Appendix A

1. Dynamic Material Flow Analysis (MFA) of aluminum: data and assumptions

We have applied a dynamic MFA in Spain for 15 years to obtain not only a picture at a specific time but also an overview of the evolution in the recent past of the whole cycle of aluminium to determine changes and trends in raw materials and waste markets and to observe the influence of the accumulated stock; altogether, this information can be useful to anticipate scenarios in the near future. The aluminum life cycle is divided into the following nine processes: bauxite mining [A], alumina production [B], primary aluminum production [C], secondary aluminum production [D], ingot cast production [E], semifinished products fabrication [F], finished products manufacturing [G], use [H] and waste management [I]. Every life cycle process produces aluminium-containing products (ACP) classified as: bauxite (a); alumina (b); primary aluminium (c); secondary aluminium (d); ingot (e); semifinished products (f); finished products (g); end of life products (h); old scrap (i) and new scrap (j). Some of the ACPs are also classified in several subtypes. Figure A.1 summarizes graphically the process and flows while Table A.1 summarizes the definitions associated to the ACP considered in this study.

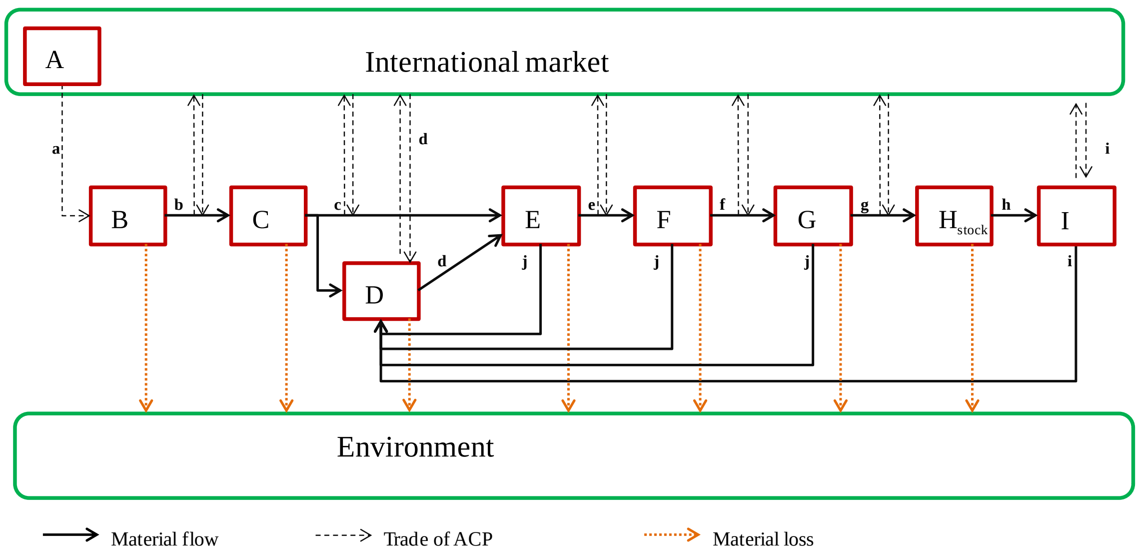

Figure A.1: Schematic life cycle of aluminium

Table A.1: Aluminium-containing products (ACP) definitions used in this study

Concepts	Definitions
Bauxite (a)	Bauxite is composed primarily of one or more aluminum hydroxide compounds, plus silica, iron and titanium oxides as the main impurities
Alumina (b)	Alumina is produced from bauxite through the use of the Bayer chemical process in alumina refineries.
Primary Aluminium (c)	Aluminium produced by the primary production process using alumina from bauxite.
Secondary aluminium (d)	Aluminium produced by the secondary production process using the old scrap and new scrap
Semifinished products (f)	Aluminum enters semifinished product mainly in aluminum alloys which are divided into wrought alloys and casting alloys which are used for producing wrought products and castings, respectively
Finished products (g)	Finished products containing aluminum are so numerous and diverse that it is difficult to categorize them distinctly, the aluminum flows thus become highly complex and we have classified aluminum final products into five categories: building, transport, packaging, engineering and cable and other
Old Scrap (i)	Old scrap is produced at the end of life of products (EOL)
New Scrap (j)	New scrap is produced in the manufacturing process; ingot casting, semifinished and final products

1.1. Accounting method of flows and stocks

There are several flows associated with each life process, and except for the use process, for each of life process; the total input consisting of flows from previous life process should be equal to ACP production and loss according to equation [Eq. A.1]. In addition, the ACP production can be calculated based on the production yield (γ) as expressed in equation [Eq. A.2]; thus, loss can be calculated as fixed in equation [Eq. A.3]. Consumption can be calculated by equations [Eq. A.4] or [Eq. A.5].

$$LP_{i,j}^{INPUT} = LP_{i,j}^{production} + LP_{i,j}^{loss} \quad \text{[Eq. A.1]}$$

$$LP_{i,j}^{production} = LP_{i,j}^{INPUT} \cdot \gamma \quad \text{[Eq. A.2]}$$

$$LP_{i,j}^{loss} = LP_{i,j}^{INPUT} \cdot (1-\gamma) \quad \text{[Eq. A.3]}$$

$$LP_{i,j}^{consumption} = LP_{i,j}^{production} + LP_{i,j}^{import} - LP_{i,j}^{\exp ort}$$ [Eq. A.4]

$$LP_{i,j}^{consumption} = LP_{i+1,j}^{INPUT}$$ [Eq. A.5]

where LP= Life Processes; i= indicator for life processes; j=indicator for the studied years; INPUT= ACP demanded by life process i in year j; production=ACP produced in life process i in year j; Loss=ACP discarded from life process i in year j; Import= ACP imports generated from life process i in year j; Export= ACP exports generated from life process i in year j; consumption=ACP consumed from life process i in year j.

Each flow is calculated in three ways; it is calculated directly based on statistics, calculated by combining statistics with coefficients and deduced using the mass balance.

1.2. Data sources and assumptions for flows accounting

1.2.1. Bauxite mining [A]

Except for small quantities of refractory grade bauxite that is not suitable for the production of alumina, Spain lacks the minerals necessary for the extraction of aluminum from metal through its conversion into alumina (IGME, 1994). Thus, Spain must import all the bauxite needed for its primary aluminum industry. Data on the import and export of bauxite (in this case, refractory bauxite) were obtained from the Spanish Ministry of Economy and Competitiveness (Datacomex, 2013). The aluminium content of bauxite varies considerably, with the available alumina (Al_2O_3) content typically ranging from 31-52% (Liu and Müller, 2013), and in this study, we have assumed an average alumina content of 44% (Schmidt and Thrane, 2009).

1.2.2. Alumina production [B]

Data on Spanish alumina production expressed as the total content of Al_2O_3 were obtained from the British Geographical Survey from 1995 to 2008 (BGS, 2001; BGS, 2005; BGS, 2010) and from the European Mineral Statistics from 2008 to 2010 (BGS, 2012). Data on the import and export, also expressed as the total content of Al_2O_3, were obtained from Spanish Ministry of Economy and Competitiveness (Datacomex, 2013). Aluminium content in alumina is assumed to be 52% according to the chemical composition. Around four or five tons of bauxite are required to produce two tons of alumina given a loss ratio between 50% and 60%, respectively (EAA, 2013b). In our study, losses were calculated as the difference between bauxite consumption and alumina production, and the average loss for the years 1995-2010 was 56.7%.

1.2.3. Primary aluminum production [C]

Data on primary aluminum production was obtained from the British Geographical Survey from 1995 to 2008 (BGS, 2001; BGS, 2005; BGS, 2010) and from the European Mineral Statistics from 2008 to 2010 (BGS, 2012). Regarding statistics data on alumina and primary aluminum and considering that the yield for this process has been established to be approximately 3% (Cullen and Allwood, 2013), we have recalculated alumina data from 1995 to 1999. Data on the import and export of primary aluminum were obtained from Spanish Ministry of Economy and Competitiveness (Datacomex, 2013). Aluminium content in primary aluminium is assumed to be 99.7% according to data from (Liu and Müller, 2013).

1.2.4. Secondary aluminum production [D]

Secondary aluminum scrap can be classified as old scrap/post-consumer scrap or new scrap which is generated during the casting [E], semifinished [F] and manufacturing production [G] life cycle stages. Secondary aluminum production involves two separate processes: remelting, which produces wrought alloys for rolled and extruded products, and refining, which produces casting alloys for shape-cast products and deoxidation aluminum (Cullen and Allwood, 2013). Remelters accept only new scrap metal or efficiently sorted old scrap whose composition is relatively known (JRC, 2010), while refiners can work with all types of scrap as their process includes refinement of the metal to remove unwanted impurities (BIR, 2008). Losses from remelting and refining are 1% and 6%, respectively, and we have assumed that losses from these processes are 5% (EAA, 2006). Scrap recycling requires the addition of pure aluminum to "sweeten" the melt and obtain the desired alloy mix (Cullen and Allwood, 2013), and we have considered that 5% of primary aluminum is used to produce secondary aluminum. We therefore removed 5% from the total primary aluminum production data [C].

To calculate the production of new scrap in the various processes [E to G], we used the averaged percentage of scrap generation obtained from the Aluminum Mass Flow Model of 2011 from the International Aluminum Institute (IAI, 2013). New scrap generation yields from casting, semifinished and manufacturing were calculated as 2.1%, 26.9% and 20.7%, respectively. Data on old scrap generation from 2004 to 2010 were obtained from the European Aluminum Association (EAA, 2008; EAA, 2013a), but there are no data from 1995 to 2003. Data for these years were estimated through the average old scrap generation related to total scrap generation obtained for 2004-2010. Data on the import and export of old scrap, as well as data on the import and export of total secondary aluminum, was obtained from the Spanish Ministry of Economy and Competitiveness (Datacomex, 2013). Thus, the import and export of new scrap was calculated as the difference between the secondary aluminum and old scrap import and export data. Finally, to calculate the quantity of new and old scrap going to remelting or refining, respectively, we used and extrapolated data from Boin and Bertram (Boin and Bertram, 2005).

1.2.5. Ingot cast production [E]

There is no data on ingot cast production, and it was calculated as the sum of primary and secondary aluminum consumption considering the yield production for this process;

the losses will be reintroduced in the remelting or refining process as new scrap as explained in the section 1.2.4. Data from ingot cast import and export was obtained from European Aluminum Association for the years 2004 to 2010. There is no data for previous years. We assume an aluminium content of 99.7%, similar to primary aluminium (Liu and Müller, 2013).

1.2.6. Semifinished products production [F]

Aluminum enters semifinished product mainly in aluminum alloys, which are divided into wrought alloys and casting alloys, used for producing wrought products and castings, respectively. Wrought products generally comprise rolled products, extruded products, and other fabricated products. In this study, we have divided the semifinished products into rolled, extruded, shape cast and others. Data for the production of rolled, extruded and other products from 1995 to 2010 were obtained from the Spanish National Statistics Institute (INE, 2013), and data on the import and export came from the Spanish Ministry of Economy and Competitiveness (Datacomex, 2013). The aluminium content in wrought products and cast products was assumed to be 95% and 90%, respectively, according to data from (Liu and Müller, 2013).

There is no data on the production and import/export of shape castings or total semifinished products. To calculate total semifinished production and shape casting production, the average yield of 73.1% obtained from the International Aluminum Institute (IAI, 2013) was applied; thus, total production was calculated from ingot cast consumption and this yield. Shape casting production was then calculated as the difference between total semifinished production and rolled, extruded and other products. To close the metal balance, we had to recalculate the new scrap generation to have the same secondary aluminum calculations due to the sum of new scrap estimations, old scrap generation from statistics and the primary aluminum added to sweeten the melt as secondary aluminum statistics. We used an iterative process, and we obtained a semifinished yield production of 82.9% instead of 73.1%.

1.2.7. Finished products manufacturing [G]

Because final products containing aluminum are so numerous and diverse that it is difficult to categorize them distinctly, the aluminum flows thus become highly complex, and we have classified aluminum final products into five categories: building, transport, packaging, engineering and cable and other. Statistics for Spain on finished products are uncertain and difficult to obtain, so to calculate the total production, we have considered an average yield production of 79.3%, and that production will be equal to semifinished consumption. Throughout the iteration process, we obtained a production yield of 75.9%. Finally, to calculate the production disaggregated by type of finished product, we used European data for the period 1995-2004 and 2004-2010 (EAA, 1995; EAA, 2006). Data on the imports and exports was from the Spanish Ministry of Economy and Competitiveness (Datacomex, 2013). We do not have data about the aluminium content in finished products, so we have assumed 100% of aluminium content in trade data. We are aware that these data are overestimated.

1.2.8. Use [H]

The use life cycle stage is different from other processes because most of the final products may serve in the use stage for a long time and will not be consumed. Therefore, an in-use stock of aluminum will gradually form and grow in a defined geographical area such as a city or a country (JRC, 2010). In fact, IAI estimates that approximately 90% of aluminum goes into products with long lifetimes, and approximately 75% of all aluminum ever produced is still in use (IAI, 2013). However, products will eventually reach their end-of-life (EOL), and the newly available aluminum scrap will be processed in the waste management stage [I]. To calculate the in-use stock we have used the following equations [Eq. A.6] and [Eq. A.7]

$$LP_j^{stock} = LP_{G,j}^{consumption} + LP_{j-1}^{stock} - LP_{I,j}^{production} - LP_j^{\mathrm{deoloss}} \qquad \text{[Eq. A.6]}$$

$$LP_j^{\mathrm{deoloss}} = P_j^{steel} \cdot D_j^{\mathrm{Al\,steel}} \qquad \text{[Eq. A.7]}$$

where stock= ACP stocked in year j, deoloss=ACP used by steel industry for deoxidation, Steel=production of steel in year j, Al steel=average consumption of deoxidation aluminium per ton steel.

1.2.9. Waste Management [I]

In this stage, we have considered the collection, selection and preparation for recycling only for the old scrap generated, while old and new scrap recycling is considered in section 1.2.4 to include remelting and refining. Old scrap generated after consumption is collected after a consumer cycle, either separately or mixed, and it is often somewhat contaminated, depending highly on its origin and collection systems. Thus, some losses are produced due to the selection, and we have assumed that they are 10% (EAA, 2006). In addition, we have assumed that approximately 1% of total mixed waste is aluminum not collected separately (Waste Watch, 2008), and we have accounted for it as a loss of aluminum. There is little information about the old scrap by type of EOL product, but in order to have an idea of the scrap generated, we have assumed that the key sources of aluminum scrap are those obtained for Europe in 2004, and considered them to be the same for all years based on information from JRC (JRC, 2010): building (7%), transport (44%), engineering and cable (13%), packaging (28%) and others (7%).

References of Appendix A

1. *Aluminium recycling in Europe: the road to high quality products*, European Aluminium Association (EAA). Brussels, 2006. http://www.alueurope.eu/wp-content/uploads/2011/08/Aluminium-recycling-in-Europe-2007.pdf
2. *Aluminium use in Europe: country profiles: 2004-2007*. European Aluminium Association (EAA). Brussels, 2008. http://www.alueurope.eu/aluminium-use-in-europe-country/
3. *Aluminium recycling in LCA.* European Aluminium Association (EAA), Brussels, 2007. http://www.alueurope.eu/wp-content/uploads/2011/09/Alu_recycling_LCA.pdf
4. *Aluminium use in Europe: country profiles*: 2007-2010. European Aluminium Association (EAA). Brussels, 2013a. http://www.alueurope.eu/aluminium-use-in-europe-country/
5. Boin, U.M.J. and Bertram, M. (2005) Melting standardized aluminum scrap: a mass balance model for Europe. *Journal of the Minerals, Metals and Materials Society*, 57(8):26–33.
6. McMillan, C. A. Modeling Temporal Aluminum Material Flows and Greenhouse Gas Emissions to Evaluate Metals Recycling Allocation in Life Cycle Assessment. Michigan. Center for Sustainable Systems, University of Michigan, February 2011. Report No. CSS11-05
7. Cullen, J.M. and Allwood, J.M. Mapping the global Flow of Aluminum: from liquid aluminum to end-use goods. *Environmental Science and Technology*, 2013, 47, 3057: 64
8. Estadísticas del comercio exterior español (DataComex). Ministerio de Economía y Competitividad (http://datacomex.comercio.es Accessed April 2013)

9. *End-of-waste Criteria for Aluminium and Aluminium Alloy Scrap: Technical Proposals*. Joint Research Centre (JRC), 2010, Institute for Prospective Technological Studies, Sevilla.

10. *Encuesta Industrial de Productos*, Instituto Nacional de Estadística (INE), Madrird, 2013. http://www.ine.es/jaxi/menu.do?type=pcaxis&path=%2Ft05%2Fp049&file=inebase&L=0

11. *European Mineral Statistics 2006-2010*, British Geological Survey (BGS), Nottingham, 2012. http://www.bgs.ac.uk/mineralsuk/statistics/europeanStatistics.html

12. *Information sheet packaging*, Waste Watch, UK, 2008. http://www.wastewatch.org.uk/data/files/resources/12/Packaging_Aug-08-FINAL-CKT.pdf

13. Liu, G. and Müller, D.B. Mapping the global journey of anthropogenic aluminium: a trade-linked multilevel material flow analysis. *Environmental Science and Technology*. Forthcoming 2013

14. *Panorama nacional minero. Aluminio 1994*. Instituto Geológico y Minero de España (IGME). Madrid. (http://www.igme.es/internet/PanoramaMinero/Historico/1994_95/ALUMINIO.pdf)

15. *Production process*. European Aluminium Association (EAA). Brussels, 2013b. http://www.alueurope.eu/about-aluminium/production-process/

16. *Report on the environmental benefits of recycling*, Bureau of International Recycling (BIR), Brussels, 2008: www.bir.org/assets/Documents/publications/brochures/BIR_CO2_report.pdf

17. Schmidt, J. and Thrane M. Life cycle assessment of aluminium production in new Alcoa smelter in Greenland. 2-0, LCA. 2009

18. *World Mineral Statistics 1995-1999*, British Geological Survey (BGS), Nottingham, 2001. http://www.bgs.ac.uk/mineralsuk/statistics/worldArchive.html

19. *World Mineral Statistics 1999-2003*, British Geological Survey (BGS), Nottingham, 2005. http://www.bgs.ac.uk/mineralsuk/statistics/worldArchive.html

20. *World Mineral Statistics 2004-2008*, British Geological Survey (BGS), Nottingham, 2010. http://www.bgs.ac.uk/mineralsuk/statistics/worldArchive.html