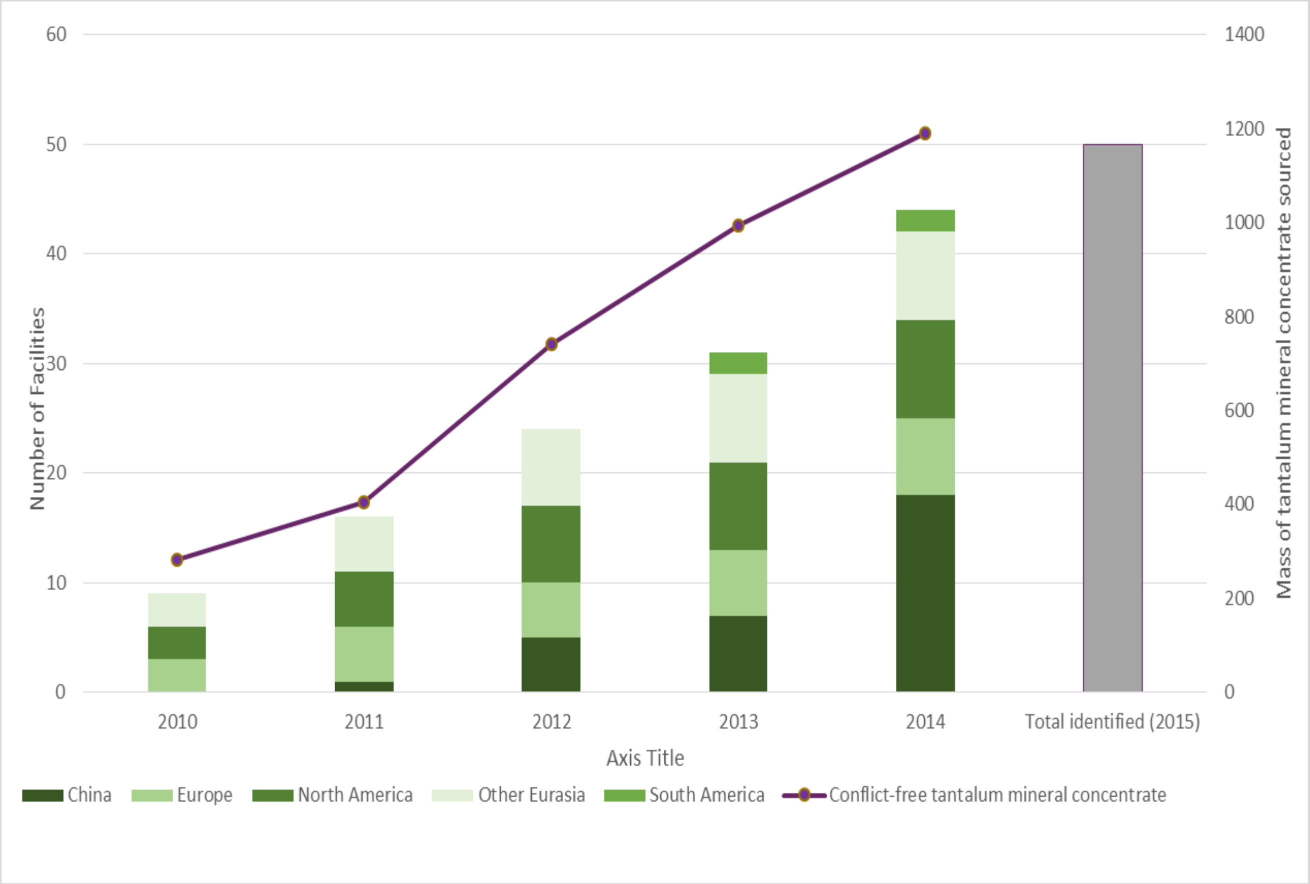


Figure 5.8 Progression of conflict-free tantalum facilities. In 2014 only two companies are non-compliant with the CFSP protocol, thus not verified as conflict-free tantalum processors.

Chapter 6

Discussion and Conclusion

The discussions in this chapter interpret the findings that emerged from the results to understand the pathways of tantalum in the production chain and possibilities of conflict-free tantalum production. This discussion reflects several dimensions that revisit the objectives of this study (see chapter 3). First, the results of the tantalum production materials profile are considered with respect to their quantities and comparison to previous studies. Second is a discussion of potentials of improvements to tantalum production system. Third, the method of analysis is considered for its strengths and weaknesses, with respect to its specific execution for the global tantalum flows analysis, and general applicability in SFA of metals. This chapter ends with suggestions for further research opportunities and a concluding summary.

6.1 Discussion of Tantalum Flows Analysis Results

6.1.1 Tantalum Production and Material Sourcing Pattern

The goal of this work to identify and characterize material pathways in the production chain of tantalum as basis to determine the quantity of tantalum production that is produced from conflict-free sources. As identified in section 5.1 and 5.2 of the results chapter, quantification of global tantalum production and production mass flows show the mass flows for tantalum starts with three main resources: tantalum mineral concentrates, tin slag, and scrap. In practice, feedstock purchased at tantalum processing stage varied for all smelting and refining facilities. Some facilities sources only primary materials (tantalum mineral concentrates and tin slag), some source secondary materials (scrap) and there were others sourcing all categories including intermediate compound and refined products such as ingots and metal powder. The global production of tantalum by 48 facilities was estimated 2800 tonnes of tantalum in 2014 sourced from 1400 tonnes of tantalum mineral concentrate, 370 tonnes of tin slag, and 990 tonnes of scrap (both post-industrial and post-consumer scrap), resulting in 35% recycling rate for global tantalum production in 2014.

Tantalum production has been previously analysed by a few studies, but shows variability that reflects the level of uncertainty around production of this metal (see chapter 2, section 2.2). The current results corroborate tantalum supply estimates from industry statistics, national agency data, and existing SFA work. It is likely that some of the best quality accounts of tantalum production are those that have been done by industry. Those statistics are mostly proprietary and what information is public is not particularly transparent. Consultancies that sell their market reports for metals industry analyses also maintain and sell data on tantalum production. The numbers in these reports are rarely available for review so it is usually challenging to deconstruct SFA studies from the configurations in which they have been published. For example, Roskill Information Services has analysed global tantalum industry and published several reports on tantalum supply and demand markets; however, their results that are available do not report on conflict-free tantalum production.

The overall account of tantalum supply for 2014 is similar to TIC results, where about 61% of supply is tantalum mineral concentrate of which about 10% is recovered from tin slag. The results of the present study show a close range: 51% of tantalum production was sourced from tantalum mineral concentrate which is estimated 1400 tonnes of tantalum mineral concentrate (normalized value) in 2014. This analysis suggests that more primary concentrate appears is produced than was earlier reported; discrepancies and updates to the estimates reported by the USGS and the industry association TIC both support the understanding that previous that global estimates were underreported. (See for example table 2.1, which shows the USGS revised their estimates several times).

Overall this study reports the recycled content of tantalum production to be almost twice the magnitude as reported in previous studies. The global estimate for scrap sourced (35%) is generally higher than previously estimated. Previous estimates based on tantalum flow analysis at national level for Japan and USA suggest the total metal input for tantalum production contained recycled content below 25% (Chen & Graedel, 2012; Graedel et al., 2011; Sibley, 2004). Based on facility-level data for global scale production which includes 48 facilities located in 12 countries – is a more complete picture provides a higher values for recycling rate that is believed to be more accurate and represents the apparent practice in the industry. However, a breakdown of scrap sourced into post-industrial and post-consumer sources was not considered in the present study. Graedel and Chen (2012), and Papp (2004) estimated a rough recycling rate of 10-25%, based on limited data from USA and Japanese studies while industry statistics from TIC reported a slightly higher recycling rate of 29% (TIC, 2016) for tantalum production in 2014. On the national and regional level, results show larger differences. For USA estimates of tantalum recycling, the scrap sourced by tantalum processors in North America (mostly USA facilities) is notably high and shows a recycling rate higher than the reported recycling rate reported in previous studies. Compared to Japan estimates from literature, the mass of scrap sourced by facilities in Japan, facilities located in Japan are mostly recyclers and were identified as refining facilities base on the production data analysed in this study. The recycling rate for the region Other Eurasia is relatively small, possibly due to absence of recyclate and the presence of large smelting facilities located with the region.

In the present study, variations in sourcing pattern depict the extent of the flexibilities and options the processing facilities have to control type of material sourced and origin of material that enter the production chain and account for tantalum global supply. Results show that the choice of source and origin is constrained by the products that the facility or company wished to produce to meet market demand. Overall, the tantalum mineral concentrate was the most used source, this could be due to the high demand for high purity tantalum grade for the capacitor market. Capacitors market is still the leading consumer of tantalum products. Aside the estimated 840 tonnes of tantalum powder used for capacitor products, a portion of the 250 tonnes flowing into the mill products are destined for wires and other component parts of capacitors.

Apparently, the electronic industry consumed more than 50 percent of tantalum produced in 2014 which includes the mass of tantalum used for fabrication of capacitors, sputtering targets and a large portion of mill products. With the increasing demand of electronic products, the demand for tantalum is likely to soar especially for high-purity grade that is currently produced by mainly processing primary tantalum resources. Consequently, sourcing of tantalum mineral likely continue to grow to meet the market demand. This suggest that scrap resources alone will not be able to meet tantalum demand in the near future, with the current state of technology and production process and quality requirement for tantalum products. The mineral production estimates based on USGS database (Bleiwas et al., 2015) already identified huge volume of tantalum mineral concentrate originates from DRC, Rwanda and neighbouring countries. Chinese facilities sourced more tantalum mineral concentrates compared to facilities in other regions. Conversely results may infer that Chinese facilities accounted for large mass of tantalum originating from DRC compared to sourcing of facilities in other regions of the world. Facilities located in Brazil show to source raw materials mainly from with the country, as most facilities receive feedstock from local tantalum mines. An example is Mineracio Tobaco has several mines located in Brazil known to account for large tantalum mineral production in the country (Tobaco, n.d).

There is a global dependence on mineral sources particularly from DRC and Rwanda. These countries have filled the gap left by Australia and as discussed in chapter of the present study, these region now represent the largest sources (Bleiwas et al., 2015). Rising demand of tantalum will underpin production and sourcing from DRC and the Central Africa region. Global dependence on these regions for tantalum supply still reflect geopolitical risk, and supply risk that can translate to short-term supply shortage. More so, considering conflicts in DRC are still ongoing and mineral from the region continues to be in high demand for global products, alternatives sources need to be developed alongside management strategies to secure ethically sourced tantalum. Geopolitical tension constitute a major risk, a regional economic weakness caused by conflict and sanctions could lead to a pronounced low mine production and global supply of tantalum mineral concentrates (Bleiwas et al., 2015; Polinares, 2013). Albeit DRC and Rwanda remain important to global supply, thus Conflict-free standards are import to this address ethical sourcing and manage supply. The sourcing practice in various regions differs potentially due to variations in process at facilities, material preferences within identical material sources and origin, choices of commonly produced metal product, material availability as well as local production practices and technologies.

6.1.2 Conflict-Free Tantalum Production

The results of the present study allow benchmarking tantalum mineral sourcing against mine production estimates with regard to the sourcing pattern and conflict-free tantalum produced at facilities that are complaint to CFSP requirements. Comparing to tantalum mineral supply estimates in 2014, the tantalum mineral sourced by conflict-free facilities accounts to 98% of total mineral production reported by USGS. Conflict free sourcing progressed significantly in five years from 2010 to 2014, from approximately 25% to almost 100% in 2014. The participation of larger producers show that there is great encouragement for facilities to become conflict-free and the pull from producers in the downstream end of the supply chain is having major impact in the operations upstream. Overall, the conflict-free tantalum production estimates show a similar performance for all regions, the two facilities identified as non-complaint are located in China and United States. The contributions of these facilities to tantalum production appear to be very low in comparison to the annual global supply. When evaluating sourcing practice of facilities in the developing countries versus developed countries, the difference in the preference for tantalum material sourced in 2014 is striking. Chinese facilities had the highest rate of primary mineral sourcing among all countries, thus will likely have the highest influence on conflict-free tantalum production estimates. However, tantalum mineral sources still account for large portion of tantalum supply – and DRC and other nations in the central African region remain the leading producers of tantalum minerals. A major concern is that dependency on the high risk conflict regions for mineral sources. This bodes challenges for future supply. Conflicts in DRC and conflict mineral trade persists amidst the implantation of trade interventions to break conflict-mineral trade links, and other security solutions to resolve civil crisis in the region. Although NGO reports prognosticates a moral renaissance in DRC, it a story that the belligerents need to re-write themselves.

On the regional split for facilities located in developing and developed countries. Facilities in developed countries tend to use a higher proportion of scrap. Those in developing countries, China particularly, have higher proportion of mineral concentrates, especially DRC concentrate. Although previous studies have often pointed to China as the destination of conflict mineral from DRC (Nest, 2011; Bleischwitz et al., 2012), the results highlights the practice of sourcing larger quantities of tantalum minerals by Chinese facilities and confirm these suspicions. China processers more frequently source mineral concentrate sourced from the DRC and neighbouring countries, compared to other processing countries. Considering Chinese facilities have the highest occurrence rate for sourcing from potential conflict mineral origins, production of tantalum from conflict-free sources will largely depend on the participation of Chinese companies in the conflict-free programs to ameliorate unethical sourcing of tantalum and geopolitical strain associated with conflict tantalum mineral production and supply chain of tantalum. Compliance mechanism will need to assure ethical sourcing by Chinese metal processing companies.

6.2 Potential for Improvement of the Tantalum Production System

CFSI already recorded a high participation of tantalum producers, and capacity to achieve conflict-free sourcing goals for tantalum minerals. Looking at the scale of conflict-free tantalum in comparison to global tantalum mine production identified in the present study, there are prospects for such mechanism to kindle sustainable management of metal supply. Although the conflict-free programs focus on only one aspect of the geopolitical risk in the supply chain of 3TG metals, the model for conflict-free tantalum could logically be extended to other metals and other issues (Young, Zhe, et al., 2014). In the current state, the focus on single criteria creates qualified effective program with impacts on increasing conflict-free production (results in chapter 4.3). Management controls of conflict-free sourcing at processing stage could extend to consider criteria for environmental sustainability by defining measure for resource efficiency, process efficiency and recycling rates to guide tantalum production practice. Resource efficiency at production stage is particularly essential for sustainable use of limited products (Alonso et al., 2007) and to reduce the environmental repercussions of their production and consumption is crucial for sustainable development . To secure supply of a critical metal such tantalum, a more sustainable production through efficient processing at the bottle-neck (smelters and refiner) can help reduce short-term scarcity implications. Possibilities of mechanism could avail sustainability certification to ameliorate adverse impacts of metal production and secure metal supply for future developments. Considering tantalum supply is one of the critical metals required for manufacturing a variety of information technology products and low-carbon energy applications.

The unbound geography of tantalum production presents opportunities and challenges for sustainable metal management. Better plans for resources management can be structured with clear knowledge of the complexities in the production chain including information on practices of the processing industries and the location of the facilities. The production and sourcing pattern at the 48 facilities assessed show varying of practice in tantalum production couples with many paths of tantalum flows in different regions and countries. Results reveal dissimilar production practice and dispersed spatial orientation in terms of type of material sourced and location of facility. Some facilities source materials in region, for instance Brazilian facilities (as discussed above) and some Chinese facilities. A number of facilities located in different regions but managed by a corporate body show the varying patterns of material sourcing and the different tantalum bearing materials sources show that exchanges between facilities. An example is the H.C. Starck group, a company which owns and manages 7 tantalum processing facilities (see Appendix A).

Considering the potentials to reduce environmental implication of tantalum production, the focus should incline to facilities engaged in the initial process of smelting. By virtue of the kind of material sourced at processing facilities, the results show that more smelters are located in the developing countries. Smelters are higher polluting than refiners (Gupta & Suri, 1993), typically at the processing stage of raw material (tantalum mineral concentrate and tin slag) the presence of processing dust, water, energy and gaseous emissions may results to high levels of environmental degradation in the regions that host the smelting facilities compared to regions with more facilities engaged in the refining process. More recyclers and refining facilities are located in USA and Japan compared to other countries. A large portion of tantalum smelting in 2014 was done by facilities located in the developing countries especially China, Brazil, Thailand and India.

6.3 Strengths and Weakness of the Bottom-up Study

This work elaborated and applied the bottom-up method to estimate tantalum production and mass flows. This study not only presents a new approach of quantifying metal production but also ventures unto the first global scale analysis of tantalum using mass flows and production information of 48 processing facilities.

Previous global scale SFA analysis of metals have been done using country-level data or industry average information, examples includes for tungsten (Leal-Ayala et al., 2015), tin (Harper et al., 2006), nickel (Reck & Graedel, 2012) and other metals (Chen & Graedel, 2012). Quantifying flows bottom-up, presents a unique way of mass flow accounting, an aggregation of granular information from smaller and manageable constitutes of the production system to a compounded sum at high-level – national, regional or global scale. Tantalum flows have been characterised at the national scale (Chen & Graedel, 2012; Sibley, 2011) and previous research on tantalum supply chain mapping identified only 32 facilities in the production chain (Soto-Viruet et al., 2013). 48 facilities were identified and analyzed in the present study accurately represent a more complete number of tantalum processing facilities involved in global tantalum production in 2014. This research was carried out using a comprehensive list and information on known tantalum processing obtained from CFSI which has close connection to the processing facilities through their auditing process for CFSP compliance. Compared to other metals such as tin and tungsten, tantalum flows have not been previous analyzed at global scale (Chen and Graedel, 2012). Main challenges in understanding the pathways of tantalum flows has been the obtaining data on this opaque production industry and complexities in trade of tantalum resources (Bleischwitz et al., 2012; Polinares, 2013). The present work is contributes to fill this gap in the literature and gain an understanding of the global flows of tantalum throughout its life cycle.

The tantalum flows account in the present study has used assumptions and data relevant to metallurgical production of tantalum and more specifically for extraction processes in identified facilities current to about 2014. Main limitation is that the current analysis is based on secondary data compiled from the information on facilities. This is both a strength and weakness. The results can be generalised within limits and can be appropriately used in a broad analysis to corroborate effects tantalum supply to global consumption in a general manner, socio-economic elements of the supply chain, and specific product availability for sustainable developments. However, because the analysis is based on ostensible practices, neither detailed recommendations nor targeted conclusions are supported. Some cases facility-level data was not available, nonetheless estimates were filled with considerations of over company-level or country-level information. This data limitation at facility-level suggest a risk of double-counting based on complexities with material tolled between companies and facilities, re-processing and re-melting of tantalum chemicals or metal powder and ingot. Detailed facility accounts would be needed to reconcile. Thus the bottom-up estimates were normalized with respect to industry statistics from TIC for global tantalum production. The variation of material flows is also problematic, these limits the reliability of facility-level data.

As would be expected in SFA studies, a descriptive overview of mass flow variables was observed. It was found in the early analyses that the bottom-up method was necessary to quantify tantalum flows and production. The conventional SFA approach is not structured for the facility-level mass flows analysis in metal production system and therefore the bottom-up method availed facility-level information to construct data spreadsheet and aggregate data to account for global tantalum flows. SFA studies often quantify metal production from national statistics and/or reported data on industry-average (Chen & Graedel, 2012); thus a new approach to quantify production flows (for nation, regional or global scale analysis) – bottom up method enhances the conventional SFA approaches.

There is value in a future study using bottom-up method to highlight the applicability of the method as an enhanced SFA approach for characterizing metal production and informing national, regional or global targets for sustainable production and consumption of metals. Although such analysis of metal flows is subject to availability of data, the results will help illuminate the supply chain of metals and guide strategies to secure metal supply required for global products. It would be interesting to apply the facility-level metal production information including conflict-free data to product-level analysis. SFA framework provide accounts at material level. More sophisticated analysis, perhaps towards goals of process/environmental optimisation of production of tantalum can be done, is left to future researchers with greater computational properties. A system-thinking approach to SFA can combine the bottom-up facility-level analysis which includes may conflict-free data analysis to other methods such as LCA for product-level analysis, in an ambitious and wider-scoped research, that looks at the conflict-free performance of 3TG metals as a part of a socioeconomic whole system. Particularly for 3TG used in ubiquitous products crucial for societal activities including electronics and new technology applications for sustainable developments such as wind turbines.

6.4 Future Research

Further research is required for ascertaining applicability of quantification approach, possibilities of conflict-free compliance mechanism and prospective recommendation for policy and industrial actions. The research opportunities suggested are:

1. More analysis using bottom-up facility method is necessary to validate the applicability of the method to quantify metal production. Future research should seek to test the bottom-up analysis of metal flows by integrating methods such as life cycle assessment for product analysis to identify the conflict-free status of products

2. It is recommended that future researches consider supply chain of other 3TG metals already indicted with conflict mineral problem. Specifically, it is desirable to expanded the application for bottom-up facility-level analysis to explore the conflict-free path of tin or tungsten Although tungsten and tin flow analysis have been studies by a number of researcher, there is a limited knowledge of the conflict-free quantities in global supply chain of tin or tungsten.

3. It is recommended that future researches pursue the interesting possibilities of conflict-free program to kindle sustainable metal management. Specifically, how programs can be expanded to consider other environmental and socio-economic criteria, and what are the fundamental requirements for effective metal sustainability certification or traceability mechanism.

6.5 Conclusion

The current study contributes to the general knowledge and understanding of pathways of metal flows, conflict-free production and global sourcing practices associated with the production of tantalum.

The intention is not to provide an absolute answer or a conclusive result, yet, it is expected to provide an understanding of pathways of material, conflict-free production and sourcing practices apparently associated with the production of tantalum. This study presents the first SFA of tantalum at global scale. This was done to understand and characterize the pathways of tantalum flows in the production chain, quantify tantalum production and identify how much tantalum is produced from conflict-free sources. The research explored a new quantification method for SFA of metal flows in metallurgical production systems.

The present study availed findings to inform possibilities of conflict-free tantalum production to ensure ethical sourcing of tantalum and secure supply. When comparing the metal sources, it is important to focus on the main sources: raw material from mineral extraction and secondary material recovered from scrap. Results show that the 35% of tantalum resources consumed in 2014 is from scrap, based on the ostensible industrial practice for the production of tantalum in 2014. This value is higher than previous estimates and reveals that there is growing interests in recycling to secure supply especially in the developed countries. Large mineral sourcing by Chinese facilities suggests production of tantalum from conflict-free sources will largely depend on the participation of Chinese companies. This study confirms that there was a significant progression of conflict-free sourcing of tantalum mineral within the first five years of implementing conflict-free sourcing and management efforts at the pinch point of the tantalum supply chain. This achievement of CFSI compliance mechanism with respect to progression to nearly 100% of conflict-free sourcing in only five year, show potentials for sustainability certification of metals. There is value for supporting and developing strategies such as the conflict-free sourcing programs that ensure ethical material sourcing is critical for security of short-term tantalum supply. The smelters and refiners remain a key to manage tantalum supply, managing production practices at this point can kindle a more sustainable supply chain of metals.

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Appendix A

Tantalum Facilities

Name of Facility	Company Name	Location	Year of first CFSP compliance (active facilities have engaged but not compliant)
Changsha South Tantalum Niobium Co. Ltd.	Changsha South Tantalum Niobium Co. Ltd.	CHINA	2014
Conghua Tantalum and Niobium Smeltry	Conghua Tantalum and Niobium Smeltry	CHINA	2012
D Block Metals, LLC.	D Block Metals, LLC	UNITED STATES	2014
Duoluoshan	Zhaoquig Duoluoshan Sapphire Rare Metal Co. Ltd.	CHINA	2013
E.S.R Electronics	Electronics Scrap Recycling, Inc.	UNITED STATES	Active
Exotech Inc.	Exotech Incorporation	UNITED STATES	2010
F&X Electro-Materials Limited	Jiangmen Fuxiang Electro-materials Limited (F&X)	CHINA	2011
FIR Metal & Resources Ltd.	FIR Metals & Resources Ltd	CHINA	2014
Global Advanced Metals -Boyertown Plant	Global Advanced Metals	UNITED STATES	2010
Global Advanced Metals - Aizu Refining plant	Global Advanced Metals	JAPAN	2010
Guangdong Zhiyuan New Material Co. Ltd.	Jiayuan Cobal Holdings	CHINA	2014
Guizhou Zhenhua Xinyun Technology	Guizhou Zhenhua Xinyun Technology	CHINA	2014
H.C. Starck - Hermsdorf GmbH	H.C. Starck Group	GERMANY	2013
H.C. Starck Co. Ltd. – Thailand	H.C. Starck Group	THAILAND	2010
H.C. Starck GmbH – Goslar	H.C. Starck Group	GERMANY	2010
H.C. Starck GmbH - Laufenburg #1	H.C. Starck Group	GERMANY	2010
H.C. Starck Inc. – Newton	H.C. Starck Group	UNITED STATES	2010
H.C. Starck Ltd. – Mito	H.C. Starck Group	JAPAN	2010
H.C. Starck Smelting GmbH & Co. KG - Laufenberg #2	H.C. Starck Group	GERMANY	2010
Hengyang King Xing Lifeng New Materials Co. Ltd.	Hengyang King Xing Lifeng New Materials Co. Ltd.	CHINA	2014
Hi-Temp	Hi-Temp Specialty metal Inc.	UNITED STATES	2011
Jiangxi Dinghai Tantalum & Niobium Co., Ltd	Jiangxi Dinghai Tantalum & Niobium Co., Ltd	CHINA	2014
Jiangxi Touhong New Raw Materials	Jiangxi Touhong New Raw Materials	CHINA	Active
JiuJiang JinXin Nonferrous Metals Co. Ltd.	JuiJiang City Jin Xin, Jiujiang Jinxin Nonferrous Metals Co., Ltd.	CHINA	2014
JiuJiang Tanbre Co. Ltd.	Jiujiang Tanbre, Jiujiang Zhongao Tantalum & Niobium Co., Ltd.	CHINA	2014
Jiujiang Zhongao Tantalum & Niobium Co., Ltd	Jiujiang Zhongao Tantalum & Niobium Co., Ltd	CHINA	2014
Kemet Blue Powder	Kemet Electronics Corporation	MEXICO	2012
Kemet Blue Powder	Kemet Electronics Corporation	UNITED STATES	2012
King-Tan Tantalum Industry Ltd.	King-Tan Tantalum Industry Ltd.	CHINA	2014

LSM Brasil S.A.	LSM Brasil S.A.	BRAZIL	2013
Metallurgical Products India Pvt. Ltd.	Metallurgical Products India Pvt. Ltd.	INDIA	2013
Mineracao Taboca S.A.	Mineracao Taboca	BRAZIL	2013
Mitsui Mining & Smelting	Mitsui Mining and Smelting Inc.	JAPAN	2011
Molycorp Silmet A.S.	Molycorp Inc.	ESTONIA	2014
Ningxia Orient Tantalum Industry Co. Ltd.	Ningxia Non-ferrous Metals Smeltery	CHINA	2012
Plansee SE Liezen	Plansee Group	AUSTRIA	2011
Plansee SE Reutte	Plansee Group	AUSTRIA	2011
QuantumClean	QuantumClean	UNITED STATES	2013
Resind Indústria eComércio	Resind Indústria eComércio Ltd.	BRAZIL	2015
RFH Tantalum Smeltry Co. Ltd.	Yanling Jincheng Tantalum & Niobium Co., Ltd	CHINA	2012
Solikamsk Metal Works	Solikamsk Magnesium Works	RUSSIAN FEDERATION	2011
Taki Chemicals	Taki Chemicals	JAPAN	2012
Telex Metals	Telex Metals	UNITED STATES	2011
Tranzact, Inc.	Tranzact, Inc.	UNITED STATES	2015
Ulba Metallurgical Plant JSC	Ulba Metallurgical Plant Joint Stock Company	KAZAKHSTAN	2012
XinXing Haorong Electronic Material Co. Ltd.	XinXing Haorong Electronic Material Co. Ltd.	CHINA	2014
Yichun Jin New MaterialCo. Ltd.	Yichun Jin Yang Rare Metal Co. Ltd.	CHINA	2013
Zhuzhou Cemented Carbide Group Co. Ltd.	Zhuzhou Cemented Carbide Group Co. Ltd.	CHINA	2012

Appendix B

Distribution of tantalum processing facilities location by region

Region	**Countries**	**Number of countries**	**Number of Facilities**	**CFSI compliant**	**CFSI active**	**Smelters**	**Refiners**
CHINA	CHINA	1	19	18	1	15	4
EUROPE	GERMANY, ESTONIA AND AUSTRIA	3	7	7	0	4	3
NORTH AMERICA	USA, MEXICO	2	11	10	1	2	9
OTHER EURASIA	JAPAN, THAILAND, INDIA, RUSSIAN, KAZAKHSTAN	5	8	8	0	4	4
SOUTH AMERICA	BRAZIL	1	3	3	0	2	1
WORLD TOTAL		**12**	**48**	**46**	**2**	**27**	**21**

Appendix C

Mapping tantalum facilities locations and attributes

CFSI ID: CID001969
Smelter Name: Ulba Metallurgical Plant JSC
Location: 102 Abay Avenue, Ust-Kamenogorsk 070005, KAZAKHSTAN
COUNTRY: KAZAKHSTAN
WESP (Developed = 0, In transit = 1 Developing = 2): 1
Date of initial compliance (audit) to a conflict-free program: 2012-07-17

Appendix C 1: Mapping geo-data of facility in caption using Google Fusion web-based application. Attribute information for each facility can be seen on the caption by using the web-based application, Green pointers represent location of tantalum processing facilities that are compliant with the CFSP protocol, while the yellow show facilities active but not compliant with the CFSP protocol.

Appendix C2: South east regional map, indicating locations of Chinese and other Asian facilities

Appendix C3: Close-up view of the locations of south Chinese facilities

Appendix D

Bottom-up estimates of production mass flows and normalized data

	Bottom-up estimates (tonnes)	Percentage (%)	Scale Factor (2800/3050)	Normalized Substance Flow (tonnes)
Total sources	**3050**		0.92	**2800**
Resource inflow at smelting	**2267**		0.92	**2081**
mineral	**1565**		0.92	**1437**
tin slag	**402**		0.92	**369**
scrap	**299**		0.92	**274**
Scrap inflow at refining	**783**		0.92	**719**
Losses at smelter in %		10%		
Losses at smelter as outflow	227		0.92	**208**
total outflows from smelters	2040		0.92	1873
Total inflow to refiner	2823		0.92	2592
losses at refiner in %		5%		
Losses at refiner as outflow	141		0.92	**130**
Total outflows from refiners	2682		0.92	2462
balancing flows			0.92	0
at smelter	**1259**		0.92	**1155**
at refiner	**742**		0.92	**681**
flows into facbrication/ use				
Oxides outflow to chemical specialty	295	11%	0.92	271
capacitors	912	34%	0.92	837
superalloy	617	23%	0.92	566
sputtering targets	349	13%	0.92	320
mill products	268	10%	0.92	246
carbide	241	9%	0.92	222
Total outflows for consumption	**2682**		0.92	**2462**