Resources, Conservation & Recycling 125 (2017) 48–69

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products

M. Bertram[a,*], S. Ramkumar[b], H. Rechberger[c], G. Rombach[d], C. Bayliss[a], K.J. Martchek[e], D.B. Müller[b], G. Liu[f]

[a] International Aluminium Institute, London, United Kingdom
[b] Department of Energy and Process Engineering Industrial Ecology Programme, Norwegian University of Science and Technology, Norway
[c] Institute for Water Quality, Resource and Waste Management, Vienna University of Technology, Austria
[d] Hydro Aluminium Rolled Products GmbH, Bonn, Germany
[e] Alcoa Corporate Center, Pittsburgh, USA
[f] SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology, and Environmental Technology, University of Southern Denmark, Denmark

ARTICLE INFO

Keywords:
Material flow analysis
Industrial ecology
Aluminium alloys
Trade
Scrap quality
Recycling

ABSTRACT

A global aluminium flow modelling tool, comprising nine trade linked regions, namely China, Europe, Japan, Middle East, North America, Other Asia, Other Producing Countries, South America and Rest of World, has been developed. The purpose of the Microsoft Excel-based tool is the quantification of regional stocks and flows of rolled, extruded and casting alloys across space and over time, giving the industry the ability to evaluate the potential to recycle aluminium scrap most efficiently. The International Aluminium Institute will update the tool annually and publish a visualisation of results at www.world-aluminium.org/statistics/massflow.

Based on primary metal production, semi-fabricated products shipment and trade data from 1950s to 2014, the tool calculates regional domestic scrap availability and metal demand of the same alloy group and differentiates new and old scrap in each group at a given point in time. An intuitive user interface allows for changes in data inputs to generate bespoke results. To solve the mass balance difference of the 'Mining and Refining' and 'Aluminium Production' processes, which occur in the tool due to conflicting data, the software STAN was used.

Modelling of year 2014 stocks and flows indicate that three-quarters of all the aluminium ever produced is still in productive use. Over 26 million tonnes of new and old scrap are supplied to cast houses world-wide annually, in the form of mixed & casting scrap (11 million tonnes), used beverage cans (3 million tonnes), other rolled scrap (6 million tonnes), extruded scrap (4 million tonnes) and other scrap (2 million tonnes).

1. Introduction: a decade of knowledge building

This paper describes the methodology, data sources and results of a tool for conducting a dynamic material flow analyses (MFA) as described by Brunner and Rechberger (2004) of aluminium. A dynamic MFA is able to quantify total stocks accumulated over time; as distinct from a static MFA, which quantifies flows and stock changes of materials or substance within a system boundary at a certain point in time.

RWTH Aachen (Rombach et al., 2001a,b, 2002; Rombach, 2002; Zapp et al., 2002, 2003) and Alcoa (Bruggink and Martchek, 2004) were among the first to perform MFA for aluminium. The aluminium sector benefited from these and more recent studies described below, and is now working for over a decade; developing, testing and publishing their own MFA work (Boin and Bertram, 2005).

Built on decades of industry data and expert knowledge, reviews of published literature and views of product lifetimes and end-of-life (EOL) product collection rates, the first global aluminium flow model (Bertram et al., 2009) was developed in 200×, initially to map current and future availability of aluminium scrap. At that time (as today), worldwide statistical data on scrap availability and aluminium recycling was not comprehensively collected and published. Collecting meaningful and comprehensive recycling statistics has proven very difficult for the aluminium industry because there are more than 1500 remelting and refining plants worldwide, many of them in small and medium size, which can switch from tolling (not included in statistics) to purchasing (included in statistics) arrangements and from scrap-based to primary-based production depending on market prices and product requirements at any time.

As the model was refined, its potential as a communication, education, lobbying and strategic planning tool was realised, as well as its

* Corresponding author.
E-mail address: bertram@world-aluminium.org (M. Bertram).

http://dx.doi.org/10.1016/j.resconrec.2017.05.014
Received 6 March 2017; Received in revised form 24 May 2017; Accepted 29 May 2017

Table 1
Countries covered in each region.

Region	Countries	Comments
China	Mainland China	Important ingot producer and a consumer of final products.
Europe	EU28, Iceland, Macedonia, Moldavia, Norway, Serbia-Montenegro, Switzerland, Turkey, Ukraine	Covering regional Europe not political to make sure political changes do not affect the European model in the future.
Japan	Japan	Excellent data quality would otherwise be diluted in "Other Asia". High per capita consumer of final products.
North America	Canada, Mexico, USA	Important ingot producer and a consumer of final products. Mexico recycles a lot of scrap from the USA and ships secondary foundry castings back to the USA. Forming a unity.
Middle East	Bahrain, Oman, Qatar, Saudi Arabia, UA Emirates, Iran	Important primary ingot producer. Dynamic region. High per capita consumer of final products.
Other Asia	India, Indonesia, Malaysia, Pakistan, Singapore, South Korea, Taiwan, Thailand, Vietnam	Diverse group with poor data quality. Covering all bauxite, alumina and aluminium producers in Asia (excluding Japan and China)
Other Producing Countries	Australia, Azerbaijan, Cameroon, Egypt, Fiji, Guinea, Kazakhstan, New Zealand, Russia, Sierra Leone, South Africa, Tanzania, Zimbabwe	Large bauxite, alumina and primary producing region.
South America	Argentina, Brazil, Dominican Republic, Guyana, Haiti, Jamaica, Suriname, Venezuela	Covering bauxite mines and high income countries in this South America.
Rest of World	All other countries not listed above	No bauxite, alumina or primary aluminium producers included in this region. Importer of semis and final products.

power, when combined with lifecycle data, to model current and future environmental impacts (Martchek, 2006; International Aluminium Institute, 2009, 2016, 2017a).

Since 2006, the International Aluminium Institute (IAI) has published annual updates to this global model, as a Microsoft Excel workbook (International Aluminium Institute, 2015). This global model has played a major role in shaping a common understanding of the magnitude of aluminium stocks and flows from mining to use and recycling, was key in the development for common definition of recycling, and brought and still brings together aluminium producers, recyclers, semis produces and users of aluminium from all over the world giving them a platform to speak to each other.

In 2012, researchers at Vienna University of Technology (TU Wien) began to analyse aluminium material flows at country-level for Austria (Buchner et al., 2014, 2015a,b) and the aluminium content in buildings stock (Kleemann et al., 2014). In 2008, the Norwegian University of Science and Technology (NTNU) started a project to analyse the global aluminium cycle in more detail. This research entailed three dimensions: (i) the differentiation of alloys and alloying elements associated with aluminium, in order to anticipate and evaluate mitigation options related to potential quality challenges (Modaresi and Müller, 2012; Modaresi et al., 2014; Løvik et al., 2014; Løvic and Müller, 2014); (ii) the use of dynamic stock-driven aluminium flow models and scenarios to anticipate changes in energy use and greenhouse gas emissions related to aluminium production and to evaluate energy saving and climate change mitigation strategies (Liu et al., 2011, 2013); and (iii) a regional differentiation of the global aluminium cycle, tracking aluminium through 66 individual countries and regions, including the trade of aluminium contained in 126 product categories along the supply chain (Liu and Müller, 2013).

With time, users of the global IAI model had expressed a desire to understand not only the volumes and timing of scrap availability but also its location and quality. Requests were also made for regional differentiation in product lifetimes, power mixes and life cycle inventory data, in order to develop environmental impact scenarios.

Therefore, in 2012, IAI began to collaborate with NTNU to transform the global model into a number of discrete but interlinked regional models, drawing on its network of bauxite, alumina and aluminium producing member companies, manufacturing and mining experts, strategists and industrial ecologists. Since 2016 the results of these regional models (China, Europe, Japan, North America, Middle East, Other Asia, Other Producing Countries, South America and Rest of World) have been published as a visualisation of the global aluminium flow (International Aluminium Institute, 2017b).

A number of other research groups have also recently explored the aluminium cycle as part of focused projects: Yale University on US country level stocks and flows (Chen and Graedel, 2012); the University of Tokyo on aluminium and its alloying elements (Hatayama et al., 2007); Tsinghua University on flows in China (Chen et al., 2010) and the University of Cambridge Wellmet 2050 project MFA (Cullen and Allwood, 2013), based in part on the IAI global model. While these research programmes illustrate stocks and flows at a given moment in time, this research project is an ongoing effort to update regularly the aluminium MFA methodology, data input and output results.

The convergence of research activities of IAI, NTNU and TU Wien has resulted in a partnership between the three institutions, with the objective to publish a modelling tool that incorporates accurate production and demand data, trade data along the value chain, alloy group information and state of the art modelling expertise. The complete tool incorporates the regional models, a separate trade balancing tool and an interface, through which input data and assumptions can be manipulated and from which reports can be generated.

This paper describes the methodology, data quality and sources for the modelling tool, as well as output results for year 2014.

2. Methodology

2.1. Scope and system boundaries

The system described in this MFA is defined by both spatial and temporal boundaries (Chen et al., 2010). The spatial boundaries of the nine regional models is shown in Table 1, while the temporal boundary is the period 1950–2014. The starting year was chosen due to the availability of data from this point forward (World Bureau of Metal Statistics began collecting statistics on the aluminium industry in 1950) and to reflect the fact that the end of World War 2 marked a significant acceleration in aluminium production and demand; inclusion of earlier years would have meant inclusion of patchy and poor quality data and volumes so low as to not impact later stocks (and flows) significantly.

As shown in Fig. 1, the aluminium cycle is described in the regional models as a chain of six processes: bauxite mining & alumina production [mining & refining]; primary and recycled aluminium production [aluminium production]; semi-fabricated product manufacture [fabrication], production of final products [manufacturing], stock of products in use [use]; and management of end-of-life (EOL) products and new scrap [scrap recovery and trading].

Demand in the fabrication stage is met via aluminium production from one or more of the following metal sources: primary aluminium