CHAPTER 3

MATERIAL FLOW ANALYSIS OF TANTALUM

3. MATERIAL FLOW ANALYSIS OF TANTALUM

3.1 Material flow analysis (MFA) - Overview

Material flow analysis is a method of mapping out quantitative data of flows and stocks of *materials* (goods or substances) within a system defined in space and time through the process chain (Brunner and Rechberger, 2004). A model comprises *processes* (where material's transformation/transport/storage takes place) and *flows* (mass flow rate which link the processes). The terms frequently used in this chapter i.e. tantalum flow, material flow of tantalum, flow of tantalum all refers to the same concept. The amount of material stored within a process is termed as *stock*. Anything outside the system boundaries is termed *input/output flows* (Cencic and Rechberger, 2008). It has now become a globally accepted decision-support tool from a resource, environmental, and waste management point of view and to assess future sustainability (Brunner and Rechberger, 2004; Habib et al., 2014; Leal-ayala et al., 2015). It is based upon the methodological principle of conservation of matter (Ayres and Ayres, 2002; Islam and Huda, 2019). The MFA leads to a better comprehensive knowledge of a reference system that ultimately results in better ecological and economic accounting of the system (Agamuthu et al., 2015; Bonnin et al., 2013). Although there may be a critical data gap on stock and flow of material (Gusukuma and Kahhat, 2018) yet, surveys, interviews, and field studies can be performed to develop the required flow and stock as given by Kahhat and Williams, 2012 (Kahhat and Williams, 2012).

In general, the MFA comprises of four steps: (1) goal and system definition (2) process chain analysis in which different processes involved in the process chain are defined for which input/output has to be quantified (3) accounting and balancing to calculate flows and stocks of material and (4) modelling and result evaluation (Ayres and Ayres, 2002; Brunner and Rechberger, 2004). MFA can be either *static* which gives a picture for a particular year or *dynamic* to show the changes in a system over a longer time interval (Müller et al., 2014).

3.2 Steps in material flow analysis

The various steps involved in material flow analysis of tantalum is presented with the help of a flowchart in *Figure 3.1* and are described in following sub-sections.

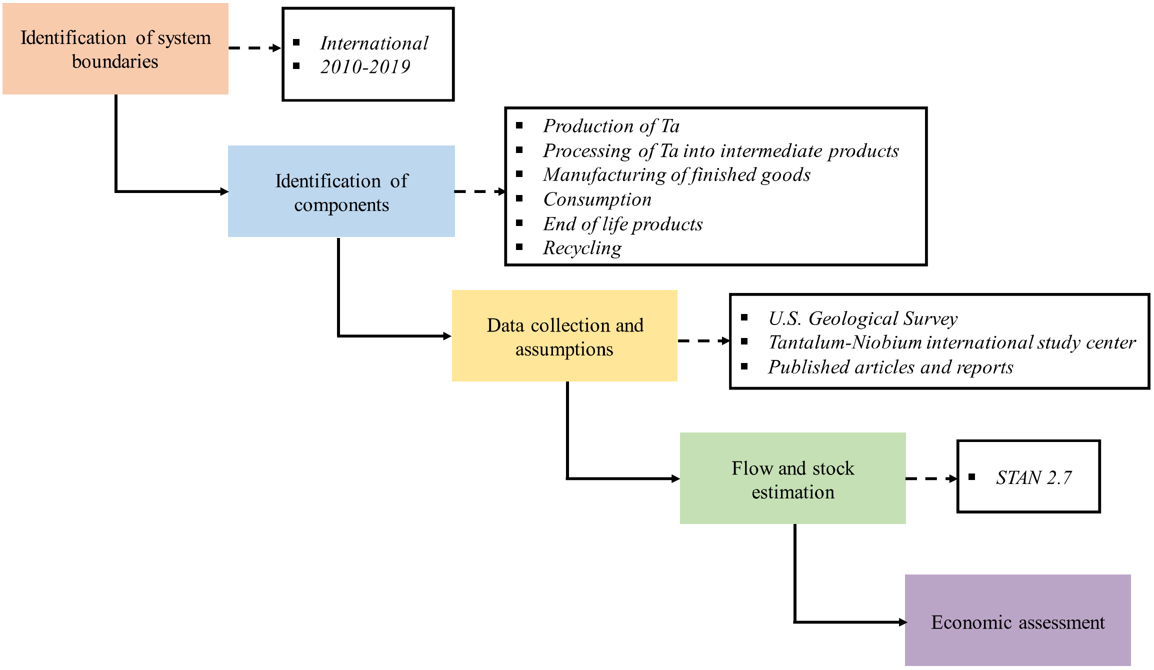

Figure 3.1 Material flow analysis framework for tantalum

3.2.1 Identification of system boundaries

The 1st step in conducting MFA is identification of system boundaries. MFA gives the systematic assessment of material's mass flow within a system boundary defined in space and time. The space boundary chosen in the present study is the globe, whereas the time boundary is confined within a decade from 2010 to 2019 to provide the most relevant information on tantalum flow over the recent past. However, the choice of such a large spatial and temporal boundary imposes a major limitation insofar as the accessibility of data for every flow of the material is concerned.

3.2.2 Data collection and assumptions

As mentioned earlier, data availability and assumptions are the principle limitation of performing MFA, which is even more challenging with regard to tantalum. An extensive data collection was performed through various scientific journals, reports, and websites to derive the global anthropogenic material flow of tantalum through its life cycle stages. Along the entire life cycle, tantalum passes through five main stages viz. production, processing, manufacturing, consumption, and EoL. Typical supply chain of tantalum is shown in *Figure 3.2*.

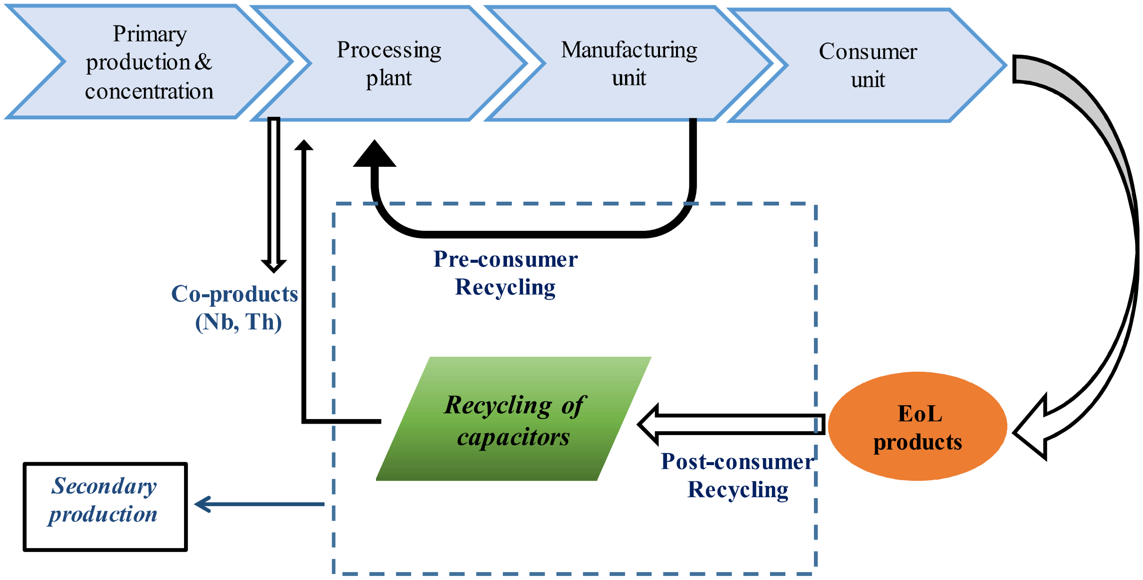

Figure 3.2 The supply chain of tantalum

In the production unit, tantalum is produced from the raw materials either by primary (natural ore) or secondary means (EoL products recycling). Then it is sent to processing unit where intermediate products (tantalum powder, ingots, sheets, rods, etc.) are manufactured. Thereafter it enters into the manufacturing unit for the fabrication of finished good. Finally, it is consumed by the users and then either discarded or enters into the recycling unit. Statistics related to the production were obtained from a bulletin published by the Tantalum-Niobium international study centre (TIC, 2016, 2020, 2021). Using the data published by the U.S. Geological Survey (U.S. Geological Survey, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021), *Figure 3.3* presents the graph on global country-wise mine production of tantalum for the year 2010-2019. Earlier input flows data, needed to determine waste flows of products expiring during 2010-2019 from production before 2010, were obtained from TIC bulletins ("Bulletin104," 2000; TIC, 2010, 2006).

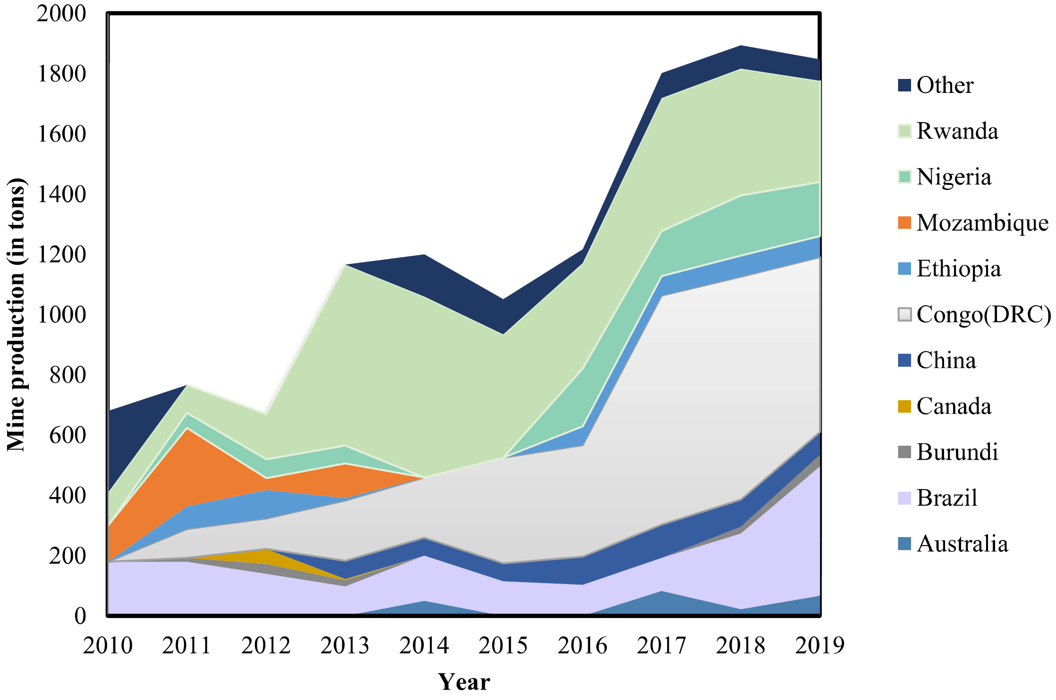

Figure 3.3 Country-wise annual tantalum production during 2010-2019 (U.S. Geological Survey, 2020, 2019, 2018, 2017, 2016, 2015, 2014, 2013, 2012)

The data on the allocation of tantalum into various product streams were taken from the Roskill information service (TIC, 2018). Due to the unavailability of data, the relative distribution of tantalum into each category is assumed to be more or less similar as shown in *Table 3.1*. However, a sensitivity analysis was done with maximum, mean, and minimum percentage of each product categories to draw its effect on total waste flow for the year 2010-2019.

Table 3.1 Consumption of tantalum in different product categories in 2016 (TIC, 2018)

capacitor	**mill products**	**carbides**	**superalloys**	**chemicals**	**sputtering targets**
34	9	7	18	17	15

After completion of the average lifetime, the product enters into the EoL stage. Average lifetime data, given in *Table 3.2* for each product category, needed to calculate the total EoL waste, was obtained from various sources in the literature (Nassar, 2017; Nomura and Momose, 2008; Oguchi et al., 2008, 2006; Smith, 1994; Streicher-porte et al., 2007). After reaching the EoL stage, the product is either recycled for resource recovery or ends up as waste. Data regarding the amount of tantalum being lost along the different life cycle stages were taken from Gille and Meier, 2012 (Gille and Meier, 2012).

Table 3.2 Average lifespan of various tantalum-based products

Product category	Product components	Average product life (Year)	Reference
Capacitor	Cellular phones	4.3	(Oguchi et al., 2006)
	Computers & business machines	7.1	(Nomura and Momose, 2008)
	Consumer electronics	6.8	(Oguchi et al., 2008)
	Automobiles	15.9	(Nassar, 2017)
	Infrastructure, industrial, and specialty	15.3	(Nomura and Momose, 2008)
Mill products		20	(Rowe, 1997)
Carbides	Cutting tools	1	(Smith, 1994)
	Wear parts	1	(Smith, 1994)
	Mining and drilling tools	30	(Smith, 1994)
Sputtering targets		7.2	(Nassar, 2017)
Superalloys		11	(Nassar, 2017)
Chemicals		8	(Nassar, 2017)

3.2.3 Flows and stock estimation

After collecting data, the next exercise is product balancing (mass balance calculations based on principle of conservation of mass) to facilitate flows and stock estimation. Free software developed by the Vienna University of Technology (TU Wien), STAN 2.7 ("TU Wien," 2006) was employed to perform the MFA. It enables the graphical modelling and analysing flows and stocks of a complex system by using predefined components, where the mass conservation is maintained throughout the flow. The STAN allows the analyst to integrate uncertainties of input data in the form of standard deviation. Besides that, the software also aids in data reconciliation, error propagation, and gross error detection (Agamuthu et al., 2015). The analysis results are visualized in the form of a Sankey diagram. The diagram shows energy or mass flow with the help of arrows where the widths of the arrows correspond to the relative magnitude of flows. Every process within the supply chain acts as a reservoir, where matter flows, processed, used, and then transferred (most probably after transformation) into another stage of the life cycle within the system boundary (Spatari et al., 2005).

The basic equation employed by the software to develop the mathematical model based on the law of mass conversation is *Eq. (3.1)*:

$$dStock = \sum F_{in} - F_{out} \qquad (3.1)$$

where F_{in} and F_{out} are input and output stock respectively and *dStock* is the accumulation of stock in a process. Under the steady-state condition where the net accumulation of stock is zero, the equation can be modified as *Eq.* (3.2):

$$\sum F_{in} = F_{out} \qquad (3.2)$$

After the completion of useful life, the product enters into the EoL category. The flow leaving the consumer unit and appearing in the EoL stage was determined using a residence time model (a model used to calculate the discard flow based on the average lifetime of product). The model accounts for the waste stream by utilizing the annual input data of tantalum for each end-use category together with the mean residence time of the product. The formula used to determine the total EoL flow of tantalum is *Eq. (3.3)*:

$$F_{i,j} = \sum_{i=1}^{6} \sum_{j=2010}^{2019} F_{i,j-RT} \qquad (3.3)$$

where,

$F_{i,j}$= EoL flow of Ta for product i in year j

i= product category counter

j= year counter

RT= residence time of the product

$F_{i,j-RT}$= amount of tantalum entering the product category i in *year* j-RT

3.2.4 Economic assessment of the waste flows

After calculating the total EoL stock and determining the recycling flow, next we assessed the economic value of the discarded material. The economic value of the recyclable material was computed by using the following *Eq. (3.4)*:

$$\begin{aligned} Total\ economic\ value\ of\ waste = {} & Total\ Ta\ content\ of\ the\ waste\ \times \\ & Assumed\ recycling\ ratio\ \times Recovery\ yield \times \\ & Price\ of\ Ta_2O_5/Kg \end{aligned} \qquad (3.4)$$

Since the largest proportion of total tantalum (34%) is consumed in the electronics sector in the form of capacitors, we considered only capacitor waste from the resource recovery point of view. Most of the literature has reported a recovery yield of tantalum from capacitor waste in the range of 90-98% (Chen et al., 2019; Mineta and Okabe, 2005; Niu et al., 2017d), a mean value of that was considered in this research for the economic assessment of waste.

3.3 The MFA model

3.3.1 Material flow analysis (MFA) of tantalum

The result of the material flow analysis of tantalum through its life cycle stages is presented in *Figure 3.4*. The rectangular boxes show each life cycle stages from which material (tantalum) passes. Each process is connected by arrows which shows the mass flow. The width of an arrows is proportional to the amount of mass flow from one life cycle stage to another whose value is shown in the ellipse. The amount of material stored in a process i.e. stock is represented by a rectangular box inside a process box. Arrows with end knot '*I & E*' refers to import (flow into the system) and export flows (flow out of the system), respectively.

It can be seen from the *Figure 3.4* that a total of 21,580 tons (primary and secondary) of tantalum was produced from 2010 to 2019. Out of this, 13,248 tons of tantalum was from primary mine production; whereas, 8,332 tons of tantalum was secondary from tin slags and pre-consumer scrap recycling. The pre-consumer scrap reclaimed during the processing and manufacturing stage plays a significant role in tantalum supply, accounting for 20-25% of the annual tantalum production (Buchert et al., 2009; Burt, 2016). During the production stage about 4% of tantalum is lost which do not return to the supply chain. After the production, tantalum enters the processing stage, where intermediate products (powder, ingots, fabricated products, etc.) are manufactured. During this stage the amount of tantalum end up as waste is around 8%, whereas, 17% of waste is recycled/refurbished and re-enter into the supply chain. These intermediate products are then treated in manufacturing units to produce finished goods. A considerable amount of scrap is generated during this stage. According to Nassar, 2017 (Nassar, 2017), 8%, 5%, and 10% of tantalum flow into the manufacturing stage is generated as scrap during capacitor, carbides, and superalloys manufacturing, respectively. A large portion of this scrap is recycled (approximately 18%) and sent back to the production unit. The outlet of the manufacturing unit shows the proportion of tantalum going into each of the product categories. It is seen that the capacitor segment accounts for the largest share of tantalum consumption (4,332t), followed by superalloys (2,293t), chemicals (2,166t), sputtering targets (1,911t), mill products (1,147t), and carbides (892t). *Figure 3.4* further shows that 10,108t of total tantalum was held in stock whereas, 2,633t left the consumer unit (for the modelled period), entering the EoL stage after completing their average lifetime.

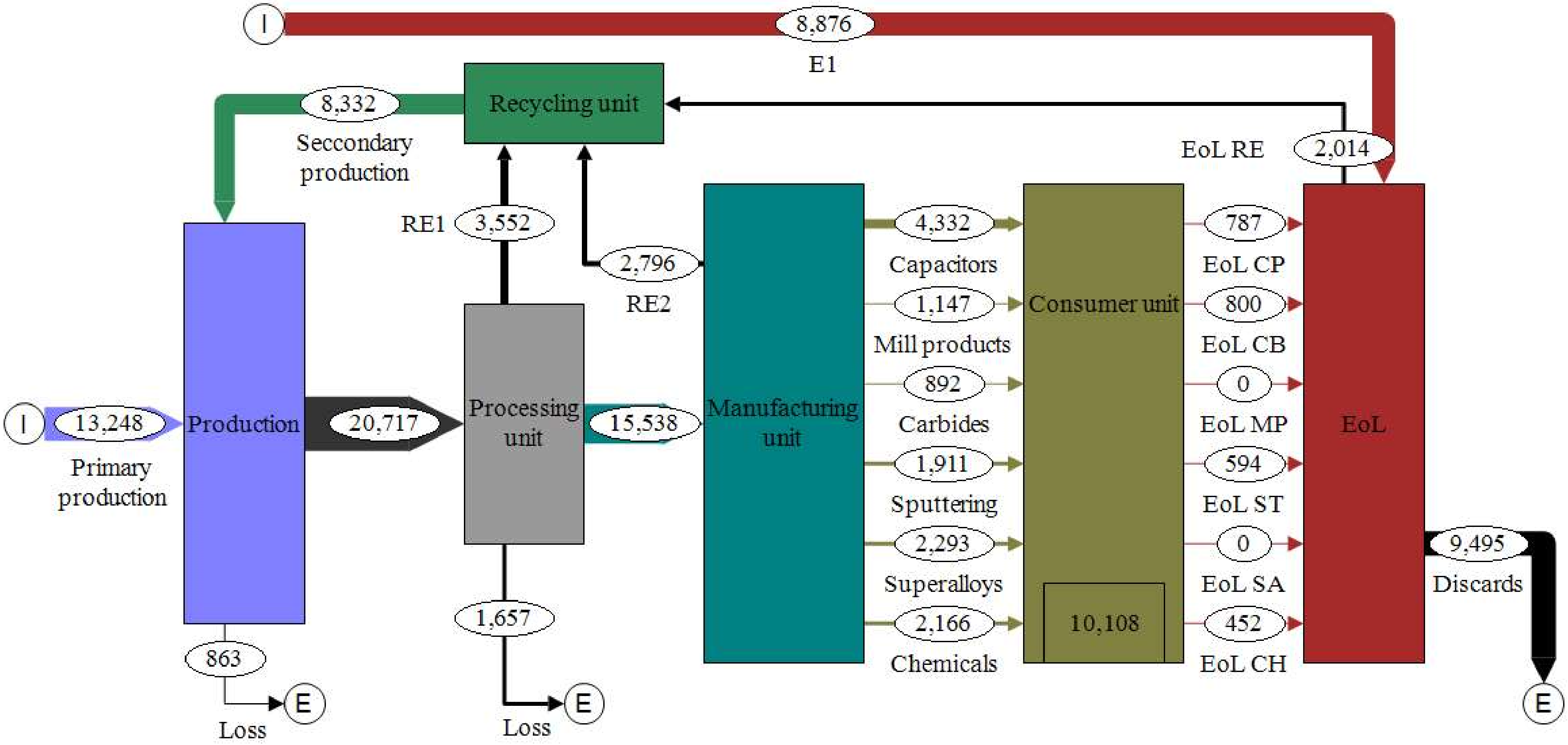

Figure 3.4 Global mass flow of tantalum for 2010-2019 (CP-Capacitor, CB-Carbides, SA-Super alloy, MP- Mill product, CH-Chemical, ST-Sputtering target, E1- waste flows from stock (CP, CB, MP, SA, CH, ST) before 2010, RE- recycling)

Figure 3.5 demonstrates year-wise data on waste flows for individual product categories. The products expiring during the modelled year (8,876t) from the stocks before 2010 were also accounted while calculating total EoL products. Out of total EoL product, the amount of tantalum being recycled was only 2,014t (i.e. less than 20% of the total EoL discards!) with the remaining (>80%) ending up in discards. A major portion of EoL product recycling is coming from mill products and the superalloy sector. However, the capacitor segment, with a huge recycling potential, is the greatest handicap with almost no recycling.

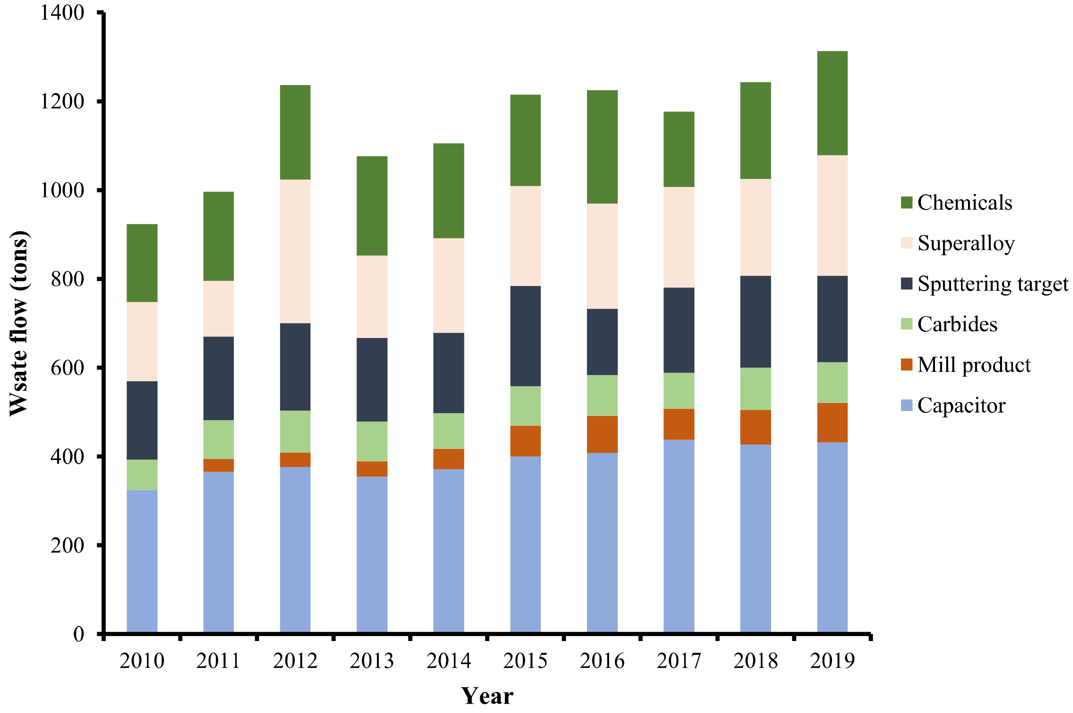

Figure 3.5 Worldwide tantalum waste generation for each product categories during 2010-2019

3.3.1 Sensitivity analysis

Due to unavailability of data for each year, it was assumed that relative distribution of tantalum into each product category is more or less same, which is not the case in real. Therefore, to get an estimate on effect of data variation on waste generation, sensitivity analysis was done for individual product category. From the data reported by Roskill for the year 2008, 2012, 2016, and projected data for 2026 (*Table 3.3*), minimum, mean, and maximum value was selected for each product category (Stratton, 2013b; TIC, 2018). The result of sensitivity analysis is presented in *Figure 3.6*. In all three cases, the amount of tantalum ending-up as waste is evident where capacitor segment accounting for largest waste generation in all three scenarios.

Table 3.3 Percentage distribution of tantalum into each product category for various years (Stratton, 2013; TIC, 2018)

	capacitor	**mill products**	**carbides**	**superalloys**	**chemicals**	**sputtering targets**
2008	47	8	11	17	6	11
2012	39	11	9	19	10	12
2016	34	9	7	18	17	15
2026	29	9	4	21	20	17

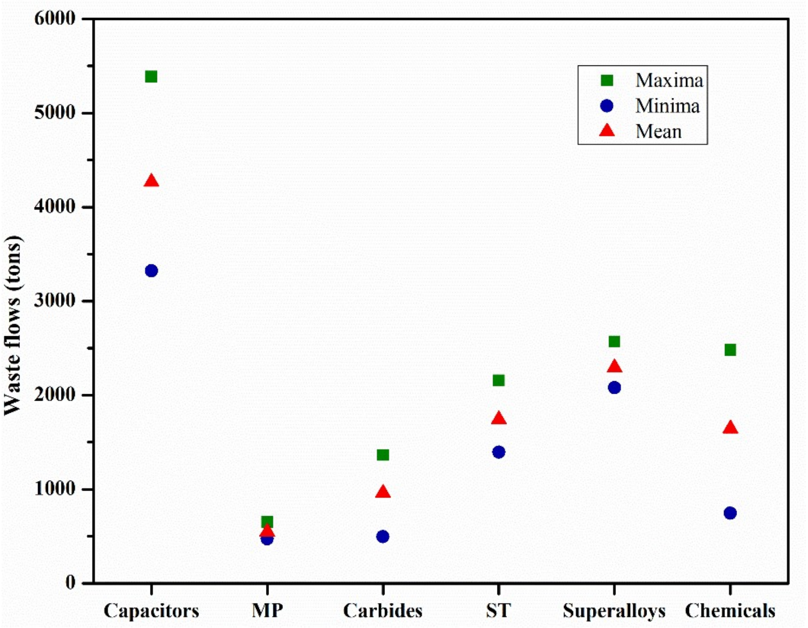

Figure 3.6 Effect of change of relative distribution of tantalum into each product category on waste generation during 2010-2019

From the above results, it can be concluded that tantalum is forming an open-loop life cycle with substantial material loss of high economic value which is described in the subsequent section.

3.4 Economic assessment of capacitor waste flow

The total economic value of waste generation from tantalum-containing e-waste (capacitor waste) was calculated using *Eq. (3.4)*. The capacitor segment, although accounts for the largest proportion of total tantalum consumption (34%), yet their contribution to EoL recycling was nil, which is why we have chosen capacitor waste for recycling point of view. To present the most feasible scenario, we considered that only 20% of tantalum from the electronic waste could be successfully collected and recycled. The annual report on mineral commodity summaries given by the U.S. Geological Survey for the year 2021 showed that the tantalum market price was 161 USD per kilogram of Ta_2O_5 in 2019. The total content of tantalum entering into the waste flow in the year 2010-2019 from the capacitor segment alone was calculated to be approximately 3190 tons which is equivalent to 3896 tons of Ta_2O_5. Based on this, the calculation was performed as follows:

$$Total\ economic\ value\ of\ waste = 3896 \times 1000 \times 0.20 \times 0.95 \times 161$$

$$\approx 120\ million\ USD$$

Thus, tantalum from e-waste alone and assuming only a 20% recycling rate, with a total value of 120 million USD, was discarded over 2010-2019. Since the recycling rate and recovery yield assumed here is not fixed in practical, that is why we have done sensitivity analysis to analyse the effect of variation of those factors on total economic value. The range for recycling ratio was varied from 5 to 50% whereas, the range for recovery yield was varied from 85 to 99%. In the most pessimistic (RR=5% and recovery yield=85%) and the optimistic scenarios (RR=50% and recovery yield=99%) studied, the economic value of the recycling from the capacitor segment ranged from 27 to 310 million USD.

Considering the scarcity of resources and risk involved in the supply of tantalum, this serves as a grave concern and at the same time, a great opportunity in the future to harness secondary means of production of a critical material like tantalum for a sustainable supply. Furthermore, the amount of tantalum lost in other product categories accounting for 64% of tantalum usage, and in other part of the supply chain, need to be considered to reach our final goal of maximum resource utilization with minimal dissipative loss along the life-cycle stages.

3.5 Identification of key causes for low recycling rate (RR) of tantalum

From the result of the MFA and the economic assessment of Ta-containing e-waste, it is clear that tantalum recycling has a huge economic potential. For any closed-loop life cycle, the amount of waste being generated along the supply chain is minimized as the material flow along the cycle is maximized. Promoting the close-loop life cycle ultimately aims to save the natural resource while keeping the environmental burden minimal. The reality is not that perfect for the tantalum life cycle. Currently, a considerable part of tantalum supply relies upon natural resources, i.e., conventional mining and artisanal or small-scale mining. Besides this, a significant amount of tantalum is lost along the life cycle. Plenty of pre-consumer scrap arising from the manufacturing of electronic components, superalloys, and tantalum carbides are presently being recycled owing to their high purity, reduced complexity, and ease in collection and processing of waste (Mancheri et al., 2018). Despite that, EoL stage recycling of tantalum is very less. The chemical characteristic of tantalum facilitates its oxidation during base metal recovery. Hence tantalum gets dissipated into the slag phase and ultimately ends up in landfilling or other construction work and evades recycling. Another cause for the low EoL recycling rate is the tiny concentration of tantalum (<0.01% in the WPCBs) with respect to other metals such as Cu (16%), Ni (2%), Ag (0.05%), Au (0.03%) (Ari, 2016) in consumer finished products which makes the tantalum recycling process economically unattractive.

Recycling aims to restrain the natural resources' consumption and bring down the environmental burden. Recycling is the strategy for closing the loop of the materials life cycle and satisfying the demand employing urban mining from EoL products. *Figure 3.7* shows the schematic diagram of existing open-loop life cycle and proposed close-loop life cycle of tantalum.

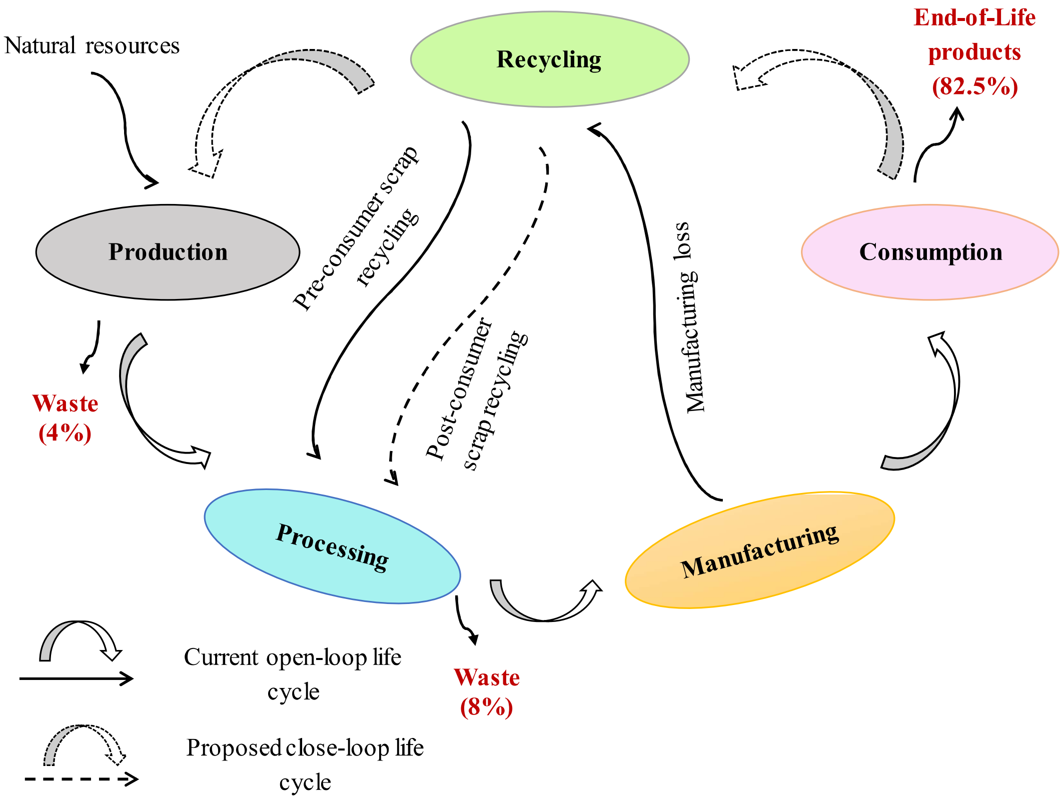

Figure 3.7 Current open-loop and proposed close-loop life-cycle of tantalum

The solid arrows in the figure represent existing open-loop life cycle, whereas, the dashed arrows represent the proposed route for closing the loop or maximizing the flow of tantalum along its life cycle stages. The dashed line from consumption unit is to make the flow of waste occurring in the reference stage to the recycling unit. Closing the loop and avoiding the loss of material in different life cycle stages will be a vital part considering the high economic value of tantalum. High recycling efficiency will greatly minimize dependency on primary resources (dominated by a few countries), which is of great importance from resource conservation standpoint.

3.6 Potential solution to improve recycling rate of tantalum

1. Recycling rate of any metal is the function of collection rates. Majority of EoL product does not reach to the recycling chain. The collection of EoL products containing tantalum is quite low. For instance, only 10% of total EoL mobile phones are currently being collected (Wansi et al., 2018). Results of the previous studies showed that a larger proportion of total EoL stock was stored by the user, mainly households and small and medium business sectors (Agamuthu et al., 2015; Gusukuma and Kahhat, 2018). Collection of these obsolete products has a higher activity due to its impact on downstream processes, i.e., recycling and environmental disposal. Several different approaches can be adopted to improve collection rate. Producers hold responsibility for financing e-waste collection and recycling. An effective take-back scheme should be implemented by extending supplier as well as consumer responsibility to promote collection of EoL waste stream from household and businesses to the supply unit. Moreover the usual habit of the consumers is to store the electronic gadgets in households even after it has become obsolete (Gurauskiene, 2011). For that, the consumers should develop awareness and consciousness about electronic waste recycling and actively participate in the environmental protection. From 2018, EU directive on Global E-waste Monitor revised the legislation by setting a target for the collection of 85% of total e-waste generation (Forti et al., 2020a). The implementation of these directives, however, should be strictly followed to build a critical mass flow of material towards the recycling.
2. From the recycler's point of view, a different approach could be adopted for the recycling of tantalum based products. Taking the example of tantalum in electronic

waste (because maximum proportion of tantalum is utilized in electronic sector), physical separation of tantalum capacitor from the WPCBs before treating it as a whole for the recovery of other base metals and precious metals could be an alternate economical way to recover the metal. By doing this loss of tantalum into the slag phase, while recovering the base metals, will be greatly minimized.

3. Besides this low collection rate, tantalum is often lost in other material flows. This loss is mainly due to tiny concentration of tantalum in comparison to other base and precious metals and lack of awareness and actionable information within the recovery framework regarding importance of critical high-tech metals present in e-waste (He et al., 2021) especially tantalum. The government should recognize strategic importance of tantalum present in e-waste. Furthermore, the government should make appropriate policies to spread awareness among people regarding the economic importance of critical metals and their dissipative losses. Also, the government should invest fund in research and development area so that the researcher may come up with a better cost-effective recycling strategies.

Regarding the existing circular economy approaches, there are various legally binding policies and legislation are enacted in different regions of the world. However, enforcement of those policies are the key issue. Various legislations are made to improve the collection rate such as e-waste collection in shops and municipalities by private operators, municipal drop-off, collection points, private pick-up, collection from repair and service centres in Belarus, various laws by Asian countries to drive formal recycling, etc. A large proportion of e-waste generated in Central Asia ends up in landfills or illegal dumping sites (Forti et al., 2020a). In Europe, the major portion of e-waste generated is regulated by the WEEE Directive (2012/19/EU) (Union, 2020) which set target for collection, recycling, reuse, and recovery. Besides this, various policies such as extended producer's responsibility, take-back scheme, setting of collection points and pick-up centres are functioning in different parts of the world (Forti et al., 2020a). Strict implementation of those policy throughout the world may help in achieve this circular economy goal.

3.7 Conclusions

This chapter mapped the global anthropogenic mass flow of tantalum for the last decade (2010-2019) through its five main life cycle stages from production to recycling and evaluated the economic value of discarded Ta-containing e-waste. The important points relevant to this chapter is given below:

- The calculation based on the average lifetime of the product showed that out of the total tantalum entering the EoL stage, only 17.5% was actually recycled with no recycling from capacitor waste. A large proportion of total tantalum entering into the EoL stage is being dissipated.
- The total economic value of waste by recycling just 20% of EoL capacitor turned out to be 120 million USD.
- Concentration and chemical nature of tantalum, low collection rate, unavailability or improper implementation of various rules and legislation related to e-waste collection and recycling are some of the key causes for low recycling rate of tantalum.
- A higher collection rate of the obsolete scrap by extending suppliers and consumers responsibility to mandate a take-back scheme, increased awareness among people and sensitization of the government and the companies involved towards the “criticality” of tantalum are needed for developing a close-loop life cycle for the metal.