Stock-driven scenarios on global material demand: the story of a lifetime

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Deriving European tantalum flows using trade and production statistics

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Abstract

Even though tantalum has a high economic importance and is associated with armed conflict, the use of tantalum throughout the supply chain of importing economies is not well understood. This chapter adds to existing qualitative descriptions of the tantalum supply chain by performing a quantified substance flow analysis (SFA) of tantalum for Europe in the year 2007. The exercise is meant to show how readily available statistical information could be used along with simple and transparent assumptions on product composition and allocation, to yield an enabling and visual representation of the supply chain for critical materials. The case of tantalum shows some surprising results. First of all, this study shows that tantalum in computer hard disks and artificial joints may be more relevant than found in previous studies. Further, we find that the tantalum consumption in Europe may be larger than expected based on geological survey reports, attributed to a high fraction of tantalum being imported in subcomponents and final products. Further research is needed to substantiate this claim, but what is clear is that a detailed SFA provides valuable insights into the consumption of tantalum as a critical material, throughout the stages in the supply chain related to the production and use of tantalum containing products. The exercise also allowed production of waste generation profiles and enabled identification of e-waste as an important focus group in order to improve tantalum recycling rates and eventually to reduce society’s dependence on scarce or conflict related raw materials.

2.1 Introduction

Tantalum is often considered a critical material because it has a high economic importance, but also a high supply risk and a problematic substitutability. Modern alloys and digital components are increasingly dependent on the availability of tantalum whereas its supply is insecure because a considerable fraction of its ores are sourced from African countries (an estimated 37% in 2008, according to Nest (Nest 2011)), where mining is sometimes associated with armed conflict (HCSS 2013). In particular, the tantalum containing Coltan mineral ores, sourced from the Democratic Republic of Congo (DRC), have become a much quoted example of a “conflict mineral” given that the revenues of artisanal Coltan mines have likely been a source of income for paramilitary groups in the east of the country. Because of the illicit nature of the mining activity, numbers on production volumes of Coltan in the DRC are quite uncertain and fluctuate wildly across the years, but they have historically reached over 50% of total African production (Nest 2011). Though environmental impacts occur, concerns about the social impacts of mining have been the primary reason that the use of tantalum and several other critical metals is now subject to certification schemes on responsible sourcing (Bleischwitz et al. 2012; Young 2018) as well as stringent regulations in the United States (Dodd-Frank 2010) and Europe (EC 2014). However, whereas the social impacts of tantalum mining are high on the international political agenda, the use of tantalum throughout the demand side of the supply chain of products is still not well understood.

Though there have been numerous studies describing the flows of critical materials (Busch et al. 2014; BIO by Deloitte 2015; Guyonnet et al. 2015), existing literature on the supply chain of tantalum is limited. Previous studies discussing the use of tantalum in various products have been able to describe the tantalum supply chain at a high level of detail, but only in a qualitative sense (Jeangrand 2005; Espinoza 2012; EU 2014). An exception to this is a study by Moran and colleagues (Moran et al. 2015), who used a hybrid life cycle assessment approach to quantify the trade of the tantalum-containing mineral ores sourced from the DRC, to the processing countries and eventually to the industries supplying the final consumption in the year 2000. Moran and colleagues show that it is possible to track where the conflict-related tantalum ends up, but their study lacks detail in importing economies because the categorization of industries gives no insight on the amounts of tantalum imported (just their value), nor does it indicate which particular products generate the final demand. The lack of detail in quantitative elaboration of the tantalum supply chain in importing regions means that policy makers have little practical information to act upon a regions dependence on the conflict-related and, possibly, supply-restricted material. There is a clear need to better understand how metals flow through the whole supply chain, as also emphasized by Bloodworth (Bloodworth 2014).

We aim to improve this understanding for tantalum in Europe, as an importing region, in the hope to contribute to solving the region's vulnerability to supply restrictions. According to Espinoza (Espinoza 2012), the European tantalum processing industry generates approximately 250 to 300 metric tonnes (t) of tantalum in different raw material forms; this is equal to roughly 27% of the average total global production of tantalum concentrates from 2005 to 2010 (1,033 t according to the U.S. Geological Survey (USGS 2012), 2007–2012). However, the relatively large share in the consumption of tantalum concentrates does not give any insight into the European dependence on tantalum in all its applications. For that purpose, we need to quantify the use of tantalum throughout the part of the supply chain that is yet unknown, being its use in products and their components.

This study provides insights into tantalum flows in Europe in the year 2007, by performing a substance flow analysis (SFA) at a high level of detail, presented in a practically enabling way. The reason for choosing this year is that the level of detail in trade and production data is highest for the year 2007 (see also Appendix 2). Based on the description of the tantalum supply chain in this year, we give an indication of the expected waste generation profile over time. Together, the SFA and the waste generation assessment should better enable European policy makers to judge the size of the European tantalum flows and give insights into the relevance of product groups when aiming to secure the material supply through, for example, recycling (Zimmermann and Gößling-Reisemann 2014; Buchert et al. 2012), redesign (Peck and Bakker 2012), or substitution (Graedel et al. 2015). The method used is relatively straightforward and mostly based on readily available statistical information from (Eurostat 2016), so the analysis could simply be repeated for other critical materials in the future. The downside of using an SFA methodology as presented here is that it is nonattributional. So, though the reason for our attention for tantalum is the social conflict related to its mining, we do not account for the origin of the imported metal, and simply present a static overview of total metal flows imported into Europe in 2007, the majority of which was produced in officially regulated mines, such as in Australia and Brazil (Nest 2011).

To complete the overview of tantalum flows, a great number of assumptions had to be made, especially on the tantalum concentrations in products and the market share of tantalum containing products in aggregated product statistics, in order to describe the tantalum flows through Europe. For some cases, we were not able to quantify flows. This shows that the knowledge on the use of critical raw materials and their economic importance is not matching the current political attention, and so we require more insight to reduce society's dependence on scarce or conflict-related raw materials. It is in the light of that discussion that we make our assumptions, crude as they may be, and describe them as transparently as possible. The Discussion section will elaborate on this and will address why we feel that the SFA approach presented here adds to existing studies on critical raw materials.

2.2 Method

In order to derive tantalum flows through Europe, we first used the available trade statistics and production statistics to determine the apparent consumption of tantalum-containing products, as discussed under Production and Trade Statistics. We define the apparent consumption as the imports plus the production, minus the exports. Second, we performed a review of tantalum concentrations in those products, as described under Section 2.2.2 (Product Composition). Combining these steps yielded the apparent consumption of tantalum through various European products (see Results), which were then categorized into production stages to result in a highly detailed flow diagram of tantalum in raw materials, semifinished products, as well as in products for final consumption, as described in the section on the *Sankey* Diagram. Finally, we assessed the expected future tantalum recycling potential from consumer wastes by assuming suitable lifetime distributions, as discussed in Section 2.2.4 (Consumer Waste Assessment). Figure 2.1 indicates how the method comprises of 13 subsequent steps and how these are covered in the sections throughout this chapter.

Essentially, we drafted a list of products containing tantalum based on pre-existing qualitative studies (step 1). For this list of products, we extracted European trade and production data from the Europroms database of Eurostat (step 2) and completed the available information to yield total weigths traded or produced (steps 3 and 4). Using the product compositions, we translated the weigths of all product flows into a list of total tantalum flows (steps 5 and 6) and subsequently allocated each flow to the relevant product in downstream production stages (steps 7, 8, and 9), so that a Sankey diagram could be drawn (step 12). Finally, we show how results from the stocktaking in the previous steps could be used to produce useful results for environmental policy and management by applying product lifetime distributions (steps 10 and 11) to show how the tantalum in products bought in a certain year becomes available as waste over time (step 13). The following sections describe these steps in more detail. It is important to state that such a stocktaking exercise is only possible under the following assumptions: First of all, we assume that no losses occur in the production of tantalum containing subcomponents and final products, neither as environmental emissions nor as preconsumer waste streams. The losses during raw material conversion are dealt with separately (see step 5). Further, we assume that tantalum inventory stocks remain constant over the year 2007, which means that we assume that all the raw materials consumed are fully transformed into consumed tantalum products and that no stocks of raw materials, components, or products were generated or addressed or to fulfill demand.

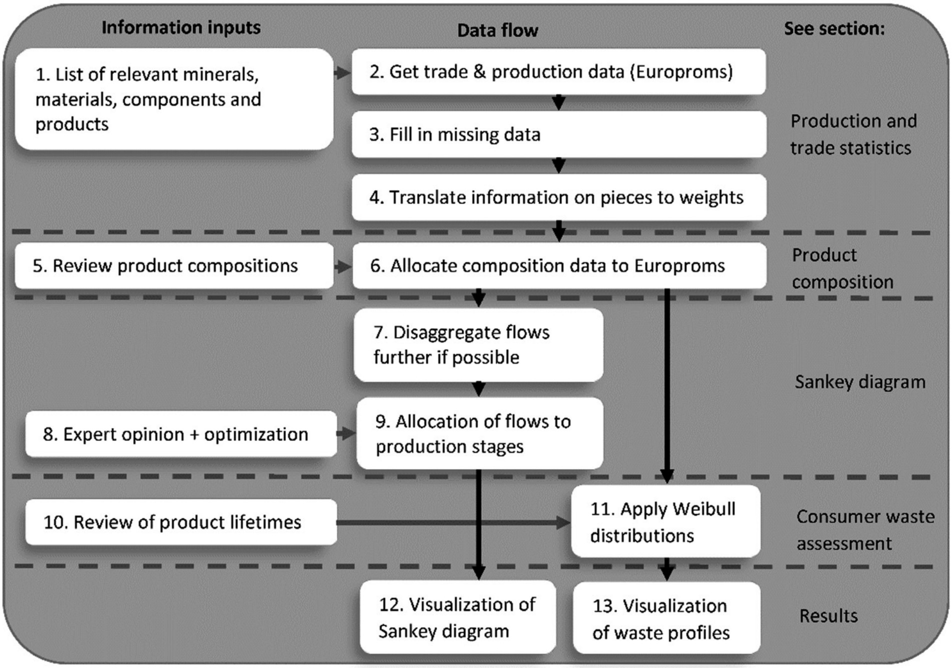

Figure 2.1. *Overview of methodological steps in this study and the sections describing them.*

2.2.1 Production and trade statistics

1) As a first step, we drafted a list of materials, products, and components that were considered relevant for tantalum, based on the two most recent qualitative studies on the tantalum supply chain (Espinoza 2012; EU 2014). Only the product descriptions that could be linked to a concrete product and a source on their tantalum concentration were used in this study, as can be seen in Table 2.1. That means that, in some cases, for example for broad categories like “tools and machinery” and the various products with “corrosion resistant surfaces,” we did not include the products listed in the qualitative studies, simply because the description is too vague to determine which fraction of these tools, valves, tanks, etc., actually contain tantalum and how much. Some other products were excluded, because we could not find any information on the product composition, even though the description was rather precise, like in the case of X-ray film and diagnostic equipment, for example. Two aggregate product categories were identified in order to accommodate the multiple applications of tantalum in both aerospace and automotive products.

Table 2.1. *Materials, sub-components & products relevant to tantalum, mentioned in previous studies.*

Espinoza (2012)	**EU (2013)**	**Used in this study**
Alloys	High Temperature Alloys	Yes
Surgical clips/medical applications	Prosthetic devices (hip joints, skull plates, mesh, clips, stents)	Yes, as one category
	hearing aids & pacemakers	Yes, separately
Capacitors	capacitors	Yes
Cutting tools	cutting tools	Yes
Aerospace and avionics applications	jet engine discs, rocket nozzles	Yes, as Aerospace
Aircraft turbines	Aerospace/gas turbines	Yes, as Aerospace
Furnace parts	High temperature furnace parts	Yes, as Furnaces
Tantalum carbides		Yes
Glass (high refractive/low scattering)	Lenses for spectacles, digital cameras and mobile phones	Yes, as Vision correction lenses & Other lenses
Surface acoustic wave filters	surface acoustic wave filters	Yes
X-rays diagnostic equipment	X-ray film	No, no information
Catalysts		No, too vague
Ingots		Yes
Tools & Machinery		No, too vague
Micro-electronics for engine management	Automotive ABS, airbag activation, engine management modules, GPS	Yes, as Automotive
Micro-electronics in safety & military equipment	Military explosive missiles	No, no information
Corrosion resistant surfaces	lining, cladding, water tanks, valves, screws, nuts, bolts	No, too vague
	laptop computers, mobile phones, digital cameras (video & still)	Yes, separately
	DVD players	Yes
	mobile phone signal masts, oil well probes	No, no information
	semi-conductors	Yes
	Ink jet printers	No, no information
	Computer hard drive discs	Yes

Finally, because the application of tantalum in GPS devices is mentioned, we decided to add them as a separate category, because global positioning system (GPS) devices are available as independent consumer electronics (one could think of the non-“built-in” use of navigational devices). We feel that, altogether, this list of products covers the most relevant uses of tantalum in society, considering that most excluded products are minor or specialty applications, whereas the bulk applications like consumer electronics and cars are covered.

2) In step 2 of the process, the items on the list were matched to their proper representation in the available statistics so that the weight of imports, exports, and total production for 2007 could be downloaded from the annual Europroms reports (Eurostat 2016). The Europroms data set conveniently combines the Eurostat production statistics, with information on imports and exports at a high level of detail (identifying 88 products, at the eight-digit level of the Prodcom classification). In most cases, the identified products were represented by multiple items in the available data. For example, the automotive category is represented by a selection of data on 12 passenger car types, four public transport vehicle types, and six freight vehicle types. Only for the raw materials, the level of detail was insufficient, so an additional disaggregation of the category "tantalum articles" had to be made, based on the British Geological Society (BGS) (BGS 2011), as will be discussed in the section on the *Sankey* Diagram (step 7). The full link between the selected product categories and the Europroms database is disclosed in Appendix 2.

3) Step 3 (see Figure 2.1) consisted of filling in the missing data. In a few cases, the Eurostat data extracts contained information on both the value and the weight of European production of the tantalum-containing products, but only the value of the imports and the exports. In those cases, we assumed the European price as a representation of the price of the imports and exports, to derive the physical amount of products from the given value of the trade.

4) In the fourth step, the units were harmonized, so that all Europroms production and trade data were expressed in kilograms (kg). Roughly half of the data in the database provided information on products by pieces. If available, the average weight, as provided by (Eurostat 2010), was used for the conversion. In six cases, an external source was used to determine the weight of the products; these are described in Table A2.2 of Appendix 2.

2.2.2 Product composition

5) Given the list of kg of products imported, exported, and produced, the next step was to review the tantalum concentrations for each of these products. We used a single number per product, thus assuming that the material content of imports products is equal to the content in domestically produced goods. Given that many of the tantalum-containing products are common household appliances, the review of compositions of electronic and electrical equipment by Oguchi and colleagues (Oguchi et al. 2011) proved to be very useful. Table 2.2 shows the full list of sources used, including a few company data sheets. In case the sources only specified the volumetric or chemical composition, the weight percentage of tantalum was derived as elaborated in Appendix 2.

Table 2.2. *Tantalum concentration in the selected products. A source is provided if applicable, if the concentration was derived using additional assumptions this is indicated in the last column.*

Product description	**Concentration (kg Ta/kg product)**	**Source of concentration data**	**Assumptions**
concentrates	0.00211456	*Derived*	The content of tantalum concentrates is a balancing factor on the raw material supply side, so we increase the concentration in order to fulfill the demand of tantalum ingots, powder, metal and oxides.
articles	1		Assuming tantalum articles are made of 100% tantalum metal
carbides	6.794E-05	*Derived*	Based on the (BGS 2011) we assumed that tantalum articles represent 76% of tantalum consumption, in addition, the carbide consumption represents 7%, so the carbide concentration is adjusted to match 100% of the consumption of carbide tools, which was the only application of carbides found in the tantalum supply chain matrix in the (EU 2014) study.
capacitors	0.367	(Ecoinvent 2007)	
HDD	0.019	(Nunney and Baily 2011; Hitachi 2007)	Assuming a 10,5% weight of the data platter (Yan et al. 2013). And an average tantalum content of the (perpendicular recording) platter according to the two sources.
Artificial joints	0.175	(Zardiackas et al. 2006)	Based on new medical alloys discussed in source
camera lenses	0.046	(Kodak 1941)	Assuming a 50% market share of tantalum containing glass lenses (containing 9.3 wt% tantalum based on the source).
vision correction lenses	0.00184		assuming 2% market share for glass lenses (myeyeware2go.com), assuming Kodak glass (same as ‘camera lenses’, see above).
other lenses	0.00184		Same as vision correction lenses
Mobile phones	0.00041	(Christian et al. 2012) & (Oguchi et al. 2011)	Average of 39 phones in two studies (additionally assuming 130 grams/phone based on (GSM Association 2006).
Laptop PCs	0.00103	(Oguchi et al. 2011)	The values here, given by the study by Oguchi only describes the tantalum content in the printed wiring boards of notebooks & PCs (thus capturing the tantalum content in the micro-electronics, but not in the harddisk). The tantalum content in their hard disks is accounted separately.
Desktop PCs	0.00088	(Oguchi et al. 2011)	
Cameras	0.00142	(Oguchi et al. 2011)	Similar to PCs, the tantalum composition of cameras given here applies only for the printed wiring board. The tantalum contained in the camera lenses is simply added to the overall camera composition in the results.
hearing aid	0.04667		We assumed 3 tantalum capacitors of a weight of 0.14, based on (engineeringprojects.com 2014) and an average of two types, according to (Ecoinvent 2007) in a total product weight of 9 grams (Alibaba.com 2015)
pacemakers	0.0186		Based on (Haddad and Serdijn 2009), we assumed the use of 10 tantalum capacitors of a weight of 0.14 g (average of two types, according to (Ecoinvent 2007)) in a total product weight of 28 grams (Medtronic 2015).
GPS	0.0043		According to (Philips 2009) a GPS device contains 6 tantalum capacitors of a weight of 0.14 g (average of two types, according to (Ecoinvent 2007) in a total average product weight of 195 grams (Carver 2016)

Product description	Concentration (kg Ta/kg product)	Source of concentration data	Assumptions
DVD players	0.00001078	(Oguchi et al. 2011)	
furnaces	6.2E-05	(Moss et al. 2013)	
carbide tools	0.0007966	*Derived*	Assuming that all tantalum carbides are used in carbide tools, the tantalum content was derived as the tantalum input divided over the mass of the tools.
TVs	0.000008	(Oguchi et al. 2011)	
Automotive (vehicles)	5.8E-06	(Cullbrand and Magnusson 2012)	The concentration was determined as the weighted average of three vehicle types: passenger cars, public transport vehicles and freight vehicles. We assumed that each vehicle contained 8 grams of tantalum, regardless of their weight.
Wavefilters	0.3305		Average material content of two types of surface acoustic wavefilters described by (Abbott et al. 2005) and (Strijbos et al. 2007)
Semiconductors	0.286		See assumptions based on (Chaneliere et al. 1998) in the SI
Aerospace	0.00092		High-temperature alloy application in aircraft engines, see SI for details

Table 2.2 shows that, in some cases, the concentration of tantalum is derived; this means that we were unable to find information on the concentration in the product or material, but that it could be derived using the amounts in connecting flows. In the case of tantalum concentrates, for example, we knew the volume of flows and we knew the required amount of tantalum in the materials requiring inputs of concentrates, because we knew the outgoing amounts of tantalum. The content of tantalum in the concentrates was set so that it fulfills this demand.

As such, we assumed no losses, similar to the assumptions further downstream, but we made sure that we at least fulfill the demand of products with a known tantalum content, without propagating uncertainty downstream through assumptions on losses during raw material processing. The uncertainty is offset to the concentration of tantalum in imported raw materials, which may therefore be slightly underestimated.

6) The list of tantalum concentrations cannot be directly multiplied with the data on product weights, because of two reasons. First of all, in some cases, only part of the considered product sales actually contain tantalum. For example, only very few semiconductors contain tantalum whereas the Europroms database does not distinguish “tantalum containing semiconductors”; it only provides the sold volumes of various semiconductors (diodes, transistors, and others). So, when we found information on the composition of tantalum-containing semiconductors, such as given in Table 2.3, we needed to also provide an assumption on the market share of the sales of semiconductors that contain tantalum, as indicated in Table A2.3 in Appendix 2. We also needed to provide a conversion factor in case the Europroms data consider products for which the concentration only applies partially. For example, “central storage units” were considered relevant because they contain hard

disk drives (HDDs), but given that they represent the usually much larger professional stacked server racks, the concentration found for a simple consumer HDD does not apply. In such cases, an additional assumption was made to determine the fraction of the subcomponent in the product to which the available concentration data apply, as listed in Appendix 2. Finally, these steps lead to the overview of tantalum flows in imports, exports, and production, thus giving the derived apparent consumption of tantalum as in Table 2.3.

Table 2.3. *Tantalum containing products & their trade and production flows (expressed in tonnes tantalum) for Europe in 2007 according to* (Eurostat 2016)*.*

Tantalum products	**Production stage**	**Export**	**Import**	**Production**	**Apparent Consumption**
Concentrates	Raw material	7	597	10	600
Carbides	Raw material	3	10	31	38
Articles	Raw material	345	493	254	401
wave filters	Sub-component	2	3	2	3
Semiconductors	Sub-component	46	39	32	25
other lenses	Sub-component	3	6	5	8
camera lenses	Sub-component	21	151	16	147
HDD	Sub-component	103	635	5	537
Capacitors	Sub-component	183	100	398	315
Cameras	Final product	16	196	5	185 (331 incl. lenses)
TVs	Final product	0	1	2	2
DVD players	Final product	0.1	2.2	0.3	2
Artificial joints	Final product	53	61	184	192
hearing aid	Final product	15	28	30	42
pacemakers	Final product	4	6	9.5	12
GPS	Final product	0.5	0.6	2.6	3
vision correction lenses	Final product	3	18	12	27
Mobile phones	Final product	122	213	216	307
passenger cars	Final product	7	16	90	98
public transport vehicles	Final product	0.5	0.1	0.3	0
freight vehicles	Final product	4	3	26	24
carbide tools	Final product	3	2	38	37
furnaces	Final product	6	1	15	9
Laptop PCs	Final product	21	149	61	189
Desktop PCs	Final product	138	123	209	195

2.2.3 Sankey diagram

7) In order to present these flows in an overall tantalum flow scheme, additional assumptions had to be made to further disaggregate and allocate the tantalum flows. First of all, information on the raw material forms of tantalum was available from the BGS (BGS 2011), which allowed us to disaggregate the lump category of “tantalum articles” into different forms of tantalum, being ingots, powders, oxides, and pure metal form. Second,

the supply of tantalum in raw material form was matched with their demand by adjusting the concentration of tantalum in the concentrates. Finally, a detailed allocation of raw material forms into final and semifinished products was applied, using the allocation rules as discussed below.

8 & 9) Except for the case of hard disks, the distribution of raw materials over subcomponent production and the subsequent distribution of subcomponents over final products was derived using an optimization routine in Microsoft Excel software based on a generalized reduced gradient algorithm (Lasdon et al. 1974) in combination with conditions set by the available qualitative studies (EU 2014). The goal-function was set to minimize the square of the mismatch between intra-European inputs and reported production (also known as the least square error approach). In simpler words, it tries to distribute the apparent consumption of a component in such a way that it fulfils the demand from all receiving final products produced in Europe, where equal importance is given to all applications of tantalum. The optimization thus does not minimize the mismatch in volume of the tantalum flows, but minimizes the error between the tantalum supply and the demand for tantalum in the production of each product (no matter if it is a major or a minor application). An example of an applied condition in the form of a discrete choice is that the metal form of tantalum is only used in hard disks and artificial joints, whereas the tantalum oxides are allocated over lenses and acoustic wave filters. The full set of applied conditions and outcomes of the two optimization steps can be found in Table 2.4a and 2.4b.

It should be noted that this allocation of flows did not always lead to a matching supply and demand. The use of flow-allocation factors from the optimization procedure simply assures that the mismatch is minimized per product. The remaining balance shortages or surpluses are reported separately in the results section. For an elaboration of the size of these flows, we refer to Appendix 2.

Using these allocations, we constructed a tantalum flow scheme for the European Union (EU) (considering the 27 member state description, or the EU27). As mentioned before, we assumed that no losses occur and that the *production* of tantalum-containing products in Europe is responsible for the apparent consumption of raw materials and subcomponents. The final overview was visualized in the form of a Sankey diagram (see step 12 in the Results section), using a javascript library for data driven documents (or d3), as inspired by and adapted from (Bostock 2012).

Table 2.4. *a) Allocation of the (apparent) consumption of raw materials to sub-components and b) Allocation of the (apparent) consumption of sub-components to final products. Determining factor is the demand from the production within Europe. Some raw materials are directly processed into final products, as indicated with an (F). The allocation of hard disks over final products is based on the indicated study, the rest is an outcome of the optimization routine as discussed in the text.*

Table 2.4a		**Allocation of tantalum raw materials**				
		FROM				
		carbides	Pure metal	oxides	powders	ingots
TO	Carbide tools (F)	100%				
	Artificial joints (F)		92%			
	Other lenses (F)			9%		
	Vision corr. lenses (F)			35%		
	Capacitors				100%	
	Semi-conductors					58%
	Wave filters			2%		
	HDDs		8%			
	Camera lenses			54%		
	High-temp. alloys					42%

Table 2.4b		**Allocation of tantalum containing sub-components**					
		FROM					
		Capacitors	Semi-conductors	Wave filters	Hard disk (Coughlin 2006)	Camera lenses	High-temp. alloys
TO	Mobile phones	13%	39.4%	8%			
	Cameras	1.5%	0.15%			100%	
	Desktop PCs	17%	2.3%		34%		
	Laptop PCs	11%	49%	0.06%	39%		
	External HDD				19%		
	Central storage				8%		
	DVD Players	0.09%	0.001%				
	GPS devices	1%		1%			
	TVs	19%	0.9%	82%			
	Hearing aid	8%		2%			
	Pacemaker	3%					
	Vehicles	19%	2.5%	5%			
	Furnaces						65%
	Aerospace						35%

2.2.4 Consumer waste assessment

10 & 11) To find out how consumer purchases of tantalum containing products in 2007 contribute to the recycling potential over time, we used the apparent consumption of final products based in Table 2.3 to represent the amount of tantalum going into the use phase. Even though the outcomes of the allocation method, as described in the previous section, did not provide a 100% match between tantalum supply (embedded in subcomponents) and its demand (through the production of final products requiring using those components), this provides the most robust estimate. Given that different products have different expected lifetimes, we assumed a Weibull lifetime distribution for each of the final products. The Weibull distribution is chosen because of its high analytical traceability and because it has the best fit of lifetime distributions for most products (Wang et al. 2013); it is a common distribution in reliability applications, next to the log-normal distribution. The Weibull probability density function $f_W(t)$, in this case representing the failure rate of a product, t years after its purchase, is given by the following equation (equation 1):

$$f_W(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{\left(\frac{t}{\eta}\right)^{\beta}} \quad ; \quad \eta > 0, \beta > 0, t > 0 \qquad \text{(eq. 1)}$$

The first distribution parameter, β, generally called the shape parameter, determines whether the mode (being the top of the bell shape) is toward the right or the left of the mean; it also determines the skewness (i.e., the sharpness of the distribution peak). The second parameter, η, determines the spread, or the statistical dispersion, of the function. Note that it is not the same as the mean (or average) lifetime. The sources for the Weibull parameters for each product are shown in Table 2.5 below. The Results section elaborates on the implications to waste generation and presents the resulting lifetime distributions in Figure 2.3a.

2.3 Results

12) The results of the SFA for tantalum, as described in the previous chapter, is shown by means of a Sankey diagram in Figure 2.2. The diagram shows the imported flows (in light green), the exported flows (in light red), and the intra-European flows of tantalum (in light blue). It shows the cascading of the consumed tantalum in raw material form (in the blue bars) through the demand for subcomponents (in green) and final products (where the color of the bars indicate different product categories).

__Table 2.5.__ Weibull parameters & distribution of failure rates for Tantalum relevant products

Final product	Shape (β)	Scale (η)	Average lifetime (yr)	Reference category & source
vision correction lenses	1.4	7.6	6.9	Small medical, (Wang et al. 2013)
Cutting Tools	2.6	15.7	13.9	Small tools, (Wang et al. 2013)
Furnaces	2.218	26.7	23.6	(EERE 2008)
Mobile phones	3.66	7.59	6.8	(Polák and Drápalová 2012)
Cameras (video/still)	1.4	8.2	7.5	(Wang et al. 2013)
Desktop PCs	2.1	9.6	8.5	(Wang et al. 2013)
Laptop PCs	1.5	5.2	4.7	(Wang et al. 2013)
External HDD & servers	2.30	13.74	12.2	(Pasha et al. 2006)
DVD players	1.7	10.5	9.4	Video & projection, (Wang et al. 2013)
GPS	1.7	9.6	8.6	Small monitoring, (Wang et al. 2013)
TVs	2.1	12	10.6	FPD TVs, (Wang et al. 2013)
Hearing aid	1.4	7.6	6.9	Small medical, (Wang et al. 2013)
Pacemakers	1.4	7.6	6.9	Small medical, (Wang et al. 2013)
Artificial joints	2.6	19.2	17.1	Prof. medical, (Wang et al. 2013)
Aerospace	0.65	10.2	13.9	Airplanes, (Nomura et al. 2013)
Automotive	1.89	10.3	9.1	Passenger cars, (Nomura et al. 2013)

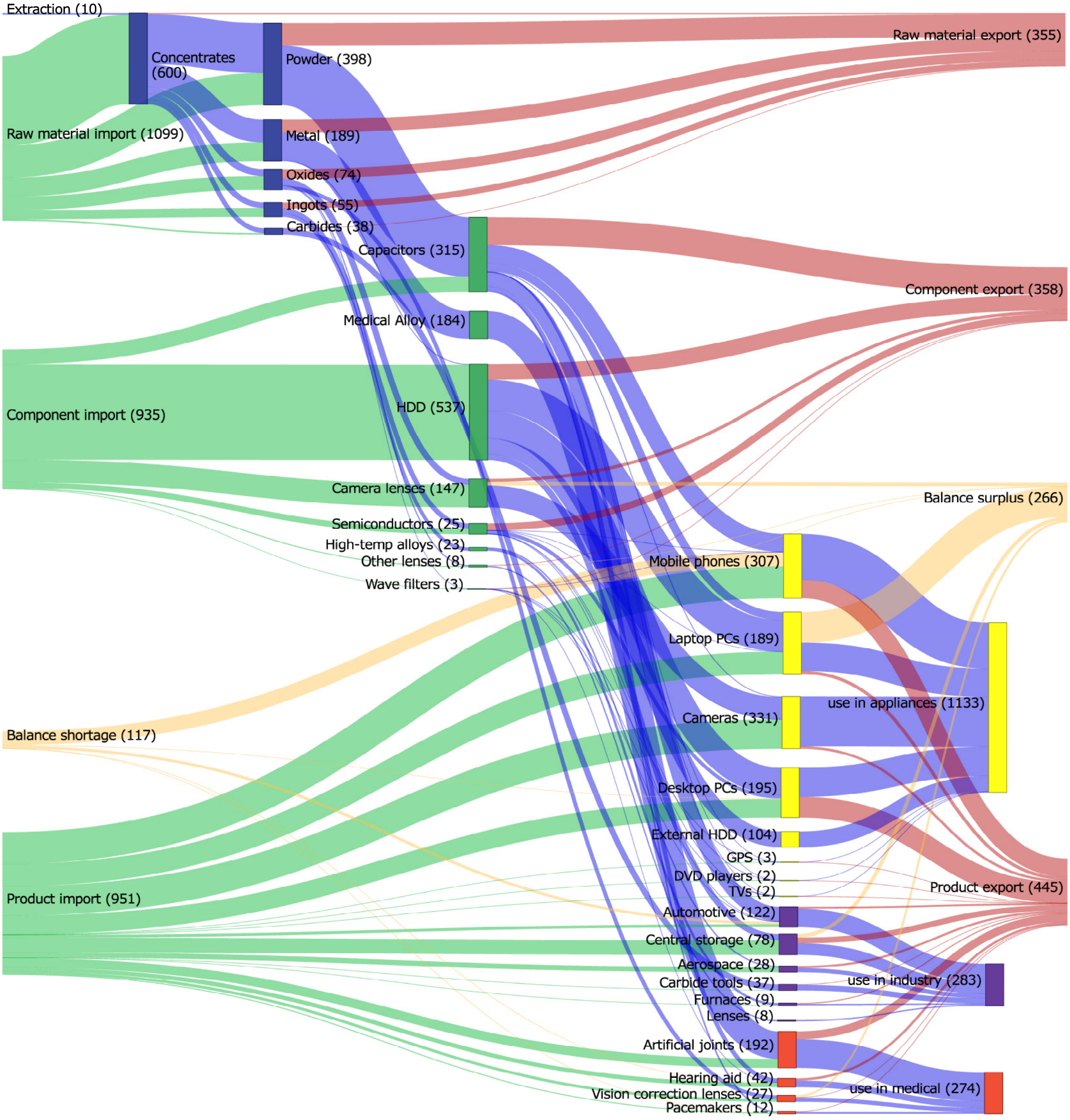

Figure 2.2. *Annual Tantalum flows through the EU27 in 2007, the numbers indicate the apparent consumption of tantalum in tonnes. For intermediate product categories this represents the production that remains within the EU27, or simply the size of the outgoing blue flow. For imports, exports and products going into use, the number indicates the total tonnes of tantalum. The template for this Sankey-diagram was inspired by and adapted from* (Bostock 2012).

Careful interpretation is required, given that the size of the bars as well as the indicated volumes for each product indicate the size of the tantalum flow through Europe (imports, exports, plus domestic production), so not its actual consumption. The actual consumption of raw materials and subcomponents is represented by the light-blue flows and are based on the allocation method as described for step 9 in the previous chapter. The resulting apparent consumption of final products is separately indicated using the bars in the lower-right corner. In the section below, these results are discussed and compared against existing studies.

Given that no previous studies made an attempt to quantify tantalum flows in Europe at this level of detail, it is difficult to compare the outcomes or even judge their quality. Something can be said, however, for example to compare the output of the European tantalum processing industry, which is 716 t, including exports in our analysis (considering tantalum powders, metal, oxides, ingots, and carbides). This does not correspond with the observation of Espinoza (Espinoza 2012, page 7), who states that this is *“between 250t and 300t tantalum per year*.” Also, the total amount of tantalum going into use in Europe through final products (1,690 t) is much larger than expected based on the total global consumption of concentrates. In fact, this would be more than the global mine production (1,400 t) as reported by the USGS. This is surprising given that the current end-of-life recycling rate, and thus the potential for secondary material to fulfill demand, is minimal at less than 1% (Graedel et al. 2011). This mismatch of reported global raw material supply and European consumption may have two main reasons; either this study used assumptions leading to a too high estimate for the tantalum concentration in products or it may indicate that the real volume of tantalum mined is much larger than reported, which is not unlikely, given that tantalum is not traded on official spot markets and partially sourced from illicit mining operations in conflict areas (Nest 2011). An observation hinting in this direction is the fact that the reported total tantalum content in global concentrates for the year 2008 increases by over 70% between two reporting years according to the USGS (USGS 2011, 2012).

The European Commission (EC 2014) review of critical raw materials for Europe gives some more numbers that could provide a perspective. It mentions the total tantalum imports to be 604 t in 2010, but it remains unclear whether these are the raw material imports only (in that case, they compare to 1,099 t in our study) or imports in all product phases combined (in which case they compare to 2,985 t of tantalum). The EC study also indicates that 40% of tantalum is used in capacitors. If we assume that they compare the use to the total raw material consumption (754 t), our study finds that 53% of the tantalum in raw material form is consumed in capacitors. So, in general, it seems that the few currently known indicators on tantalum consumption are not very comparable to our outcomes. This brings up the question as to why the total tantalum consumption found is so much larger than expected.

One of the items that stands out in our analysis is the large consumption of tantalum in hard disks for storage of digital data. This is a category that has only been mentioned in one of the qualitative studies (see Table 2.1) and never as a crucial product. However, the results in this study indicate that hard disks are responsible for 537 t of tantalum, when assuming a tantalum content based on a patent (Hitachi 2007) and an X-ray based composition analysis (Nunney and Baily 2011) for consumer-type hard disks using a perpendicular recording mechanism. Our study is the first, to our knowledge, to highlight such a high importance of tantalum in hard disks, thus indicating a direction for further research.

Another interesting finding is the relatively high importance of tantalum in artificial joints. Though the assumption on tantalum concentration for this product category is based on a selection of medical materials in a single source (Zardiackas et al. 2006), so insights may be improved given further research, the fact that Europe would have a relatively high demand for prosthetic devices seems plausible given the high occurrence of hip-and-knee replacement surgery (OECD 2011) and the prominent demographic aging trends (Walker 2010).

It is clear that the results presented in Figure 2.2 contain both expected and unexpected elements, but the lack of quantitative data to check the outcomes shows that the supply chain of tantalum, like many critical raw materials, is still not well enough understood. An exercise like the one presented here generates valuable insights on the relevance of individual products and into the importance of product imports. The true value of the SFA, however, lies in identifying ways to overcome the dependence on tantalum in Europe and in solving its criticality through recycling, for example. The next section goes into this topic.

13) Applying the Weibull distributions discussed in step 11 of the method section to the apparent consumption of final products, as found in Table 2.5, gives the expected amounts of tantalum waste as a consequence of European consumption in 2007. As an example of what is possible when combining the SFA with information on product lifetimes, Figure 2.3 presents a waste generation profile for the seven products containing the most tantalum.

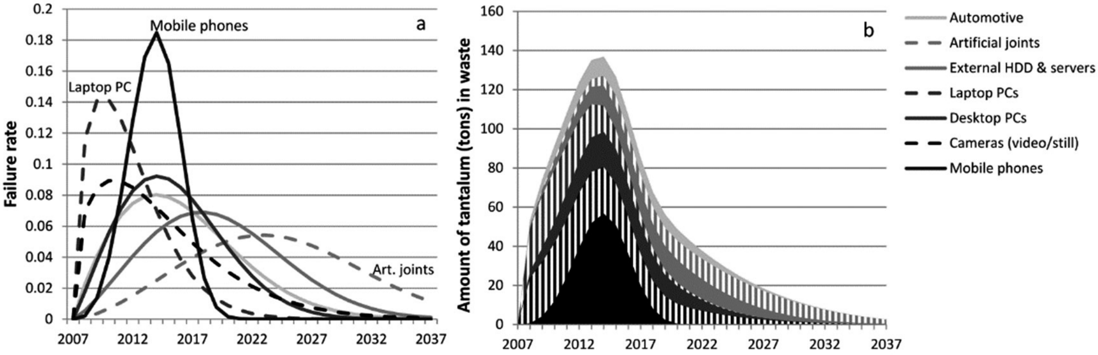

Figure 2.3a-b. *Expected waste generation profile of tantalum contained in seven major applications consumed in Europe in 2007. Major applications are defined as those products with an apparent consumption above 100 tonnes per year (see Figure 2.2), where external hard disks and central storage in servers are shown as one product category. a) shows the probability density function of the product failure rate in the form of a Weibull distribution based on the parameters in Table 2.5; simply said, it shows which fraction of the products are discarded in a particular year after purchase. b) shows the resulting expected volumes of tantalum in wastes as a result of purchases in 2007 only.*

The waste generation profile in Figure 2.3 shows that some of the major tantalum-containing products purchased in 2007 will be discarded and thus become available for recycling over a very long time period, spanning up to 30 years. The good news, however, is that the majority of tantalum is contained in household and consumer electronics, which have a relatively high collection rate estimated at 85% (EU 2012), a relatively high recycling and reuse rate (generally above 80%; see (Eurostat 2015)), and average lifetimes that are mostly limited to around 15 years. Based on this graph, which builds upon the detailed elaboration of the tantalum supply chain above, we identify consumer e-waste as a potential hotspot in terms of recycling potential for tantalum. One can imagine that the application of lifetime distributions to SFA results, like we have done here, may have several other useful applications. We will elaborate on this and on the more-general conclusions of our research in the following section.

2.4 Discussion and conclusions

The results section showed that performing an SFA based on detailed production and trade statistics gives insight into the use of tantalum throughout Europe. It allows identification of current knowledge gaps, whereas the visualization in the form of a Sankey diagram highlighted the importance of imported tantalum-containing products and components. Additionally, the identified hotspots for recycling are useful outcomes of this exercise, given that they provide clues on how to efficiently improve recycling rates and eventually to reduce Europe's dependence on tantalum as a scarce and conflict-related raw material.

However, the results presented here should be interpreted carefully for several reasons. First of all, we have not been able to cover the full extent of tantalum-containing product categories as found in the previous qualitative literature. Though only a limited number of minor products were excluded based on the lack of data, further research into the tantalum content of these products could help alleviate uncertainty. Second, the availability of data in the Europroms database only allowed for the full analysis of relevant products for the year 2007, which is probably not a very accurate description of the current situation. It should be stressed that the Eurostat data are simply indispensable, but application in SFA requires maintenance of trade and production statistics at the highest level of detail. Finally, and perhaps most important, during this research we found that gathering information on product compositions is surprisingly tedious. This study uses information on tantalum concentrations for products and components from a wide variety of sources, often nonscientific, and often requiring rough assumptions or interpretation. The sheer difficulty of gathering concentration data is an indication that the uncertainty of these numbers is high. This is a possible explanation to why the size of tantalum flows in our results are much larger than expected, but the uncertainty in benchmarks of total global consumption defining these expectations may be just as uncertain.

More generally, one could say that though the complexity of products, in terms of the components and materials they contain, has increased rapidly over the last decades, our understanding of their elemental compositions is clearly lagging behind. For many products, neither consumers nor producers simply have any clue what they contain. So although the discussion on the scarcity, responsible sourcing, and criticality of many materials is still high on the political agenda, research into their supply chains is stuck to a case-by-case approach, without a reliable source for benchmarking results to global numbers. For the case of tantalum, one suggested approach may be to attempt to reconcile data about the supply of tantalum (similar to the study by Moran et al. (2015)) and the data presented here. This would require harmonization of the years of study as well as an extension of focus to include both regulated and conflict-related tantalum mining.

Regardless of the approach, we feel that dealing with criticality questions in a more encompassing manner calls for a comprehensive product composition inventory for multiple critical materials. Such a proposed database should allow storage of information on product compositions at various levels of detail (raw materials, subcomponents, and final products) and should enable documentation of the change of product compositions over time as well, given that we found that the material content of products can be quite dynamic.

Concluding, we found that it is currently possible, yet tedious, to perform a detailed SFA for tantalum in Europe based on the available trade and production statistics by Eurostat. We provided a step-wise approach, which could serve as an example of how to draft SFAs for a variety of other scarce or critical materials. Based on the tantalum example, we feel that doing this gives valuable insights into both the economy-wide dependence on these materials as well as clues on how to reduce this dependence most efficiently. For tantalum, we have shown that the European market is highly dependent on imports of product components and final products, which leads to a much higher consumption than expected based on previously available indications. We identified computer hard disks and artificial joints as items with a surprisingly large contribution to the use of tantalum and have shown that consumer electronics should be the main focus when aiming for an improved recycling rate. The application of lifetime distributions to SFA results may have numerous applications. One of them may be the dynamic assessment of recycling potential over multiple years, which could inform a cost-benefit assessment when planning for effective deployment of tantalum-specific recycling and processing capacity in a European context.

Two factors play a crucial role in facilitating future analyses of other materials in a similar way, one being the availability of the detailed trade and production data, both for raw materials and products, beyond the year of our current analysis and the second being the suggested development of a product composition inventory. Given the two, we feel that it should be possible to rapidly increase our knowledge on the demand side of supply chains of critical materials other than tantalum.

Acknowledgements

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