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Trade linked global aluminium cycle

An overview of supply chain and expansion of model to differentiate beverage can cycle

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ABSTRACT

Globalization has provided huge opportunities for countries around the world to explore beyond their individual boundaries more than ever. Societies in many developing countries are leapfrogging and most importantly, it has changed the face of the earth and mind of the people. An empty land is no more of no use today, if one has a capacity or some kind of skill, business starts booming even on a barren land today. Nevertheless, as the two sides of a coin, it also has a fate of duality. Rich are becoming richer and the poor remain at the same place, resulting in skyrocketing inequality between the two. However, some try to manage well and struggle hard to get outside of the dark and start becoming a part of the new world. India and China are perhaps a suitable example for this case and the world is starting to get influenced by their progress.

A normal global aluminium cycle may draft some minor, rough and sketchy details of our globalized societies just characterizing flows and stocks with the help of tools like material flow analysis (MFA). However, the similar kind of analysis coupled with the idea of trade linkage among the societies, has given an enormous potential to cast more or less a clear picture of how the world is being influenced by globalization. Thanks to the team at the Norwegian Institute of Science and Technology(NTNU), (Liu & Müller, 2013c) who came up with the idea and published the first trade linked global aluminium cycle. The model has been gaining popularity in the field of industrial ecology and fields related to metal cycle studies and others. International Aluminium Institute (IAI) has already adopted the NTNU model into their global aluminium cycle studies.

The NTNU model has highlighted some remarkable connections between countries/regions around the world in the journey of anthropogenic aluminium cycle. For instance, Southern hemisphere supplies the primary resources to the Northern hemisphere, where the production and consumption of aluminium are concentrated which also possesses largest potential for recycling. Similarly, along the various lifecycle stages of aluminium, more developed countries tend to process stages after bauxite refining and entertains more consumption based cycles. Moreover, the model is believed to have a great potential to dissipate quality information regarding the global aluminium cycle, patterns and risks involved with supply chain security, value chain management and cross-boundary environmental impacts mitigation.

This master's thesis has remodelled the NTNU model with an updated database covering a temporal boundary from 1900 to 2014 and all countries of the world. The spatial boundary for the regional level

cycle has been borrowed from the IAI to compare the outputs with their model. Methods from the NTNU model was applied and the results was analysed using STAN to remove outlies due to conflicting data.

Similarly, two other subsidiary tasks have been undertaken along with the global aluminium cycle studies. First, average physical mass has been estimated to fill in the data gaps in terms of physical mass in kilograms in the trades reported for the product category SITC-1, 7321(passenger motor car other than buses). Based upon the availability of data, average mass for the product for the US has been calculated as 4.6 ton and that for the European market has been calculated as 1.045 ton.

Likewise, beverage can data for the Europe has been analysed for the period of 2008-2015. The can beverage market in Europe has been divided into beer and soft drinks category, which are packed in refillable and non-refillable glass and pet besides aluminium cans. On average 40% of packaging for beer falls under aluminium cans whereas 15% of packaging for soft drinks falls under aluminium cans.

Acknowledgement

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Sincerely,

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Contents

1 Introduction

Since the advent of industrialization, humans have been exploiting natural resources more than ever. Extracting oil, wood, minerals, ores and other materials from lithosphere, there has been a massive change in peoples' lifestyle and landscape around the world since then. With technological advancement, global population has also been increasing which is further adding pressure to the use of the resources. United Nations Environmental Programme (UNEP, 2011) states that 20th century brought a remarkable 'progress' for the human civilization. It highlights that annual extraction of construction materials grew by a factor of 34, ores and minerals by factor of 27, fossil fuels by a factor of 12, biomass by a factor of 3.6 and total material extraction by a factor of about 8 while GDP grew 23-fold (Figure 1-1.)

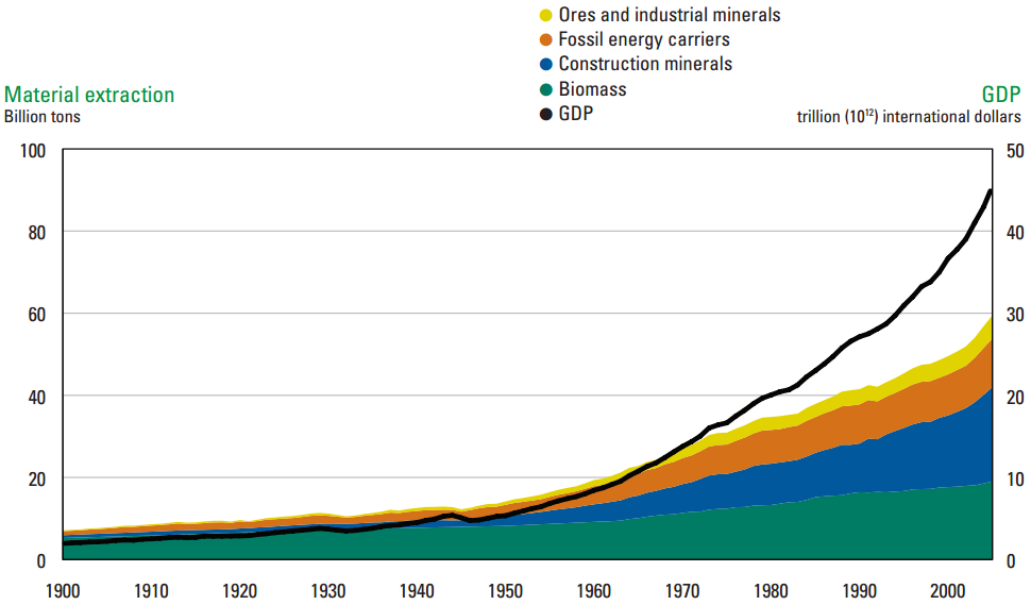


Figure 1-1Global material extraction in billion tons, 1900-2005

Source: Krausmann et al., 2009 (UNEP, 2011)

Introduction

Nevertheless, civilizations are paying a huge price to achieve the so called ‘progress’ by emitting greenhouse gases through various industrial activities like mining ores, producing various products, changing landscape, building infrastructures, generating wastes, etcetera and mostly burning fossil fuels. The future is even daunting as both population and industrial activities are increasing in the developing nations. Intergovernmental Panel on Climate Change (IPCC) states, warming of the climate system is unequivocal and many observations since 1950’s are unprecedented over decades to millennia (IPCC, 2014). It further concludes that the increment of anthropogenic greenhouse gas emissions is associated with industrial activities and are further considered extremely likely to cause the observed warming since the mid twentieth century.

The figure above also gives a general idea of historical production of metals as ores form the basis for producing metals. Figure 1-2(plotted on logarithmic scale) below, captures production of some 12 major metals that are highly used in the Anthropocene. All the metals’ production rate is rapidly increasing since 1900s except for mercury, which declined after 1970-1980s with issues of toxicity. One of the most notable factors in this figure is also the growth rate of production of aluminium that has crossed three-fold since 1900. The industrial production process of the metal was discovered in the late 1880s, which rapidly penetrated market with its phenomenal physical properties and its use has been growing ever since.

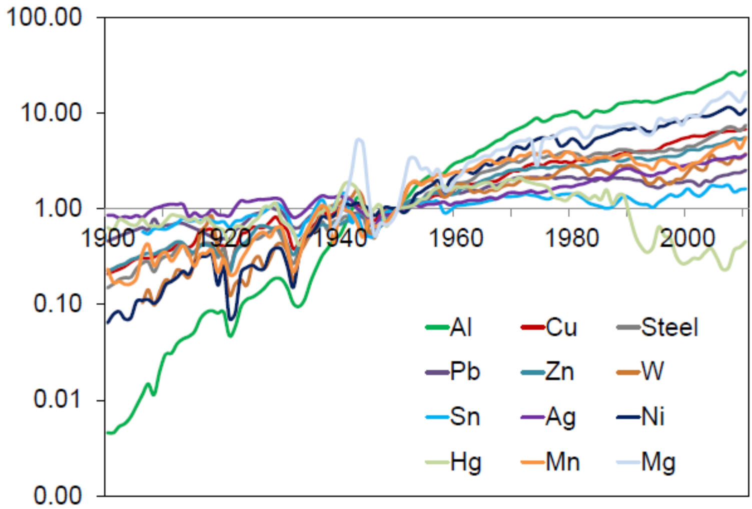


Figure 1-2 Global historical production of twelve major metals

Source :(Liu, 2013)

Aluminium is second most used metal after iron (Liu & Müller, 2013a) and has an increasing demand in global market. It is a versatile element with wide range of applications in numerous sectors like building and construction, transportation, packaging, mechanical / electrical engineering and many others. It is strong and weighs just 2.7 g/cm^3 (1/3rd of weight of steel). Aluminium sheets/foils is impermeable and considered very suitable for food/ beverage packaging. It is also good conductor of heat and electricity, great reflector, easily formable, and has so many other useful properties including infinite possibility of recycling. United States Geological Survey (USGS, 2010) has estimated an increment of global aluminium consumption in 2025 by a factor of over 2.5 compared to that of 2006 level (45.3 Mega Ton). And by 2050 it is expected to increase by three times (IEA, 2009). It has been estimated that, almost 75% of aluminium ever produced(1 billion since 1886) is still in use (Marlen Bertram, Martchek, & Rombach, 2009). Similarly, due to its popularity, it has been noted that the historical growth has prominently shifted aluminium stocks from natural reservoir to the built environment where it would last for a significant period (Liu & Müller, 2013a).

However, with the growing demand of the metal in this era of globalization, with flooding policies on transition to a low-carbon economy and a non-toxic environment, there arise numerous questions and concerns regarding the use of the metal in future. For example; resource depletion, greenhouse gas emissions, cross-boundary environmental impacts like carbon leakage, raw material criticality and supply chain disruption , etcetera (Erdmann & Graedel, 2011; Liu, Bangs, & Müller, 2011; Liu & Müller, 2013c). Moreover, while associating its entailing greenhouse gas emissions with 2^0C target (limiting atmospheric temperature as per UNFCCC COP agreements); there is not enough rooms for reducing the emissions through only technological advancements ; for instance after a reduction of 86% of perfluorocarbon emissions (PFC) over past twenty years (IAI, 2010; Liu et al., 2011). As such reducing emissions from primary production might have a high level of uncertainty (USDOE, 2007) especially, at the hour of meeting growing demand. Secondary aluminium production requires about 95% less energy than primary production, but as there is currently limited scrap availability due to growing in-use stocks, the challenge of meeting the 2^0C target through secondary production is also tougher (Liu et al., 2011).

As such, in depth knowledge of global aluminium cycle could highlight rooms for improvements in the system, which could pave pathways for making policies in line with global interest of reducing environmental impacts and meeting the 2^0C target. In this context, it is equally important to highlight available approaches with transparency that could illuminate linkage of supply chain in the global aluminium industry along with the global cycle. This particular idea is also a focal point of an ongoing project called ‘MinFuture’, organized by Ecologic Institute EU (funded by European Commission) collaborating with numerous bodies and Norwegian Institute of Science and Technology (NTNU) is one of them. This Master’s Thesis is also aimed to contribute a little to the project through findings from the research on global aluminium cycle and supply chain analysis.

Adjoining Table1 lists, available studies (A-N) related to aluminium cycle (some also highlight greenhouse gas emissions from aluminium industries) following mainly two principles - Life Cycle Analysis (LCA) and Material/Substance Flow Analysis (MFA/SFA). LCA based studies (A-E) focus mainly on primary production where D-E concentrates on light-weighting use of aluminium on vehicles. As per the previous studies conducted at the NTNU (Liu et al., 2011), these studies (A-E), do not consider aggregate effects, interaction within the whole cycle and time dimension, so they cannot form a basis for absolute emission reduction on a sectoral or a regional context. However, the gaps can be filled by applying MFA/SFA method. F-G follow MFA/SFA approach but they only cover a single or specific years.

Dynamic modelling that was introduced in 1970s using historical consumption data and product lifetimes (Bever, 1976), is further refined in studies H-I and for the US in J-K. However, the models F-K lack environmental aspects and only focus on stocks and flows. Study L on the other hand carries environmental dimension, and provide a basis for further development of the model to cater policy makers for future environmental impacts mitigation programs. Finally, studies M-N provide a global MFA model that covers future aluminium flows along with emissions. However, they lack in-use stocks, which is a significant entity to define emission reduction potential from recycling since the in-use stocks are directly related to scrap availability. NTNU then developed its own model (Liu et al., 2011) which addresses the dynamic anthropogenic aluminium cycle that allows to analyse material flows and resulting energy use and greenhouse gas emissions for the US for a period of 1900-2008.

Table 1 Previous studies related to global cycle and GHG emission undertaken by

Index	Title of Study	Method	Source	Emiss.Reduc. App.	Temp./Geogr.
A	Environmental Profile Report for European Al Industry	LCA	(EAA, 2008, 2013)	+	1900-2007/US
B	Not All Primary Aluminium Is Created Equal: Life Cycle Greenhouse Gas Emissions from 1990-2005	LCA	(McMillan,et al.,2009)	+	90-2005/Global
C	Greenhouse Emissions in Primary Aluminium Smelter Cast Houses-A Life Cycle Analysis	LCA	(Koltun et al., 2009)	+	-
D	Greenhouse Gas Emissions Payback for Light-weighted Vehicles Using Aluminium and High-Strength Steel	LCA	(Kim, et al., 2010)	+	-
E	Analysis of greenhouse gas emissions related to aluminium transport applications	LCA	(Bertram, et al., 2009)	+	-
F	Aluminium Recycling in the United States in 2000	MFA	(USGS, 2006)	-	2000/US
G	Substance flow analysis of aluminium in mainland China for 2001, 2004 and 2007: Exploring its initial sources, eventual sinks and the pathways linking them	MFA	(Chen, , et al., 2010)	-	2001,2004, 207/China
H	Statistical analysis of metal scrap generation: the case of aluminium in Germany	MFA	(Melo, 1999)	-	1985-1995 /Germany
I	Iron, steel and aluminium in the UK: material flows and their economic dimensions	MFA	(K. Dahlström,et al.,2004)	-	2001 / UK
J	Assessment of the recycling potential of aluminium in Japan, the United States, Europe and China	MFA	(Hatayama, et al., 2009)	-	2000-2050/Japn,Chin EU and the US
K	Quantifying U.S. aluminium in-use stocks and their relationship with economic output	MFA	(McMillan, et al., 2010)	-	1900-2007/US
L	Aluminium Stock and Flows in U.S. Passenger Vehicles and Implications for Energy Use	MFA	(Cheah, et al., 2009)	+	1975-2035/US
M	Future carbon dioxide emissions in the global material flow of primary aluminium	MFA	(Schwarz, , et al., 2001)	+	1995-2010/Global
N	Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050	MFA	(M Allwood et al,2010)	+	2050/Global

The model calculates flows using industry and governmental statistical data, calculated transfer coefficients and derivation by mass balance principle. Besides, it also uses historic trade data for some 110 aluminium-containing products and adjusts statistical shipment data of the product categories going to manufacturing by assumed yield ratios. Energy use and GHG emissions corresponding to the US aluminium cycle are calculated using coefficients based on output of various process excluding some processes like manufacture and use.

Besides models integrated with dimensions of emission, very few models have been developed that could analyse the supply chain and trade links on a country or a regional level. As globalization, has elevated international trade, trade linked global metal cycle could provide powerful information regarding global concern of materials depletion, supply chain disruption and others as stated earlier. Models like ‘WellMet2050’, a project in University of Cambridge mapped global metal flow for aluminium (Cullen & Allwood, 2013) but it neither breaks down into country level resolution nor includes stocks information. (Rauch, 2009) includes a complete country coverage of in-use stocks for aluminium and few other metals. However, the study only covers the year 2000 and draws data from linear regression of GDP and nighttime satellite imagery data thus tend to have higher uncertainty. ‘STAF’ project at Yale University has developed ‘multilevel cycles’ of metals like copper (Graedel et al., 2004), zinc (Graedel et al., 2005), silver (Johnson et al., 2005) and others but the trades of the analysed systems are considered on an aggregated level and the results of the global metal cycles are presented on a ‘best estimate’ basis.

NTNU then published the first trade linked global aluminium cycle (Liu & Müller, 2013c) following a dynamic MFA approach on a country level. It covers over 290 countries/regions and 126 different aluminium-containing commodities, reported in the

UN Comtrade (pseudonym for United Nations International Trade Statistics Database) The study has been gaining popularity in the field of global metal cycle research. World Aluminium, International Aluminium Institute (IAI) has already adopted the NTNU model for their study on global aluminium cycle. NTNU also collaborated with IAI sharing annual updates on regional level trade data and the trade linked regional level global aluminium cycle from 2014-2016. The model traces journey of aluminium highlighting production of raw materials in Southern hemisphere to production and consumption of final products and potential for recycling in the Northern hemisphere. The model believes to deliver potential insights for policy makers in resource criticality, supply chain security, value chain management and cross-boundary environmental impact mitigation (Liu & Müller, 2013b)..

The NTNU model extracts trade data from the UN Comtrade. The database has mainly three inconsistencies mainly as follows. First, missing physical mass expressed in units of kilograms, second, missing number of items. Third, imbalanced bilateral trades that occur due to trade valuations (imports > exports in terms of monetary units of $), and the way some country report their trade to the UN Comtrade (for example, hiding some partner countries and reporting total aggregated trade instead) Figure 1-3 below shows the basic pattern of trade flows reported in the UN Comtrade. The NTNU model only adjusts Case 3 and Case 4 and neglects the unit given in number of items. The two cases are adjusted by calculating world average price ($/kg) where world average price is the unit price for a commodity ($/kg) for a same period all around the world. So, the missing mass is calculated by the following expression;

$$\text{Missing mass} = \$\,(value\ of\ the\ missing\ mass) \div \frac{\$}{kg} \quad 1.1$$

	$	Kg	#
Case 1	+	+	+
Case 2	+	+	-
Case 3	+	-	+
Case 4	+	-	-

Figure 1-3 Trend of Reported Trade Flows in the UN Comtrade

The goal of this master's thesis is to understand patterns of linkage among countries in the world economy along the journey of aluminium cycle. Understanding the sources, pathways and destinations of the anthropogenic aluminium cycle on a country level, it is also aimed to look into regional level. Besides, NTNU model is a precious tool, which should be preserved, fine-tuned and expanded along with the passage of time. Thus, this master's thesis has also been envisaged in line with this concept to review and refine the original system. Two minor errors related to adjusting missing mass and compiling set of commodities will be resolved. Expansion of the original system would be focused on beverage cans. Used Beverage Cans could be remelted and sent back into the production system in just about 60 days cycle after they enter the market. Thus, it holds a great potential of scraps supply as normally other aluminium products stay in the use phase for a longer period. Overall, this master's thesis is aimed to revive the NTNU model by reviewing, refining, expanding the original system to differentiate beverage can from the system and analyse supply chain in the global aluminium cycle for the year 2014.

2 Methodology

This section illustrates the system definition for the trade linked global aluminium cycle based on previously developed models at the NTNU (Liu et al., 2011; Liu, Bangs, & Müller, 2013; Liu & Müller, 2013b, 2013c). It covers methodology in detail and presents all the data, sources and tools that have been used to quantify historical aluminium stocks and flows, modelling, data reconciliation and visualization.

2.1 System Definition of the global anthropogenic aluminium cycle

2.1.1 Life Cycle of Aluminium

In simple terms, the life cycle of aluminium can be described as a pathway of aluminium from the point of its production, which goes into use and later discarded after certain period. Some portion of the discarded aluminium is then delivered to landfills or incineration plants as wastes; some are recycled into production of secondary aluminium while some are reused in different ways. However, the global cycle in reality is much more complex than it seems. Moreover, globalization has woven it through a complex fabric of trade and information technology that has a great potential to transform relationships among countries in our world and alter the pathways of global aluminium cycle.

A more detailed technical description of the global aluminium cycle can be found in Figure 2-1 while the major processes are briefly explained below;

- ***Mining and Refining***

  The source for primary aluminium production is mainly the bauxite ore. It primarily occurs in tropical and sub-tropical regions like Africa, South America, Australia, and etcetera. The basic mining process includes preparation of site, digging, crushing, and transportation of the crushed bauxite and rehabilitation of the mined site. Around 15 % of world bauxite mined are used for chemical, abrasive and refractory products like aluminium flakes and powders, artificial corundums etcetera (USGS, 1932). Thus, these leave the metallurgical aluminium cycle.

Refining of the bauxite to produce alumina is followed by Bayer's process which normally consists of four process; Digestions, clarification, precipitation and calcination. The main idea is to obtain aluminium oxide (Al_2O_3), i.e. alumina from aluminium hydroxide compounds in bauxite.

- ***Primary and Secondary Production of Aluminium***

In general, aluminium industries include primary and secondary aluminium production facilities. Primary aluminium production follows the Hall-Héroult electrolytic process that transforms alumina into molten aluminium. The molten aluminium is then alloyed, cleaned and cast into different kinds of ingots (billets, T-bars, slabs, etcetera). It requires approximately 37 GJ of thermal energy and 58 GJ of electricity per ton of sawn aluminium ingots (EAA, 2013). As such, the production of primary aluminium is highly energy intensive especially in the form of electricity consumption.

Recycling of the aluminium on the other hand can reduce energy intensity by over 90% compared to primary production (Liu et al., 2011). As per (EAA, 2013), the production route however, is very diverse and fragmented compared to primary aluminium production. The report adds that aluminium-recycling industries includes remelters and recyclers treating new scraps and old scraps respectively. New scraps contain almost pure aluminium that come from production and fabrication of various products. Remelters then process these new scraps to produce aluminium (alloy) ingots. Old scraps are collected once aluminium products are discarded after use and aluminium concentration in these scraps are often lower than new scraps, which require additional effort to remove impurities. Recyclers (also termed as refiners) then process these old scraps to produce foundry ingots. These foundry ingots are generally based on aluminium-silicon alloy with addition of some other metals like copper and magnesium. These foundry ingots are used to produce aluminium castings based upon certain national, international or aerospace specifications (EAA, 2013).

- ***Semi-Manufacturing and Manufacturing Process:***

The ingots produced from primary or secondary production undergo fabrication process where they are mainly rolled, extruded or casted and transformed into various semi products like sheets, foil etcetera, which are commonly termed as semis products. These semis products are then further processed to manufacture different kinds of final products like parts of bodies of a car, doors or window frames, cans etcetera.

- ***Use***

As discussed earlier, aluminium has wide verities of application in buildings and construction, transportation, mechanical and electrical engineering, consumer durables, packaging and others. Its remarkable physical properties like strength, durability and longer lifetime, make it exist into the techno sphere for a long period. As such, there is a great potential of accumulation of aluminium in the built environment as in-use stocks and future availability of scraps. (Liu & Müller, 2013a). It has already been estimated that, almost 75% of aluminium ever produced (1 billion since 1886) is still in use (Marlen Bertram et al., 2009).

- ***Waste Management and Recycling***

New scraps generated from various production and fabrication processes are usually of known quality and composition, and so has the potential of extensive recycling efficiency (Liu, 2013). While the old scrap recycling depends on the collection rate and available processing technologies for processing different categories (Reck & Graedel, 2012). Those scraps which arrive closer to the final product stage during manufacturing, becomes more complex to be identified for sorting while a big fraction of semi-manufacturing scraps are easily recycled internally (Liu, 2013).

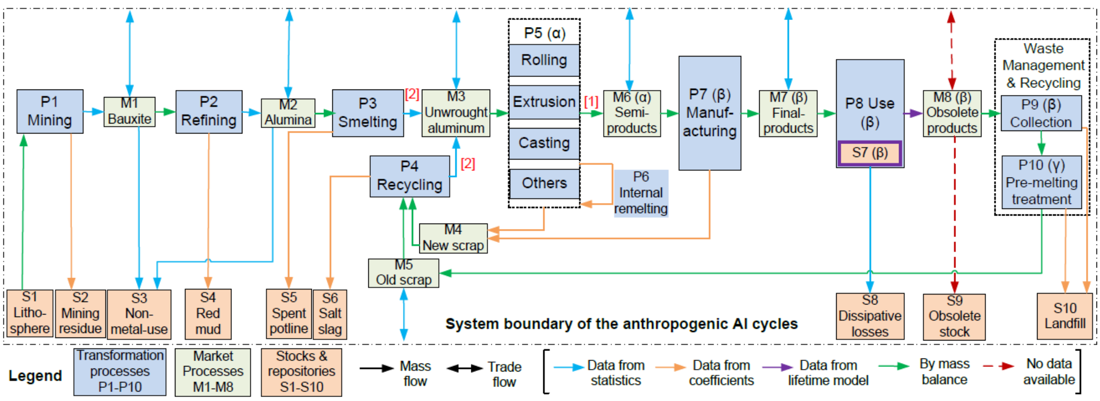


Figure 2-1 System Definition of the Anthropogenic Aluminium Cycle

Source: (Liu & Müller, 2013b)

The system definition presented above in Figure 2-1 has been continued from the previous studies at the NTNU(Liu & Müller, 2013b) and kept intact. It consists of color-coded processes, flows and stocks to highlight groups of entities that differ from one another. Blue boxes represent transformation processes where a material is processed once it moves from one process to another. Given the notation as P, there are 10 transformation processes in the system. These processes balance inputs and outputs of industrial facilities. Similarly, market processes (8 green boxes) balance domestic and foreign inputs and outputs in physical masses, which are connected by domestic, flows (one direction arrows) and trade flows (two-direction arrows). Three types of flows have been defined as domestic flows, trade flows and loss flows in order to characterize the international trade flows and their links with domestic flows. This was proposed by (Dahlström, Ekins, He, Davis, & Clift, 2004) and (Müller, T. Wang, B. Duval, & T. E. Graedel, 2006) and implemented by (Liu & Müller, 2013b). Loss flows (orange arrows) are linked to various environmental repositories (orange boxes) such as lithosphere, mining residue etcetera.

Similarly, the system definition comprises of following four groups of stocks; Group (i) – Ore stocks in the Lithosphere: S1. Although in theory it contains all aluminium ores e.g. cryolite, alunite etcetera but as per the commercial practice, since past century, only bauxite has been considered as the main ore stock for this repository. Group (ii) Stocks in the environmental repositories: S2, S4, S5, S6, S10. These include both deposited loses which are either landfilled or deposited in residue/slag ponds. This group also contains S3 and S8, which are dissipative, loses that are either destroyed from its metallic form or depleted into the environment. Group (iii) in-use stocks: S7. These are the existing aluminium materials/components in the built environment that are providing services to the citizens. Group (iv) Obsolete or hibernating stocks: S9.

These are such materials which are not in functional use but have not entered the waste stream either (Müller et al. 2006; Liu et al. 2011; Krook et al. 2011; Chen and Shi, 2012, as stated in Liu, 2013). Also besides these four groups of long term stocks, there may exist other short term in commercial stocks in industry, market or government inventories (Liu, 2013).

Similarly, semi-manufacturing processes and products (α, P5 and M6), manufacturing processes and products (β, P7, P8, P9, M7, and M8), and the pre-treatment of postconsumer scrap (γ, P10) are further disaggregated in the model. The values for α and β differ slightly in various studies undertaken at NTNU related to global aluminium cycle. For this master thesis, the values are considered as; α = 4 i.e. the four semis prodcuts(rolling, extrusion, casting and others) and β = 7 i.e. end use products category which are building and construction (B&C), transportation (Trans), containers and packaging(C&P), machinery and equipment (M&E), electrical engineering (EE), consumer durables (CD) and others (Others).

2.1.2 Temporal and Geographical Boundary

The temporal boundary for this study has been considered from 1900 to 2014. While the geographical boundary consists of all countries in the world, regional definition applied in this study (Figure 2-2) is however different from the original model (Liu & Müller, 2013b) and follows the one applied by International Aluminium Institute (IAI) in their global aluminium cycle studies (M. Bertram et al., 2017). .

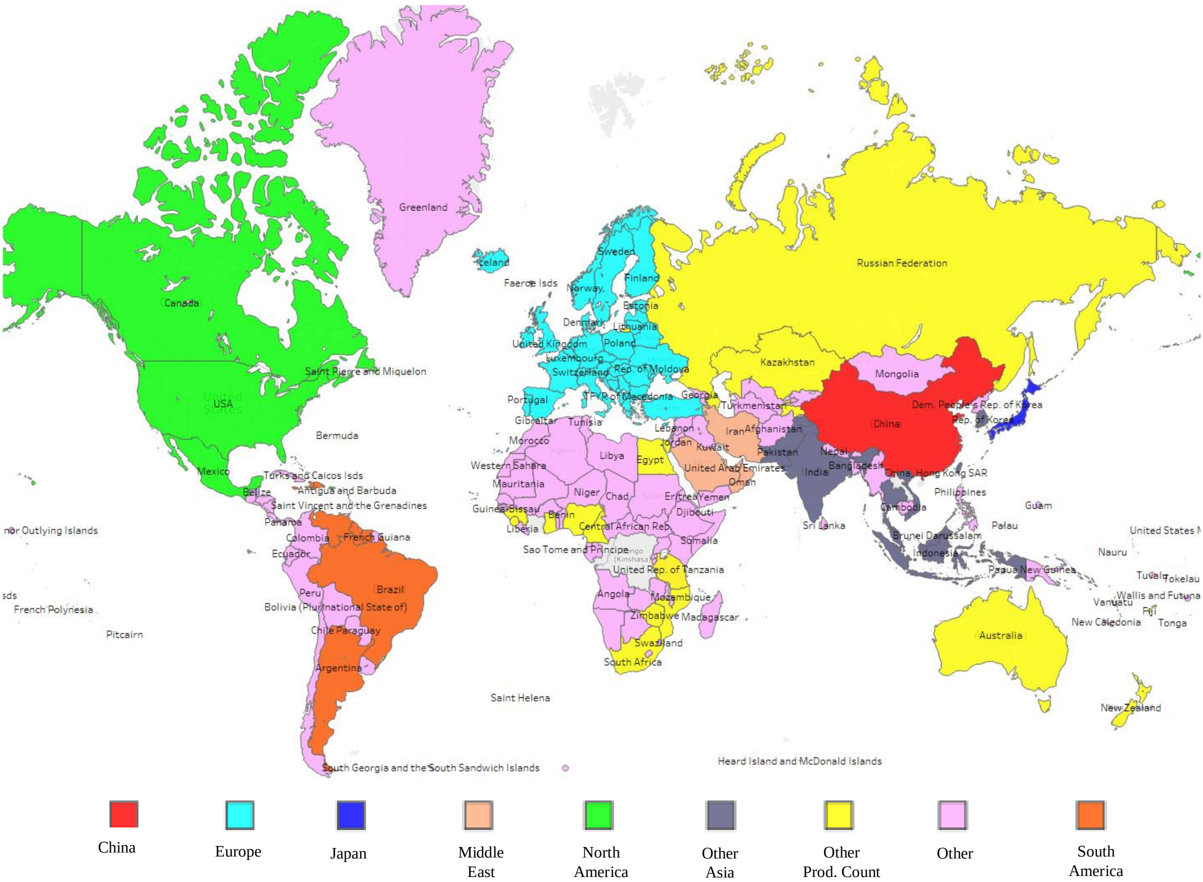


Figure 2-2 Regional Definition Applied in the model as per IAI

2.2 Dynamic stocks and flows models of the aluminium cycle

2.2.1 Generic stocks and flows accounting methods

Methods applied to calculate generic stocks and flows in this study is based upon the model built by (Liu & Müller, 2013b). The basic 4 methods applied for calculating the generic stocks and flows are as follows;

- ***Quantified using industry and government statistics***

All of the production, trade data and domestic shipment data were taken from national, regional or international statistical organizations. Details are given in Table 3

- ***Calculated using estimates of transfer coefficients***

All of the transfer coefficients, yield losses along the life cycle for example, fabrication loss, forming loss, recycling loss etcetera have been borrowed from (Liu & Müller, 2013b) which were estimated from various literature and industry experts.

- ***Simulated using a production driven top-down model:***

Following the previous model, the estimation of in-use stocks and flows leaving use were calculated similarly by using the historical aluminium apparent consumption in different product categories and a lifetime model.

- ***Derived from the mass balance principle:***

Almost all the transformation and market processes comply with mass balance principle. The calculated apparent consumption of products also matches with the sum of production and yield losses from adjoining transformation process. Moreover, the calculated data for selected countries like Japan, China and the US for 2014, have been validated comparing with data available from the global aluminium cycle model prepared by IAI (IAI, 2016). However due to difference in some parameters especially mean lifetime, data from the two model differ slightly.

The mathematical details for the calculation of generic stocks and flows using a simple generic MFA diagram is shown below;

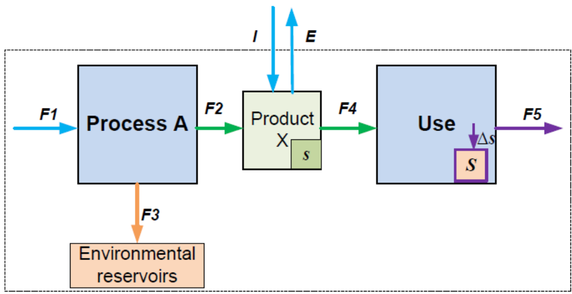


Figure 2-3 A simple generic MFA diagram to calculate stocks and flows Source(Liu, 2013)

All stocks and flows were calculated in aluminium metallic equivalent for each year by multiplying the flow of goods in physical mass ($M_{totalmass}$) with their specific aluminium contents($C_{Al\%}$):

$$Al_{equivalent} = M_{totalmass} \times C_{Al\%} \quad (2.1)$$

If k is the transfer coefficient of flow F3to flow F1, then for Process A;

$$F1 = F2 \times F3 \quad (2.2)$$

$$F3 = k \times F1 \quad (2.3)$$

Now for the market process of product X, I and E are the imports and exports of the product from other sources (countries/regions). If $\Delta stock$ is the stock change from previous year to the current year, the apparent consumption of the product (F4) is then given by the following expression;

$$F4 = F2 + \mathrm{I} - \mathrm{E} \pm \Delta\mathrm{stock} \qquad (2.4)$$

As per (Müller et al., 2006, as stated in liu,2013), the production driven top-down approach estimates the stocks in use and outflows from the use phase given by the inflows and its lifetime. Whereas bottom-up approach uses statistics of quantities of products in use which has to be multiplied by its aluminium concentration to get the overall result, thus (Liu & Müller, 2013b) chose the historic consumption data to get the historic change of stock through top-down approach. This study has adopted similar method to calculate the historic change of stock, stocks in use and the outflows. So, if the lifetime distribution of the product is *L(t,t')*, the outflow (F5) of end of life products can be calculated by the equation

$$F5_t = \int_{t0}^{t} L(t,t') \times F4(t')dt' \qquad (2.5)$$

Similarly, the adding the stock change from t_0 to t would give the total in-use stock at time t. It can be expressed as follows;

$$\Delta S_t = \int_{t0}^{t} (F4 - F5)\,\mathrm{dt} \qquad (2.6)$$

The models uses normal distribution to calculate the lifetime distribution of the products with average lifetime τ and standard deviation σ. So, when the product enters the use phase at time t and leaves after end of life at time t', then with known average lifetime(τ) and standard deviation (σ), the lifetime distribution of product categories can be calculate as follows;

$$L(t,t') = \frac{1}{\sigma \times \sqrt{2\pi}} \times \frac{t-t'-\tau}{e^{2\sigma^2}} \qquad (2.7)$$

2.2.2 Calculation of historical stocks and flows

As discussed earlier, the model uses production driven top-down approach to calculate the historical stocks and flows. The equations $F5_t = \int_{t0}^{t} L(t,t') \times F4(t')dt'$ (2.5) and $\Delta S_t = \int_{t0}^{t} (F4 - F5)\,\mathrm{dt}$ (2.6) gives the mathematical expression for the calculations. The model takes domestic shipment (DS) data of semis-products wherever it is known and uses method [1] in Figure 2-1, to calculate the flows into use, as shown in Table 2. Whereas for the cases when DS is not known, method [2] in Figure 2-1is followed to calculate the flows into use, as shown in Table 2

The domestic shipment data available for some 19 countries are shown in Table 4. This model has used full data set for the countries highlighted in orange in Table 4, whereas the latest historical domestic shipment data has been continued until 2014 for rest of the countries in the table.

Table 2 Method to calculate flows into use (Liu & Müller, 2013c)

No.	If DS is reported	Countries	Method to determine X_{M7-P8}
[1]	Yes	Argentina, Australia, Austria, Belgium, Brazil, China, France, Germany, India, Italy, Japan, Netherlands, Norway, Russia, South Africa, Spain, Switzerland, U.K., U.S.	$X_{M7-P8} = DS + X_{0-M6} - X_{P7-M4} + X_{0-M7} - X_{M7-0}$
[2]	No	All other countries	We first calculate apparent consumption of unwrought aluminium: $X_{M3-P5} = X_{P3-M3} + X_{P4-M3} + X_{0-M3} - X_{M3-0}$ Then flows into use are determined as: $X_{M7-P8} = X_{M3-P5} - X_{P5-M4} + X_{0-M6} - X_{M6-0} - X_{P7-M4} + X_{0-M7} - X_{M7-0}$

Methodology

The overall data volume of this model is also considerable. It contains over 21 million trade data points for 124 aluminium containing commodities i.e. bauxite, alumininа, unwrought Aluminium, semis and final products. It also included over 50,000 production, consumption and coefficient data points. Data for production of bauxite, alumina, primary aluminium and available secondary aluminium are summarized in Table 3. Also, revised data and sources for secondary aluminium is shown in Table 5.

Table 3 Data and sources for bauxite, alumina and aluminium

Item	Data used in the model	Data Sources
Bauxite Reserves	1995-2011	(USGS 1996-2011)
	2012 - 2014	(USGS Mineral Year Book, 2012-2014, Bauxite & Alumina)
	1900-1994	(Lyew-Allee 1997)
Bauxite Productioin	1946-2010	(USGS 1932-2011)
	2011-2014	(USGS Mineral Year Book, 2011-2014, Bauxite & Alumina)
	1913-1945 and U.S. data after 1989	(BGS various years)
Alumina Production	1968-2010	(USGS 1932-2011)
	2011-2014	(USGS Mineral Year Book, 2011-2014, Bauxite & Alumina)
Primary Aluminium Production	1890-1900 for Switzerland, France, US, and UK	(Metallgesellschaft 1889-2007)
	1890-1913	(Mitchell 2007)
	1913-1930	(BGS various years)
	1931-2010	(USGS 1932-2011)
	2011-2014	(USGS Mineral Year Book, 2011-2014,Aluminium)
Secondary Aluminium Production	1954-2006	(Metallgesellschaft 1889-2007)
	1997-2007 for major European countries	(EAA 2011)
	1913-2008 for U.S.	(USGS 1932-2011)
	1941-1993 for Japan	(Mitchell 2007)
	1954-2008 for Germany	(Metallgesellschaft 1889-2007)
	1962-2007 for Australia	(ABARE 2010)
	1956-1995 for China	(CNIA 2008)
	1992-2007 for Russia	(Burstein and Grishaev 2003)

Table 4 Domestic end use shipment data for 19 countries

S.No.	Countries	Domestic end-use shimpent	Source
1	Argentina	1996-2014	(CAIAMA 2002-2011)
2	Australia	1981-2009 (2), 1957-1980 (7,8)	(2)(GARC 2011), (8) (Govett & Larsen 1981) (7) (CommonWealth of Australia 1960)
3	Austria	1962-1997 (1)	(1) (Metallgesellschaft 1889-2007)
4	Belgium	1962-1997 (1)	"
5	Brazil	1950-2009 (2) & 2010-2014(3)	(2) (GARC 2011); (3) (IAI,2016)
6	China	1950-2009 (2) & 2010-2014(3)	"
7	France	1962-1997 (1)	(Metallgesellschaft 1889-2007)
8	Germany	1954-2006 (1)	"
9	India	1950-2009 (2) & 2010-2014(3)	(2) (GARC 2011); (3) (IAI,2016)
10	Italy	1962-1994 (1)	(Metallgesellschaft 1889-2007)
11	Japan	1950-2009 (2) & 2010-2014(3)	(2) (GARC 2011); (3) (IAI,2016)
12	Netherlands	1962-1970 & 1982-1997 (1)	(Metallgesellschaft 1889-2007)
13	Norway	1978-1998 (1)	"
14	Russia	1950-1990 (2) & 2010-2014(3)	(2) (GARC 2011); (3) (IAI,2016)
15	South Africa	1950-2009 (2) & 2010-2014(3)	"
16	Spain	1969-1997 (1)	(Metallgesellschaft 1889-2007)
17	Switzerland	1962-1997 (1)	"
18	U.K.	1962-1997 (1)	"
19	U.S.	1950-2009 (2, 9*) & 2010-2014(4)	(GARC 2011); (4) USGS MYB 2014 Al.

Table 5 Revised data for secondary aluminium production

Countries	Data used in the moded	Data Sources
Argentina	2003-2010	(USGS Mineral Year Book, 2003-2010, Aluminium)
Australia	2003-2013	(USGS Mineral Year Book, 2003-2013, Aluminium)
Austria	1999-2013	(USGS Mineral Year Book, 1999-2013, Aluminium)
Brazil	1999-2013	(USGS Mineral Year Book, 1999-2013, Aluminium)
Canada	1998-2014.	(USGS Mineral Year Book, 1998-2014, Aluminium)
China	1996-2014	NTNU Database
Taiwan	1900-2014	NTNU Database
Denmark	1996-2013	(USGS Mineral Year Book, 1996-2013, Aluminium)
Finland	1999-2013	(USGS Mineral Year Book, 1999-2013, Aluminium)
France	2007-2013	(USGS Mineral Year Book, 2007-2013, Aluminium)
Germany	2007-2013	(USGS Mineral Year Book, 2007-2013, Aluminium)
Greece	2008-2014	NTNU Database
Italy	2008-2013	(USGS Mineral Year Book, 2008-2013, Aluminium)
Japan	2010-2014	(USGS Mineral Year Book, 2010-2013, Aluminium)
Netherlands	2005-2006.	(USGS Mineral Year Book, 2005-2006, Aluminium)
Norway	2008-2013	(USGS Mineral Year Book, 2008-2013, Aluminium)
Poland	2006-2013	(USGS Mineral Year Book, 2006-2013, Aluminium)
Portugal	2000-2011	(USGS Mineral Year Book, 2000-2011, Aluminium)
Romania	2000-2011	(USGS Mineral Year Book, 2000-2011, Aluminium)
Czechoslovakia (former)	1999-2013	(USGS Mineral Year Book, 1999-2013, Aluminium)
Spain	1998-2010	(USGS Mineral Year Book, 1998-2010, Aluminium)
Sweden	2003-2013	(USGS Mineral Year Book, 2003-2013, Aluminium)
Switzerland	1999-2013.	(USGS Mineral Year Book, 1999-2013, Aluminium)
United Kingdom	2008-2013	(USGS Mineral Year Book, 2008-2013, Aluminium)
United States	2009-2014	(USGS Mineral Year Book, 2008-2014, Aluminium)

While methods for calculating lifetime, distribution has already been discussed in section 2.2.1, the standard deviation is set as 30% of the mean values for all the product categories.

Table 6 Mean value (τ) of lifetime for product category for regional level cycle

Product Categories (α)	EU	NA	SA	CN	OA	ME	OP	ROW	JP
Bldg & Const	50	75	50	40	50	50	40	50	40
Transportation	13	20	15	15	15	15	10	15	10
Packaging	1	1	1	1	1	1	1	1	1
Machinery & Equipment	15	30	20	20	20	20	20	20	20
Electrical Engineering	20	20	20	20	20	20	20	20	20
Consumer Durables	8	12	12	12	12	12	10	12	10
Other	10	10	10	10	10	10	10	10	10

Table 6 summarizes the mean value assumption (τ) for the regional level cycle. The standard deviation is kept intact as 30% of the mean value for all the product categories. All of the mean value of lifetime has been borrowed from (Liu & Müller, 2013b) where the ones highlighted in orange i. e. Data for regions OA(Other Asia), ME(Middle East) and ROW(Rest of the World) have been considered from the region 'Rest of the world' in previous model (Liu & Müller, 2013b). Data for JP(Japan) and OP (Other Producing Countries) have been taken from the region 'Developed Asia & Ocenia' from the previous model whereas data for EU(Europe), NA(North America) and China have been kept intact.

2.2.3 Uncertainty and sensitivity analysis

Primary production data and semis shipment data (for the US) for the anthropogenic aluminium cycles are freely available from various sources like USGS (USGS, 2017), BGS (BGS, 2017) etcetera. Besides, sources like World Bureau of Metal Statistics

(WBMS, 2017) and The Aluminium Association (The Aluminum Association, 2017) etcetera, have more data available in terms of secondary production data and semis shipments data. However, they are not freely available. Previous models barely had some data gaps and conducted a full fledge uncertainty and sensitivity analysis (Liu & Müller, 2013b, 2013c). This model however has conducted uncertainty calculations/analysis for the regional level cycle using software called STAN (STAN, 2017) (subSTance flow Analysis) .

2.3 Reconciliation of trade data and trade network analysis

All the trade data for the 124 product categories have been extracted from the UN Comtrade. These trade data are reported in monetary values (current US $), physical mass in kilograms and physical quantities in Number of items. However, 10% of the data has gaps in terms of missing mass in kilograms. Each flow from one country A to another country B can be reported twice and in theory, these mirror flows should match. But in reality, they hardly do, so there is inconsistency in the data reported in the UN Comtrade. Besides there is inconsistency regarding the trade valuation as majority of the imports are considered as CIF (Cost Insurance Freight) and exports are considered as FOB (Free on Board). Therefore, the monetary value in dollar for the imports is greater than that for the exports.

The model has not considered the inconsistency regarding the trade valuation, but has resolved the physical data gaps (missing mass in kilograms) with an algorithm as shown in Figure 2-4 The algorithm to identify and resolve physical trade data gaps and bilateral trade data inconsistencies in the UN Comtrade data (Paulik, et.al; 2012 as stated in Liu & Müller, 2013c, 2013b); The following steps have been performed to resolve the data gaps :

First, outliers are identified and removed when the ratio of a certain value in question relative to its neighbour is larger than a factor of 10 (i.e. when the value in question is smaller than 1 Mega ton) or 3(i.e. when the vale in question is bigger than 1 Mega ton)

Second, the physical data gaps are filled by converting monetary values into physical values through the approximation of "world average price" when physical values are not available, similar as done in (Dittrich and Bringezu 2010).

Then, the physical trade data of each product category are multiplied by their respective aluminium concentrations, which were derived from an intensive literature review, and finally aggregate them into different product categories.

The previous model used mean value of the physical mass in the bilateral trade. But in this model the exported values (both monetary value in $ and physical mass in kilograms) were dominated by the import values with an assumption that the importers are more conscious while reporting their import trade data and they are not serious while reporting their export trade data.

Moreover, for the regional level cycle, the trade data of the countries within a same region has been cancelled to calculate the actual trade of regions among one another. For example, trade between the UK and Germany has been cancelled since the trade is inside Europe.

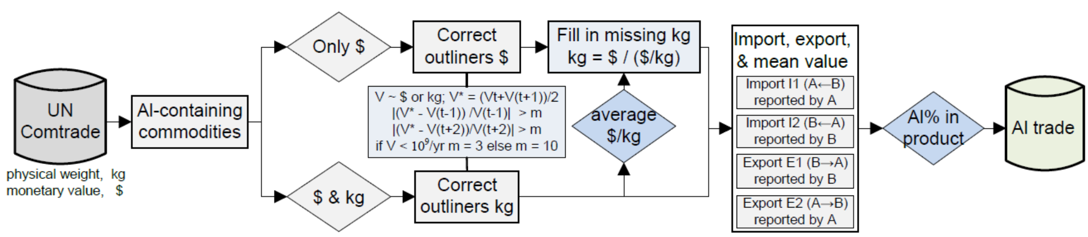


Figure 2-4 The algorithm to identify and resolve physical trade data gaps and bilateral trade data inconsistencies in the UN Comtrade data

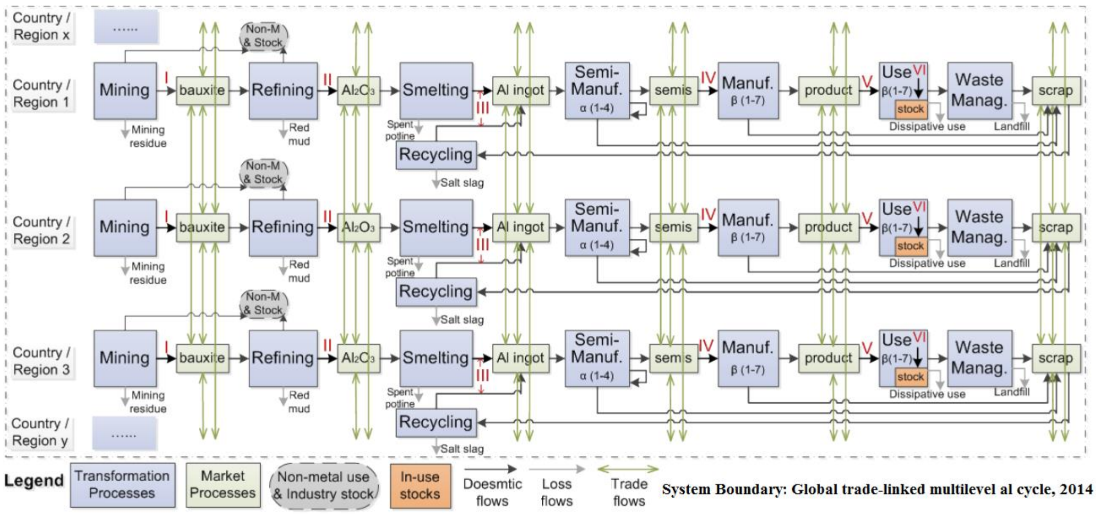


Figure 2-5 System definition for the trade linked multilevel global Al. cycle

Source: (Liu & Müller, 2013c)

While the system definition in Figure 2-5 resembles the system definition in Figure 2-1, the latter has been simplified and countries/regions are stacked and connected in levels to highlight the trade link between countries/regions more clearly.

2.4 Method to fill in data gaps in terms of missing mass from reported number of items in UN COMTRADE

This study has also been devoted in finding another option to fill in data gaps in terms of missing mass in kilograms in the UN Comtrade data. The trade data for the 124 products from 1962 to 2014 has been analysed and prepared a set of top 20 products ranked on the basis of total traded quantity (and mass in kilograms). One of commodity was selected (SITC-1 7231) and through literature review an average value has been estimated which could be utilized in filling in the data gaps for the product.

2.5 Expansion of the anthropogenic aluminium cycle to differentiate beverage can

A system definition has been proposed upon literature review as the attempt of meeting with certain company representative or industrial expert was unsuccessful. The study only covers the US and Europe due to availability of data.

3 Results and Interpretation

3.1 Simulation result for the World Model

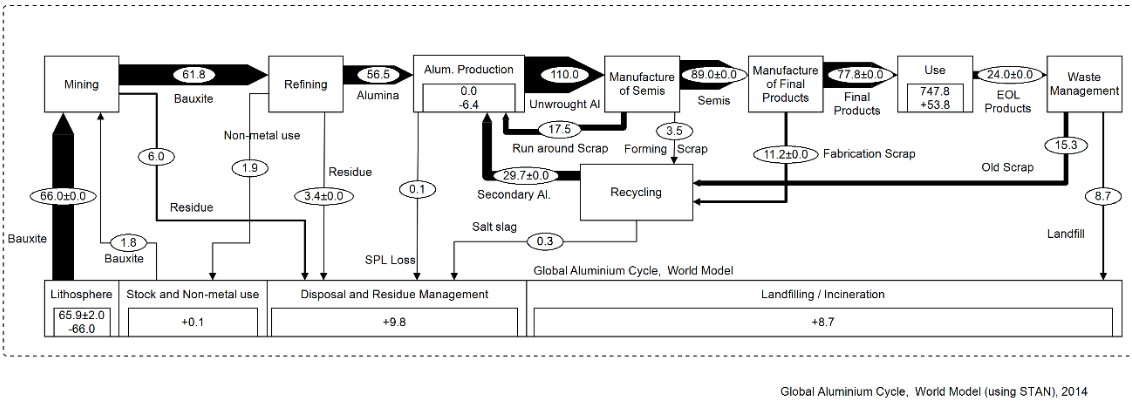


Figure 3-1 Results from the World Model for the year 2014 in (Mega Ton)

Figure 3-1 shows the results (for 2014) from the dynamic MFA modelling simulated for global aluminium cycle from 1900 to 2014 on both country and regional level. There was around 30 Mt of recycled aluminium, 11 Mt of unwrought aluminium production, 89Mt of semis, 78 Mt of final products, and 9 Mt landfilled globally. The global aluminium stock is calculated as 0.81Gt or 111 kg/capita in 2014(adding the previous year stock and stock change). This result has been obtained following an uncertainty calculation with the help of STAN and has a confidence level of 68%.

IAI calculated the global aluminium stock in 2014 as 0.94 Gt which was recently published in their paper (M. Bertram et al., 2017). There is a difference of almost a magnitude between the two results. It has been noticed that mean lifetime assumption adopted in the two models are quite different from one another. As lifetime distribution is one of the vital parameters that has a great potential to affect the outflow, stock and the stock change and thereby other following flows for instance the oldscrap flows and the landfill flows. Table 7 shows the difference between the mean lifetime assumptions for the end-use aluminium products. The overall mean lifetimes adopted by this model is very low especially in the Transportation and electrical engineering products. However, transportation lifetimes were combined from three into one (Auto truck, Aerospace and Truck, bus etcetera) and electrical engineering from two to one (cable and others) while drawing set of this data.

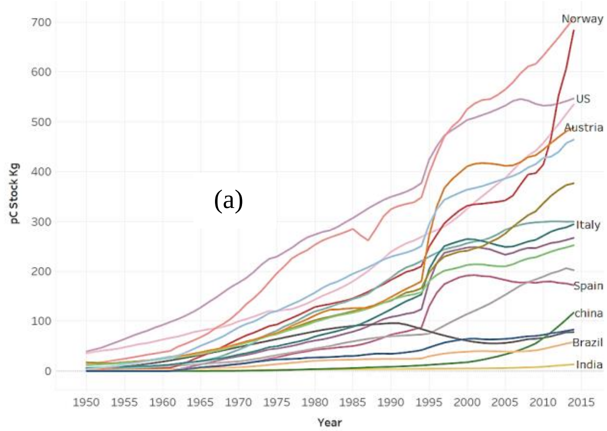
Table 7 Difference between mean lifetimes for the end use products (IAI - This Model)

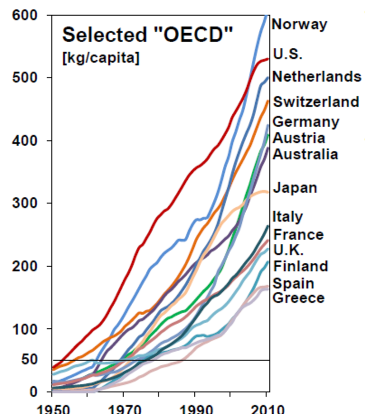
Product Categories (α)	EU	NA	SA	CN	OA	ME	OP	ROW	JP
Bldg & Const	10	-15	0	-5	0	0	10	0	20
Transportation	72	65	85	80	85	67	90	85	72
Packaging	0	0	0	0	0	0	0	0	0
Machinery & Equipment	25	10	20	20	20	20	20	20	20
Electrical Engineering	40	50	40	40	40	40	40	40	40
Consumer Durables	0	-4	3	-2	3	-4	5	3	-2
Other	10	10	10	10	10	10	10	10	10

Comparing other flows with the results from IAI model for 2014, there is a metal loss of 2 MT more in the IAI model from aluminium production, both model calculates equal amount of unwrought al production/consumption. The model estimates 9Mt of semis more than the IAI model. The reason could possibly be that, the semis domestic end shipment data for US are taken from the USGS mineral yearbook for various years and it could possibly contain the shipment data for Canada as well. End of life products and outflows to landfill are calculated more in this model compared to the IAI model, and the lower mean lifetime assumption of this model could justify this.

3.2 Simulation results for the Historical in-use stock calculation

Figure 3-2 shows the historical in-use stock for selected countries. The results from this model has been compared with that from the previous model(b) (Liu & Müller, 2013b). The model(a) is more or less calculating similar results. In both the figures, industrialized countries were slowly growing their stocks and started increasing around 80s-90s. China Brazil, India were pretty low however, China is taking peak (passed 100kg pc) and Netherlands (reaching 700kg pc) is skyrocketing (the red curve below Norway) along with Norway (passed 700 kg pc). Countries lie Germany, Us, Australia, Japan etcetera are slowly stabilizing.





(b) (Liu & Müller, 2013b).

Figure 3-2 Historical in-use stock calculation

3.3 Simulation results from the trade-linked multilevel global Al cycle

	Product	1.China	2.US	3.India	4.Japan	5.Germany	6.Russian Federation	7.Brazil	8.Indonesia	9.UK	10.France	11.Italy	12.Mexico	13.Turkey	14.South Korea	15.Saudi Arabia	16.Spain	17.Canada	18.Iran	19.Thailand	20.Australia
I	Bauxite	15.5	0.0	4.0	0.0	0.0	2.3	8.3	0.7	0.0	0.0	0.0	0.0	0.2	0.0	0.5	0.0	0.0	0.2	0.0	17.3
II	Alumina	24.8	2.3	2.6	0.1	0.7	2.9	5.5	0.1	0.0	0.3	0.0	0.0	0.1	0.0	0.1	0.7	0.8	0.4	0.0	10.6
III	Primary Al	28.2	1.7	2.3	0.0	0.5	3.7	1.0	0.2	0.0	0.4	0.1	0.0	0.1	0.0	0.7	0.2	2.8	0.4	0.0	1.7
IV	Semis	35.4	11.3	2.9	3.6	4.9	0.6	1.6	0.9	1.3	1.4	1.8	1.8	0.3	0.9	0.8	0.9	0.6	0.3	0.9	0.4
V	Into Use	29.8	9.1	2.4	2.9	3.9	0.4	1.3	0.7	1.0	1.1	1.5	1.4	0.2	0.7	0.6	0.7	0.5	0.2	0.8	0.4
VI	EOL	3.8	6.9	0.6	1.9	1.6	1.1	0.7	0.2	1.1	0.8	0.6	1.0	0.2	0.4	0.2	0.7	0.6	0.1	0.2	0.5
VII	∆Stock	0.1	0.5	0.0	0.3	0.4	0.1	0.1	0.0	0.3	0.3	0.3	0.3	0.0	0.2	0.2	0.2	0.5	0.0	0.1	0.5

Figure 3-3 Table Heat map showing various phases of aluminium cycle for top 20 countries as per GDP PPP in 2016 (International dollars) - Units in Mega Ton

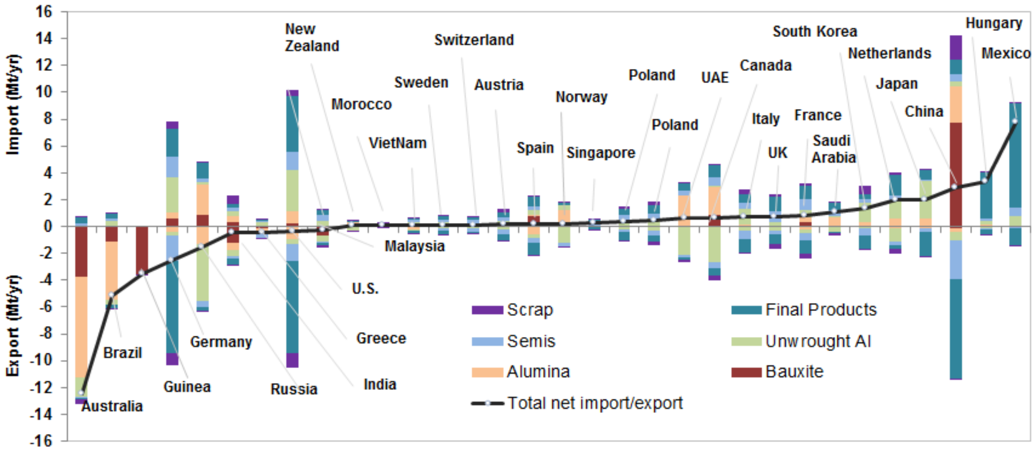


Figure 3-4 Net import and export of selected countires in, 2014

Source of graphics : (Liu & Müller, 2013c)

From Figure 3-3 and Figure 3-4, it can be inferred that China is the biggest producer of alumina, aluminium, semis and final products. It also produces some bauxite and imports huge amount of bauxite to hold its growing economy in the sector. US seems to be following China but it highly depends upon other countries for bauxite and semis. Australia on the other hand is a huge exporter of bauxite and alumina thus has a great potential of affecting the upstream market. Similarly, Brazil and Guinea also possess some potential in the upstream international market. India is coming in to the scene in the exporting of bauxite. Russia and Canada are exporting unwrought aluminium. In Figure 3-4, it can also be seen that countries above the central neutral line are all net importers while below the line are net exporters.

Results and Interpretation

The simulation results show that the global anthropogenic aluminium cycle is highly controlled by bilateral trades. Raw materials, ingots, semis, final products and scraps are traded from country to country by transforming into various forms all along the anthropogenic cycle. While looking at the biggest trade in terms of mass of aluminium above 500 kilo ton, the US is exporting over 5000 kilo tons of final products to Mexico, Germany is exporting over 3000 kilo tons of final products to Hungary. Australia is exporting around 3500 kilo tons of bauxite to China. Alumina of this scale is flowing from Australia to China, Saudi Arabia and UAE. Similarly, there is also the flow of unwrought Al above 500kilo tons for e.g from Russia to japan, Turkey, from Canada to the US. However, there is very little flow of scrap and semis of this scale. Just over 500 kilo tons of scrap is moving from the US TO China. And just over 600 kilo tons of semis is flowing from US to Mexico.

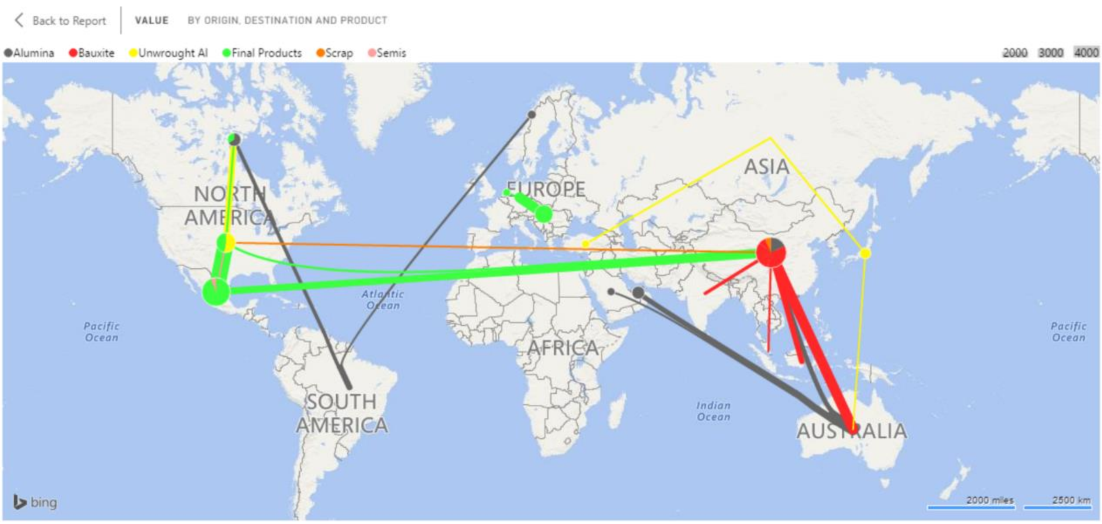


Figure 3-5 Global trade link of aluminium containing products above 500 kilo tons

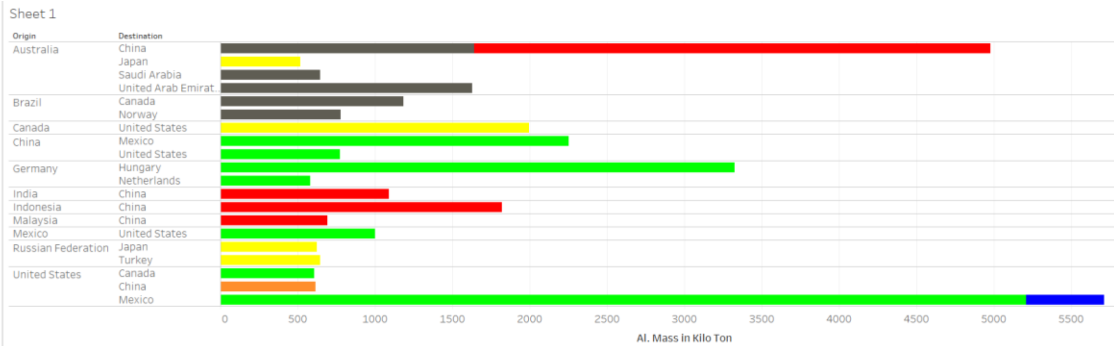


Figure 3-7 Graph showing the data for Figure 3-5

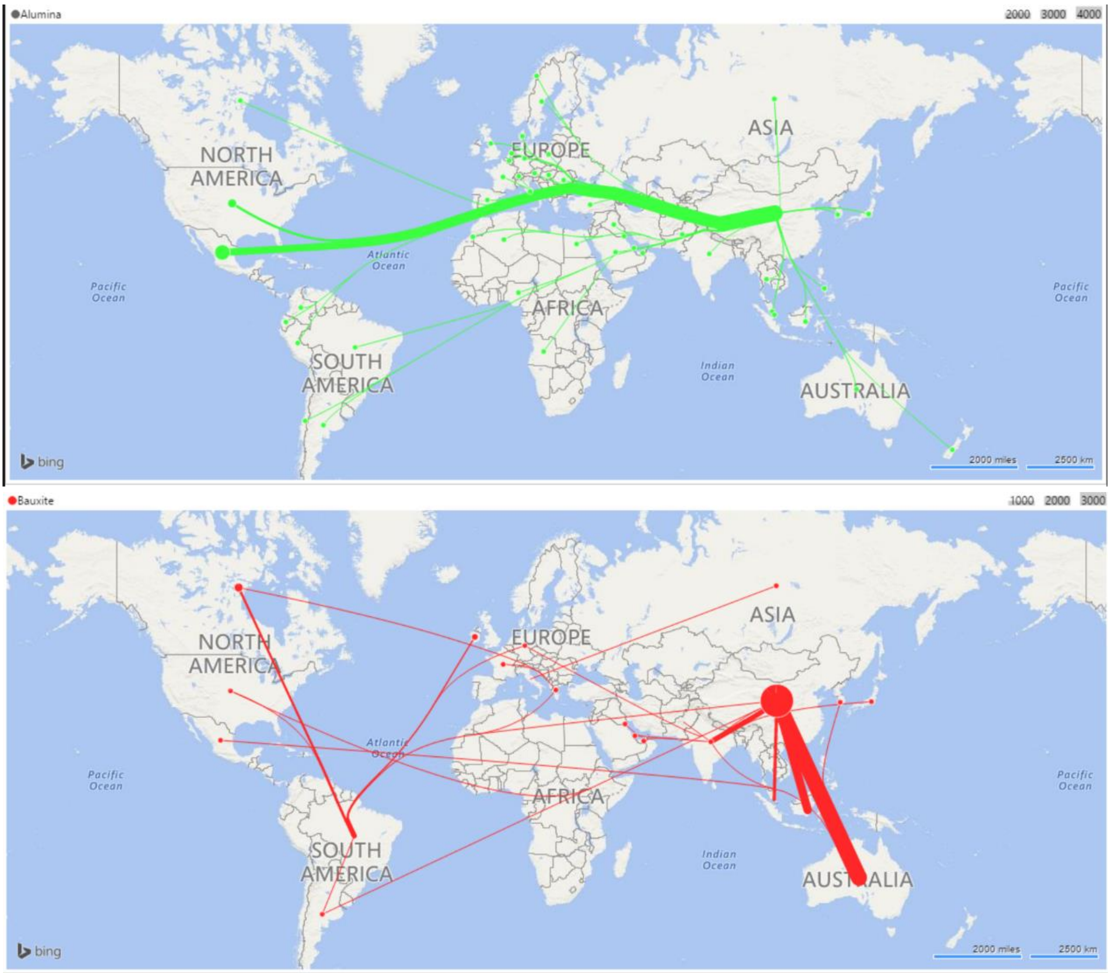


Figure 3-6 Bauxite (red) >10 kilo ton and Alumina (green) > 100 kilo ton

3.4 Regional level cycle

The regional level global aluminium cycle was simulated for the nine regions for 2014 as shown in Figure 2-2. Europe is importing bauxite and unwrought aluminium i.e. it is following a production and consumption based economy as its net exports of final products is negligible. As per the Figure 3-8 below Europe is producing around 7 kilo ton secondary aluminium which is almost double than that calculated by the IAI model (M. Bertram et al., 2017). This model is producing almost double the mass of end of life products than that by the IAI model, which must be caused by the lifetime distribution assumption, as discussed earlier in section 3.1 and Table 7. North America, Japan and Other region is also following, Europe's pattern i.e. production and consumption based cycle. The aluminium cycle for South America lies in the upstream process where it is producing bauxite and exporting alumina whereas its own production and consumption of aluminium is very low. The presence of China is from the bauxite production and follows a full-fledged cycle exporting some final products. Middle East is processing alumina and exporting unwrought aluminium and Other Producing countries is producing bauxite and exporting bauxite and alumina.

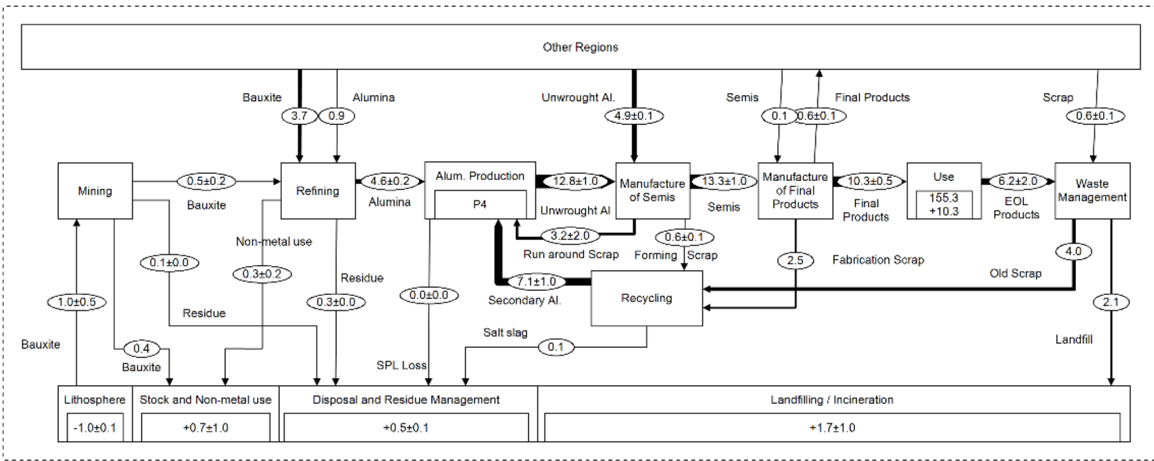
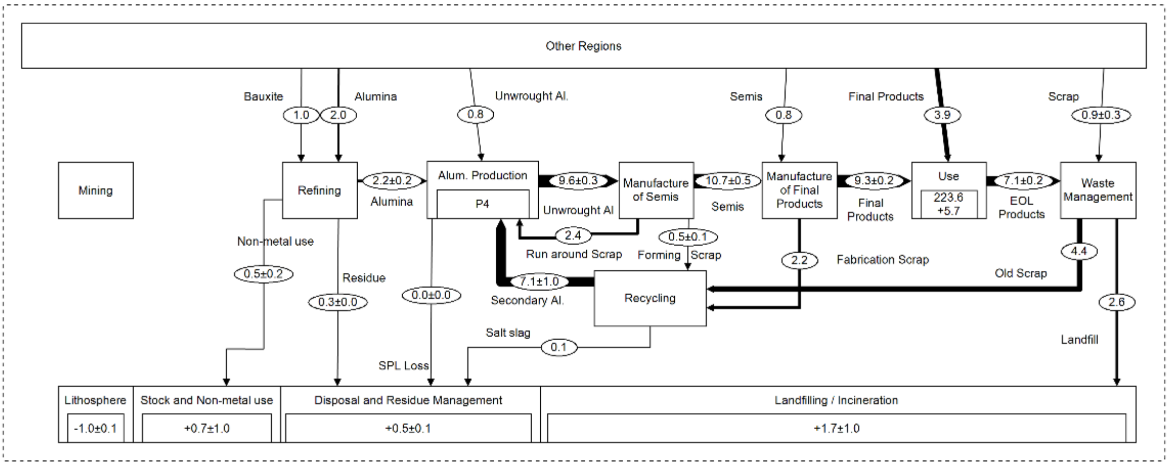


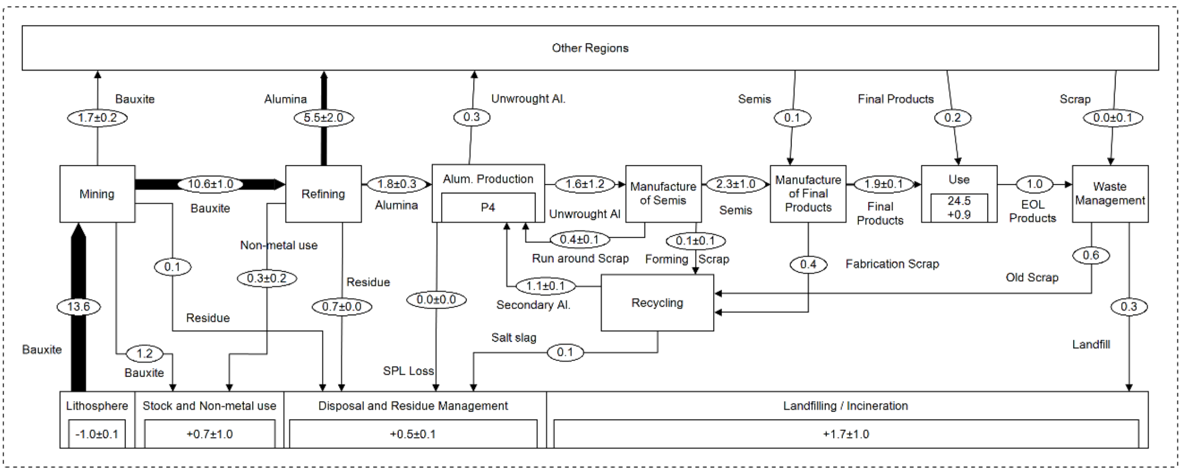
Figure 3-8 Global Al cycle Europe, 2014

Global cycle Figures for all the other regions are presented below;



Global Aluminium Cycle, North America (using STAN), 2014

Figure 3-10 Global Al cycle North America, 2014



Global Aluminium Cycle, South America (using STAN), 2014

Figure 3-9 Global Al cycle South America, 2014

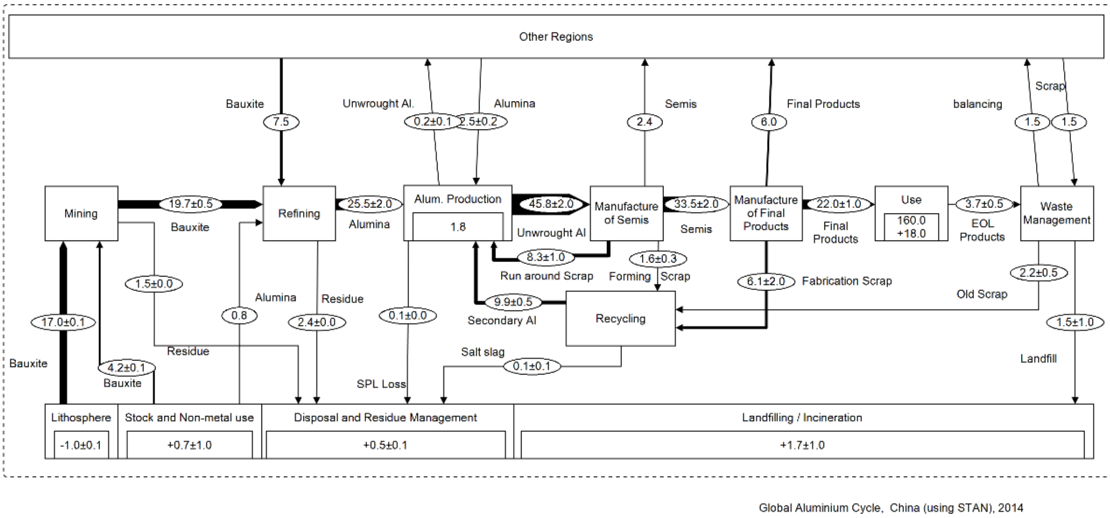


Figure 3-12 Global Al cycle China, 2014

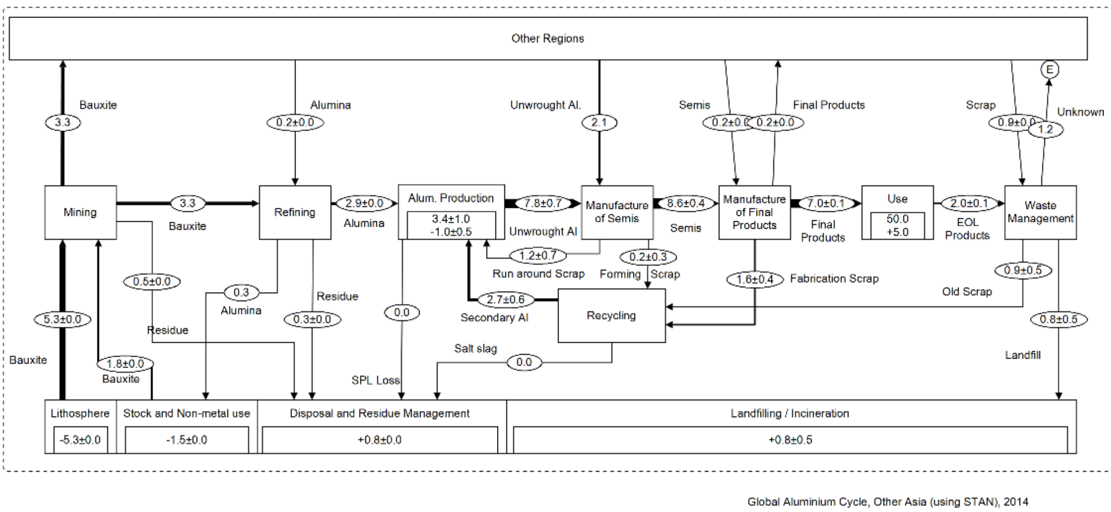


Figure 3-11 Global Al cycle for Other Asia, 2014

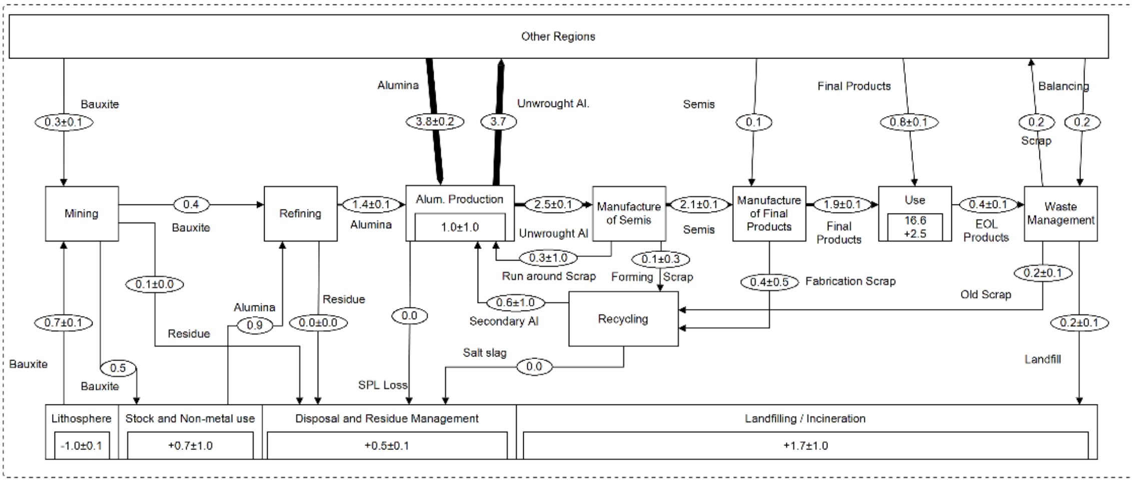


Figure 3-14 Global Al cycle for Middle East, 2014

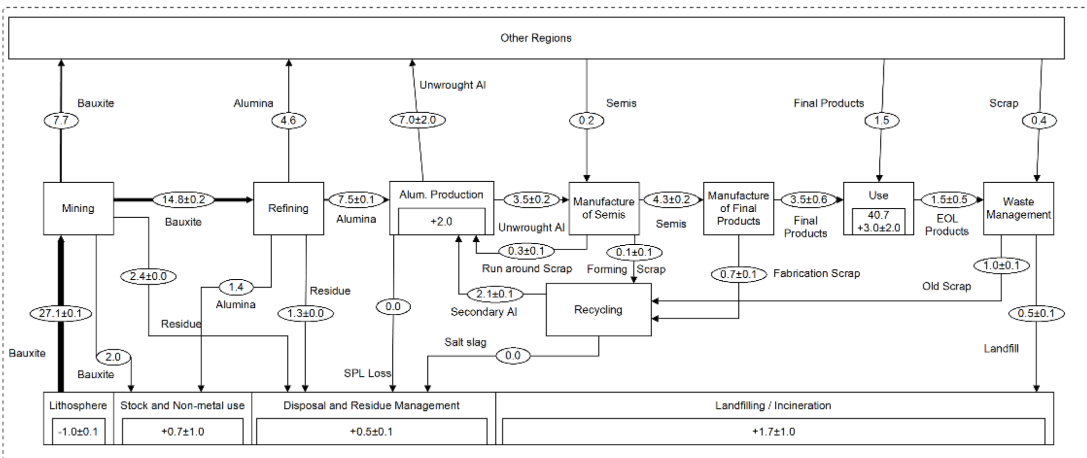
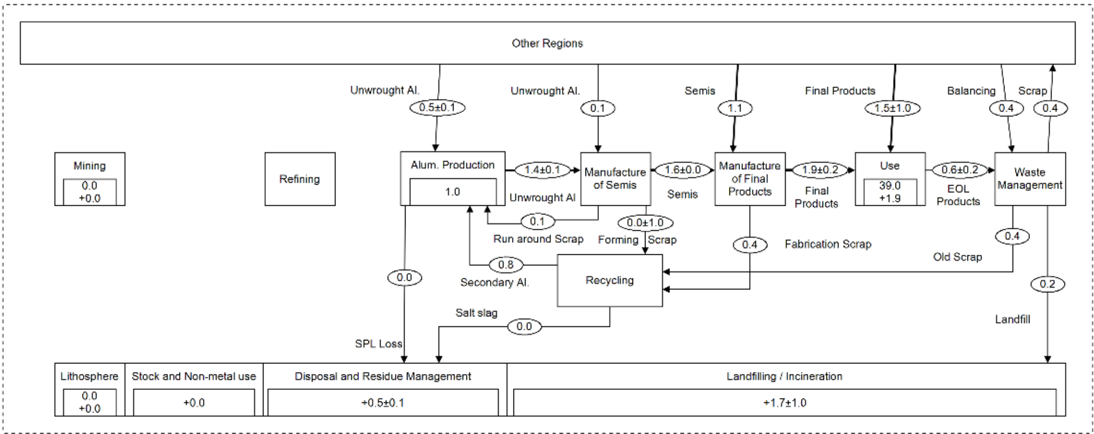
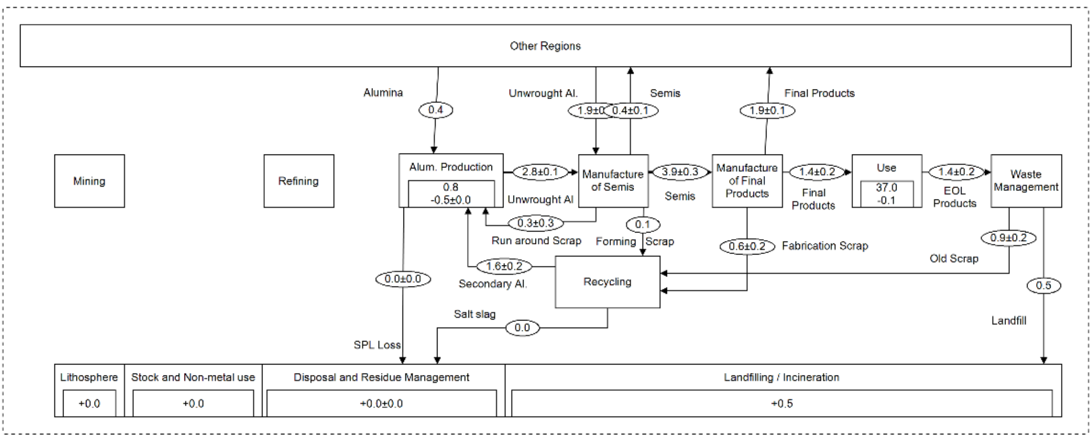


Figure 3-13 Global Al cycle for Other Producing Counries, 2014



Global Aluminium Cycle, Others (using STAN), 2014

Figure 3-16 Global Al cycle for Others, 2014



Global Aluminium Cycle, Japan (using STAN), 2014

Figure 3-15 Global Al cycle for Japan, 2014

After all the regional individual regional cycles were analysed through STAN, the results are shown through Sankey in the figure Figure 3-17. Bauxite is flowing from mining to refining, alumina is flowing from refining to production, and similarly ingots are flowing from production to fabrication, semis products are flowing from fabrication to manufacturing. Smartly, final products are flowing from manufacturing to use and so on. All the horizontal flows within same region is the domestic shipment. Flows preceding regions are exports while the flows following regions are exports. The data extracted from the regional modelling that has been used in the Sankey diagram for the flows is given in

Table 8 Data for Sankey diagram termed as 'flows' in the truthstudio app in (kilo ton)

EU	bauxite	min res	alumina	alumina res	ingot	semis	final P	fabri scrap	outflow	old scr suply	landfill
NA	739	95	787	372	1,699	12,407	3,421	3,617	7,390	4,644	2,746
SA	21	3	2,071	297	5,735	11,095	6,068	2,640	8,602	5,428	3,174
CH	10,643	1,240	1,415	734	1,254	2,300	1,742	486	1,264	768	496
OA	15,323	1,549	24,644	2,435	33,203	34,890	22,293	6,174	3,819	2,282	1,537
ME	1,934	572	2,205	295	1,933	7,700	5,146	1,689	2,017	1,272	745
OP	678	68	419	41	1,412	1,800	1,871	487	507	319	188
OT	16,891	2,466	4,748	1,330	1,488	3,800	2,964	803	1,837	1,188	649
JP	4	1	-	-	-	1,400	1,524	461	1,408	917	491

Table 9 Data for Sankey diagram termed as 'tooltip' in the truthstudio app

Year	Region	Primary Al	Secondary Al	Total
2014	EU	4,360	3,545	7,905
2014	NA	4,554	4,267	8,821
2014	SA	1,538	383	1,921
2014	CH	28,215	5,633	33,848
2014	OA	2,957	139	3,096
2014	ME	5,268	10	5,278
2014	OP	7,443	782	8,224
2014	OT	2	-	2
2014	JP	46	142	188

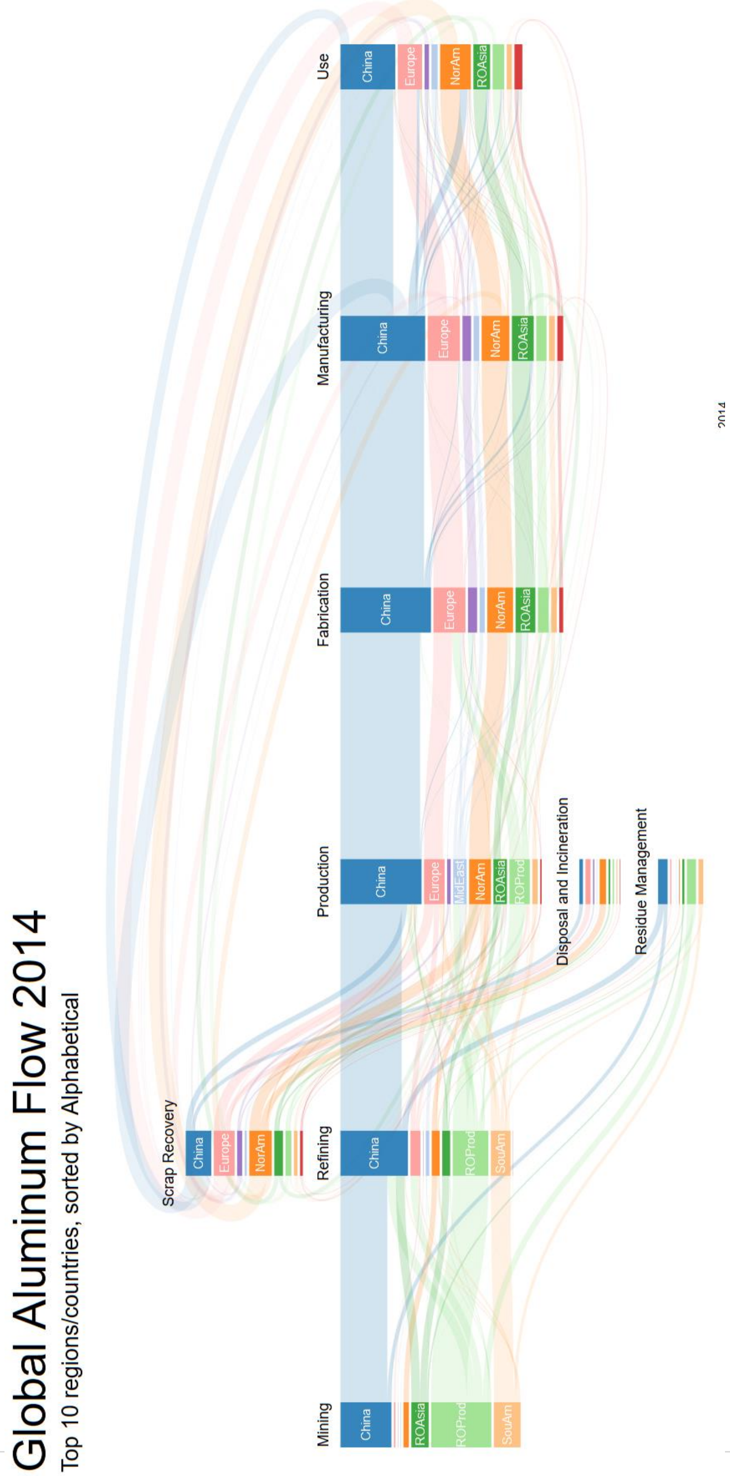


Figure 3-17 Sankey diagram for the regional level global aluminium cycle for 2014

3.5 Selecting top 20 aluminium containing products with most masses in kg being traded in comtrade

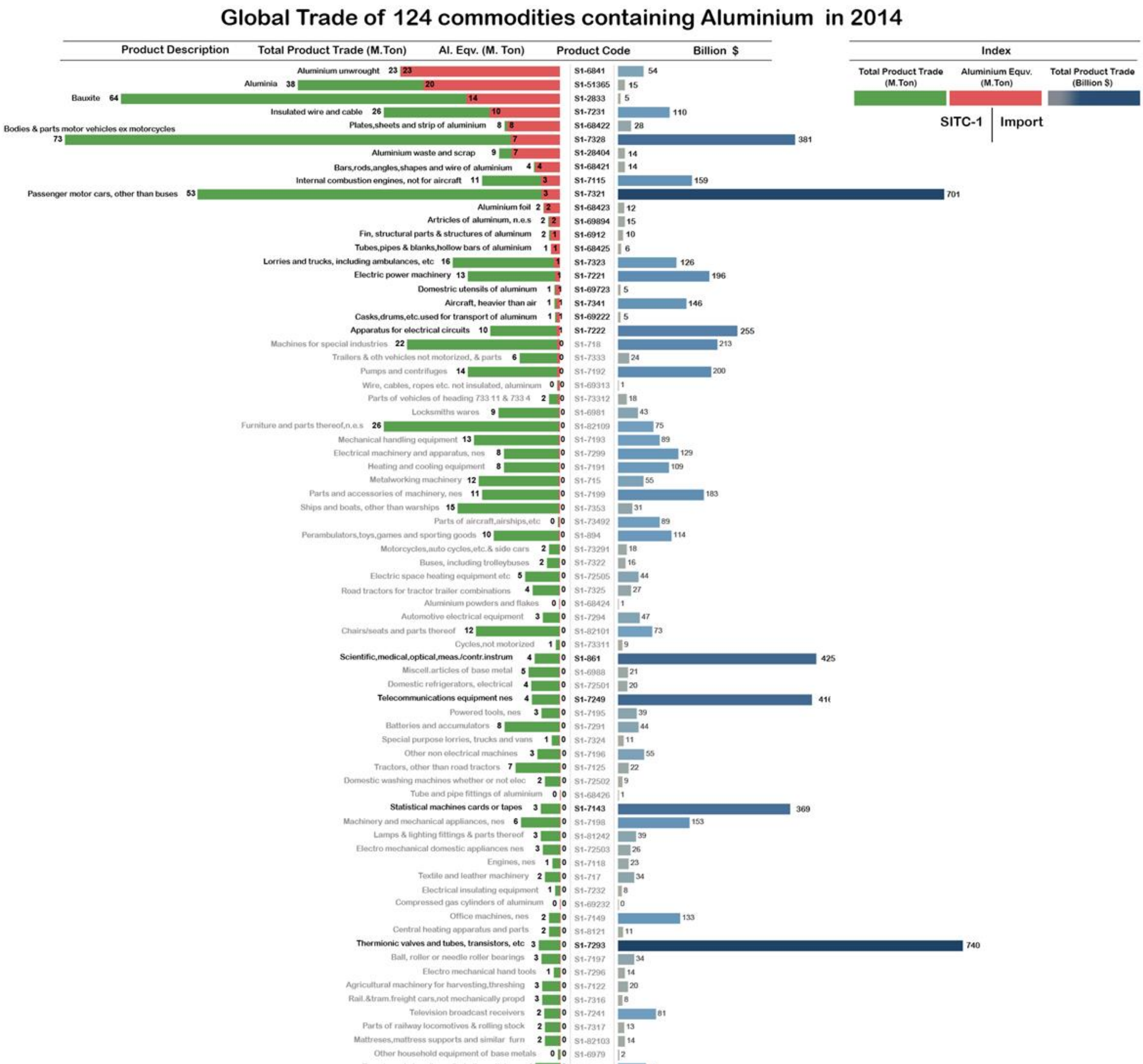


Figure 3-18 Ranking of aluminium containing products as per maximum kilograms traded as per UN comtrade

3.5.1 Method for getting average weight for the passenger motor cars

EUROPE

US

http://s3.caradvice.com.au/thumb/300/163/wp-content/uploads/2015/07/volkswagen-golf.jpg

Table 10 Historical weight of cars in the US and EU

Top-selling vehicle model in the EU	Mass in kg
Golf I (1974–1983)	750
VW Golf II (1983–1992)	845
VW Golf III (1993–2001)	960
VW Golf IV (1997–2004)	1187
VW Golf V (2004–2008)	1155
VW Golf VI (2008–2013)	1217
VW Golf VII (2013–)	1205
Total	7319
Average mass of car in the EU	**1045.571429**
Top-selling vehicle model in the US	**Mass in kg**
Ford F150 (1973–1979)	4000
Ford F150 (1980–1986)	3750
Ford F150 (1987–1991)	4250
Ford F150 (1992–1996)	4750
Ford F150 (1997–2003)	4750
Ford F150 (2004–2008)	5500
Ford F150 (2009–)	5500
Total	32500
Average mass of car in the US	**4642.857143**

Source (icct, 2014)

Source for pictures:

With the historical analysis of weight of cars in the US, and that for the Europe, the average weight has been estimated to be 4.6 ton and 1 ton respectively. However, the idea to supply an average weight to the missing mass in kilograms, for the product (S1-7321) for all countries is not fulfilled in this study. However, for the case of US and Europe, the estimated data could be used for the purpose.

3.6 Proposed System definition for differentiating cans from the anthropogenic global aluminium cycle

Data for the beverage cans were available for the Europe. On average, it was found that European market has 40 % of cans packed with beers while 15 % of cans are packed with soft drinks. Following tables shows the general packaging that is most popular in the European beverage market.

Source (for Table 11 and 12): (BCME, 2008-2015)

Table 11 Packaging of beer in European beverage market

Beer							
Beverage	Year	Cans	NR_Glass	R_Glass	NR_PET	R_PET	
Beer	2008	36%	18%	42%	4%	0%	100%
Beer	2009	37%	18%	40%	4%	0%	100%
Beer	2010	39%	18%	39%	4%	0%	100%
Beer	2011	42%	18%	37%	4%	0%	100%
Beer	2012	41%	20%	35%	4%	0%	100%
Beer	2013	42%	20%	34%	4%	0%	100%
Beer	2014	42%	20%	33%	4%	0%	100%
	AVG	40%					

Table 12 Packaging of soft drink in European beverage market

Soft drinks							
Beverage	Year	Cans	NR_Glass	R_Glass	NR_PET	R_PET	
Soft drinks	2008	14%	2%	6%	65%	12%	100%
Soft drinks	2009	14%	1%	6%	66%	12%	100%
Soft drinks	2010	15%	1%	6%	67%	12%	100%
Soft drinks	2011	15%	1%	5%	68%	10%	100%
Soft drinks	2012	15%	1%	5%	70%	9%	100%
Soft drinks	2013	15%	1%	5%	73%	6%	100%
Soft drinks	2014	16%	1%	4%	72%	6%	100%
	AVG	15%					

3.6.1 Method to Calculate Beverage can cycle

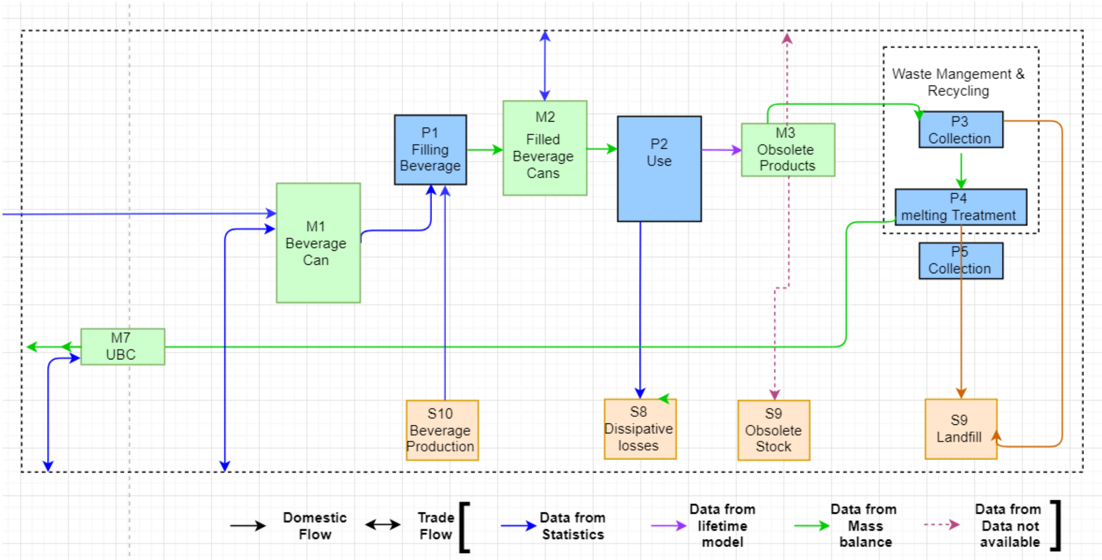


Figure 3-19 Proposed system definition for differentiating beverage can from the global aluminium cycle

The system definition in Figure 3-20 has been proposed for the can cycle after manufacturing phase in the upstream process. Through the average % value for packaging of beers and soft drinks, trade data can be collected from the UN comtrade. Because in the UN comtrade beer and soft drinks are distinguished in Table 13.As other data were not available during the study, a simpe system definition has been proposed. Source(Table 13) : UN Comtrade (https://comtrade.un.org/)

Table 13 Product code & description for beer and non alcoholic beverage in UN comtrade.

Product Code	Product Description
HS96 - 220290	Description: Waters, including mineral waters and aerated waters, containing added sugar or other sweetening matter or flavoured, and other non-alcoholic beverages,
HS96 - 220300	Beer

4 Conclusion

Reconciled results of the anthropogenic trade linked global aluminium cycle for the year 2014 on both country and regional level were calculated using MatLab, Excel and STAN. Total in-use stock for 2014 has been calculated as 0.81 Gt or 111 kg per capita on a global basis. 110 Mt of unwrought Al production, 78 Mt of Final proudest and 24 Mt of end of life products are calculated for the 2014 global cycle. The Production of unwrought aluminium is matching with the IAI model, however due to the mean lifetime assumption; outflow from this model is double in comparison to the IAI model for 2014. Thus, it is advised to review the mean lifetime assumption for various products for various countries and regions.

Average mass for the product S1-7321 for the US and Europe has been calculated as 4.6 ton and 1 ton respectively. This could be used to estimate the missing mass for the US and Europe; however for other countries/regions a further study could solve the case.

Besides, percentage of cans in the European beverage market has been found to be 40% in beer and 15% in soft drinks. Although the study could not conduct global cycle for the beverage cans, a simple system definition has been proposed which could provide basis for developing the cycle.

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