A dynamic analysis of anthropogenic aluminum stocks and flows in the United States from 1900 to 2009 has been conducted. Key findings include: (1) historical cumulative aluminum input into the U.S. anthroposphere amounts to 438 Tg, with only about 35% of it accumulating in domestic in-use stock; (2) less than 5% of most flows take place before 1950, while more than 50% of them happen after 1990; (3) flows into fabrication, manufacturing, and use processes, as well as trade flows, are vulnerable to energy crises; basically, after an energy crisis, the U.S. tends to produce less primary aluminum, less semis, as well as less final products, and therefore import less bauxite and alumina but import more unwrought aluminum and final products; (4) the U.S. has been a net importer of aluminum from the life cycle perspective, with its total annual net import increasing from 1945 to 2005; (5) as a result of the continuous increase of net import, total domestic stock of aluminum in the U.S. dramatically increases in the period of 1945–2009 and amounts to 316 Tg in 2009, about nine times of that in 1900; (6) in-use stock comprises about 48% of total domestic stock in 2009 and is dominated by two sectors, Buildings and Construction (32%) and Transportation (35%); (7) total per-capita stock in use of aluminum keeps increasing until 2009 and currently amounts to 490 kg; (8) per-capita stock of aluminum in Transportation sector increases substantially after 1990s because of the light-weighting of automobiles, while that in the Buildings and Construction and Electrical Engineering sectors seems have reached a saturation level after 2005.

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1. Introduction

The study of anthropogenic resource cycles can offer new perspectives on a variety of topics, including resource availability, resource utilization, recycling potential, and environmental policy (Reck et al., 2008). Especially for metals, anthropogenic stocks and flows analysis provides insights into (1) identifying factors driving changes of metals demand, (2) quantifying recovery efficiencies of metals at the end-of-life (EOL) stage, (3) estimating international trade of metals embedded in all kinds of products, and (4) assessing emissions or loss of metals back into natural environments (Chen and Shi, 2012; Chen et al., 2010; Eckelman and Graedel, 2007; Gordon et al., 2003; Reck et al., 2008; Spatari et al., 2005; Wang et al., 2007). In addition, quantified resource cycles help to evaluate the future availability of metals, estimate the potential for urban mining, and explore patterns of metals use in societal evolution from the perspective of stocks.

Aluminum is widely recognized for its technological versatility, and its rate of use now cedes first place only to steel among the metals. If measured by volume rather than by weight, aluminum now exceeds in quantity all other non-ferrous metals combined, including copper and its alloys, lead, tin, and zinc (Altenpohl and Kaufman, 1998). However, production of alumina and primary aluminum is highly resource, energy, and emissions intensive. In addition, although the energy required for producing secondary aluminum might be only 5–10% of that needed for primary aluminum (Melo, 1999), there are still substantial environmental emissions, such as diesel oxidation products, associated with the separation and remelting of aluminum scrap (European Aluminum Association, 2008; Zhang et al., 2007; Zhang et al., 2008). Since industrial production of aluminum began in 1888 (Altenpohl and Kaufman, 1998), the United States has played a very important role in the global aluminum industry. According to U.S. Geological Survey (2009), historical cumulative apparent consumption of aluminum in the United States from 1900 to 2009 is more than 255 Tg, about 28% of global cumulative production in...
that period. Therefore, it is important to conduct a multi-year dynamic analysis of aluminum stocks and flows in the United States.

By applying the material flow analysis (MFA) or substance flow analysis (SFA) framework of aluminum which has been developed and used in (Chen and Shi, 2009, Chen and Shi, 2012; Chen et al., 2010), this paper reports on a dynamic analysis of aluminum stocks and flows in the United States from 1900 to 2009, aiming at quantifying how much aluminum has entered, left, passed through, and accumulated in the U.S. anthroposphere. The paper is organized as follows: Section 2 defines the scope and system boundaries, and describes the accounting methods and data preparation; Sections 3 and 4 present results on flows and stocks, respectively; Section 5 discusses uncertainties and policy implications of the results. The paper ends with a summary and conclusion.

2. Methodology

2.1. Scope and System Boundaries

The system analyzed in SFA is defined by spatial and temporal boundaries (Chen et al., 2010). The spatial system boundary of the current study is the geographical border of the United States, while the temporal boundary is the period 1900-2009. As in Chen et al. (2010) and Chen and Shi (2012), all stocks and flows values of this study refer to the average annual mass of aluminum in pure form (i.e., not the mass of aluminum-containing mixtures and alloys). For bauxite and alumina, where aluminum exists in chemical compound form, the mass of aluminum is calculated according to the mass of aluminum included in Al₂O₃.

The life cycle of aluminum in the anthroposphere is composed of four principal life stages, as illustrated by Fig. S1 in the Supplementary Material: Production (P), Fabrication and Manufacturing (F&M), Use (U), and Waste Management and Recycling (WM&R). Except for the Use stage, each of these life stages is divided into several sub-stages depicted as solid line rectangles in Fig. S1 and described in Table S1 in the Supplementary Material. In this paper, both the four principal life stages and their sub-stages are referred to as life processes. Every life process generates aluminum-containing products (ACPs) as specified in Table S2. More details about anthropogenic aluminum life cycle are available at Chen and Shi (2009), Chen et al. (2010), and the Supplementary Material of this paper.

2.2. Accounting Methods of Stocks and Flows

Details on identifying and accounting for stocks and flows are described in the Supplementary Material. For the convenience of readers, we summarize some essential information here. Stocks are categorized into four groups: (1) bauxite ore stocks, (2) in-use stocks, (3) hibernating stocks, and (4) loss stocks. Loss stocks are then divided into four categories according to their existence states: (1) tailing ponds, (2) slag repositories and landfills, (3) obsolete stocks and exports of EOL products, and (4) non-metallic use. For each life process, the total input consisting of flows from previous life process and import should be equal to total output comprising flows to the next life process and export. All these flows are then classified into four groups: (1) the trade flows and (2) the loss flows, both of which take place along the whole life cycle of aluminum; (3) the transformation flows that transform aluminum from chemical compounds to refined metal, from pure metal to alloys, and from simple products to complex components of final products; and (4) the recycling flows of aluminum scrap, including old scrap from in-use stock and new scrap from Production and F&M stages.

By collecting data as mentioned in Section 2.3, each flow is calculated in one of four ways: (1) calculated directly based on statistics, such as the trade flows; (2) calculated by combining statistics with coefficients, such as the loss flows; (3) modeled by the “top-down” method, such as the old scrap generation; and (4) deduced by mass balance. With results on all flows available, annual changes of various stocks are determined, and each stock is deduced by accumulating its annual change from the initial year, 1900, to the final year, 2009.

2.3. Data Classification and Preparation

Details on data collection and compilation are described in the Supplementary Material. All data are grouped into six categories: (1) data on production, apparent consumption, or shipments of ACPs; (2) data on import and export of ACPs; (3) data on aluminum contents of various ACPs; (4) data on loss rates of aluminum from different life processes; (5) data on the composition of some flows, such as flows from Fabrication to Manufacturing processes; and (6) data on lifespans of final products in the Use stage.

Data sources are various, including governmental or industrial statistics, such as online database of U.S. Geological Survey (U.S. Geological Survey, 2006; 2011) and annual Aluminum Statistical Review compiled by the Aluminum Association (The Aluminum Association, 2010); books or research reports, such as Aluminum Recycling (Schlesinger, 2007) and many reports on aluminum material flow analysis (European Aluminum Association and Organisation of European Aluminium Refiners and Remelters, 2004; Troyes University of Technology, 2009), aluminum life cycle assessment (European Aluminum Association, 2008; International Aluminium Institute, 2007; PE Americas, 2010; The Aluminium Association, 1998), or aluminum contents (Ducker Worldwide, 2008a,b); academic papers, such as Recalde et al. (2008) and Wang and Graedel (2010); standards on ACPs, such as SECSPC (2004a,b); and other information, such as Anonymous (2011a).

3. Results on Flows

Historical cumulative aluminum cycles for the period of 1900-2009 in the United States are shown in Fig. 1. In this section, results on flow analysis are elaborated in the sequence from top (trade flows) to bottom (loss flows) and from left (bauxite mining) to right (scrap recovery). The section ends with a summary of total input, output, and accumulation of aluminum in the U.S. anthroposphere.

3.1. Evolution of Aluminum Trade Quantity and Composition

Traded ACPs measured in this study are listed in the Supplementary Material according to their relationship with each life process of aluminum life cycle. These ACPs are then classified into five categories: 1) Bauxite and Alumina, 2) EOL Products and Scrap, 3) Unwrought Aluminum, 4) Semis, and 5) Final Products. The first and second categories could be regarded as raw materials to produce unwrought aluminum (the third category), while the fourth and fifth categories could be regarded as further fabricated or manufactured products of unwrought aluminum. Unfortunately, trade of aluminum embedded in EOL Products could not be quantified due to data unavailability.

Trade of aluminum before 1940 was negligible compared to later years, as shown in Fig. 2(a). After 1945, both total import and total export of aluminum in the United States experienced an increasing trend until very recent times. As a result, the U.S. has been a net importer of aluminum for more than a century. During this 110-year period, the U.S. accumulated net import of aluminum was more than 280 Tg.

Analysis of net import of aluminum by categories, as illustrated in Fig. 2(b), shows that aluminum was mainly imported into the U.S. in the form of bauxite and alumina, particularly before 1990; and the
Fig. 1. The cumulative anthropogenic aluminum cycle for the United States, 1900–2009. All flow values are in Tg (million metric tons) Al. For the trade flows, net import or net export, instead of gross import or gross export, is indicated. The widths of the arrows roughly reveal the relative magnitude of the flows.
U.S. has been a net importer of unwrought aluminum since 1960, particularly when net import of bauxite and alumina decreased after 1980. Before 1982, the U.S. was a net exporter of final products, at an annual rate that increased until 1973. After 1983, however, the U.S. mostly served as a net exporter of alumina because the production of primary aluminum, which is energy intensive, was reduced. Concomitantly, the U.S. increased its net import of unwrought aluminum, semis, and final products. One interpretation of these results could be that the energy crises stimulated the U.S. to transfer its energy-intensive industry to other countries.

It appears that crises had substantial impacts on aluminum trade, and usually were turning points of the long-term trade evolution. As illustrated by Fig. 2(b), World War II was the first crisis that resulted in obvious change of the U.S. aluminum trade. Net import of bauxite and alumina increased quickly during the war period and suddenly decreased in 1945 as the war was over. More interestingly, during or after the shock of each energy crisis in 1973, 1979 and 1990 (Anonymous, 2011b), the U.S. reduced its import of bauxite and alumina because the production of primary aluminum, which is energy intensive, was reduced. Consequently, the increasing domestic production of alumina resulted in a growing gap between domestic supply and demand of bauxite, and thus a growing net import of bauxite from 1945 until the first energy crisis in 1973. Second, U.S. primary aluminum production began to exceed alumina production in the end of 1960s. Thus, the net import of alumina increased rapidly throughout the 1970s and remained stable during the period 1980 to 2000.

According to U.S. Geological Survey (2011), the U.S. domestic reserves of bauxite were less than 0.1% of global reserves in 2010. Therefore, it is mainly because of the U.S. lack of domestic bauxite ore that most of its bauxite supply came from imports after 1945. A particularly notable feature of the dynamic cycle is the impact of crises on bauxite and alumina production (Fig. 3). First, World War II resulted in a dramatic but short increase of production. Second, after each of the three energy crises and the 2008 financial crisis, production of both bauxite and alumina decreased substantially.

### 3.2. Domestic Production of Bauxite and Alumina

The life cycle of aluminum in the anthroposphere begins with bauxite mining. Before 1945, the U.S. basically relied upon domestic mining of bauxite for alumina refining, and domestic production of alumina for primary aluminum smelting (Fig. 3 and Fig. S.8 in the Supplementary Material). However, the gap between domestic supply and demand for both bauxite and alumina became substantial after 1945. First, domestic mining of bauxite in the period 1945 to 1980 remained stable. It then decreased year by year to almost zero in the 2000s. Consequently, the increasing domestic production of alumina resulted in a growing gap between domestic supply and demand of bauxite, and thus a growing net import of bauxite from 1945 until the first energy crisis in 1973. Second, U.S. primary aluminum production began to exceed alumina production in the end of 1960s. Thus, the net import of alumina increased rapidly throughout the 1970s and remained stable during the period 1980 to 2000.

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### 3.3. Flows of Unwrought Aluminum into the Fabrication Process

Unwrought aluminum comprises both primary aluminum and secondary aluminum. As illustrated by Fig. 4, except around the 1920–1921 and 1929–1933 economic crises, total unwrought aluminum flow into the fabrication process (TUAFlow) in the United States grew year after year before 1938 and had a sharp increase during the Second World War. Then, after a short term decrease, TUAFlow grew continuously again until 1974 just after the first oil crisis broke out.

There are several features of particular interest during the period 1900–1974: (1) TUAFlow was dominated by domestic primary aluminum production, which accounted for more than 70% in most years; (2) the share of secondary aluminum in TUAFlow was relatively stable from 1954 to 1974, with 14–18% of TUAFlow from new scrap and only 4–6% from old scrap; (3) the U.S. was a net exporter of unwrought aluminum before 1960, while after that was basically a net importer; (4) after a sharp increase from 1939 to 1945, the U.S.
share of global primary aluminum production decreased continuously, from about 52% in 1945 to less than 32% in 1974.

TUAFlow was relatively stable from 1974 to 1990, and then after a big increase in the 1990s declined after 2000. Some features during the period of 1975-2009 should be noted: (1) domestic primary aluminum production in the U.S. showed a declining trend, and seemed very vulnerable to the several energy crises that occurred during this period (Fig. 3); consequently, the share of domestically-produced primary aluminum in TUAFlow decreased from 76% in 1974 to only 25% in 2009; (2) secondary aluminum production increased substantially during this period, with its share of TUAFlow increasing from 19% in 1974 to 37% in 2009; however, more than half of the secondary aluminum was from new scrap rather than old scrap; (3) the U.S. net import of unwrought aluminum greatly increased, with its share of TUAFlow growing from only 5% in 1974 to about 38% in 2009, revealing the fact that the U.S. moved a large part of its primary aluminum production capacity to other countries; (4) consequently, the share of U.S. primary aluminum production in global production decreased during this period, from 32% in 1974 to only 5% in 2009.

3.4. Flows of Foundry Castings and Mill Products into Manufacturing Process

Between the fabrication process and the manufacturing process, flows of aluminum leave the former in the form of semi-products (semis) classified into eight groups (Fig. 5(a)), while enter the latter into seven end-use sectors (Fig. 5(b)). The total amount of these flows increased more or less continuously from 1900 to 2000, with the exception of three obvious decreases in 1973–1975, 1978–1982, and 1989–1991. Note that these three decreases coincided with and therefore might result from the energy crises of 1973, 1979 and 1990 (Anonymous, 2011b). After the peak value totaling more than 9000 Gg in 2000, the total aluminum flows into manufacturing decreased sharply in 2001 (the year of the 9/11 attacks) and then decreased again to about 4500 Gg in 2009 (only 50% of that in 2000) after the financial crisis.

Sheet & Plate semis have dominated these flows throughout the entire period of our analysis, with Extruded Products and Foundry Castings also being important (Fig. 5(a)). Annually, Sheet & Plate accounted for about 40–50% of these flows after 1981; these materials were mostly used by three end-use sectors, Containers and Packaging (C&P), Transportation (Trans), and Building and Construction (B&C). Foundry Castings accounted for about 13–14% of the total in the 1980s and then increased to 25% around 2000. This is because about 60–75% of Foundry Castings were used by the Trans sector owing to the light weighting trend of automobiles. As for Extruded Products, more than 35% and more than 25% were used by B&C and Trans sectors after 1995, respectively. From 1955 to 2009, the share of Foil in flows leaving the fabrication process was 6–7%, with more than 60% of it used to produce C&P materials. The share of Electrical Conductors decreased from 6–9% in the 1960s to 3–4% in the 2000s; all of it entered the Electrical Engineering (EE) sector. Finally, Wire, Forgings & Impacts, and Powder & Paste accounted for only 2–3% of the flows leaving the fabrication processes after 1980.

If analyzed from the manufacturing side (Fig. 5(b)), aluminum flows leaving the fabrication process while entering the manufacturing process were dominated by B&C, C&P and Trans, with these three sectors having the biggest share before 1978, from 1979 to 1994, and after 1995, respectively. The shares of both B&C and EE have been decreasing since 1970, and the shares of the other three sectors, Consumer Durables (ConDur), Machinery and Equipment (M&E), and Others, remained relatively stable. More details on the distribution of flows from fabrication to manufacturing by both semis and end-use sectors are available in the Supplementary Material.

3.5. Input, Output and Change of the Aluminum In-use Stock

Input flows of aluminum into the Use stage came largely from domestic manufacturing, with modest adjustments related to the trade of aluminum embedded in final products. Comparing Fig. 6(a) with Fig. 5(b)
Since 1900, the composition of these output flows is determined by both the composition of flows into Use and the average lifespans of different final products. Thus, the share of B&C sector in total scrap generation was relatively small (less than 10% before 2000 and about 14% in 2009) because of the several decades-long lifespan, while the share of the C&P sector has grown rapidly since 1960 because of its one-year lifespan. Note that the share of Trans has been increasing since 1990 and now is the biggest among all the seven sectors. Unlike China, where the output flow from aluminum deoxidizers in the steel industry became large after 2000 (Chen and Shi, 2012), the share of deoxidizer loss in total output flow in the U.S. was quite small compared to the level of scrap generation.

The change of aluminum in-use stock in the U.S., calculated as the difference between input flow and output flow, showed different features in different periods as illustrated by Fig. 6(c): in 1900–1973, it experienced a continuously increasing trend; in 1974–1991, it fluctuated between 1.0 Gg and 3.5 Gg, with three sharp decreases coinciding with the three energy crises in this period; in 1992–2000, it increased very rapidly because of the increase in the Trans sector; and in 2001–2009, it experienced two sudden decreases coinciding with the 9/11 attack and the 2008 financial crisis.

3.6. Recovery of Aluminum Scrap

Aluminum scrap includes both new (prompt) scrap and old (post-consumer) scrap. Details on quantifying the amount of new scrap from various fabrication processes and manufacturing process are described in the Supplementary Material. The loss rates of new scrap in the processes of Collection of EOL Products and Scrap (CES) and Treatment of Scrap (TS) are both assumed to be zero, while the loss rate in the Melting of Scrap (MS) process is assumed to be 5% (European Aluminum Association, 2008).

Although old scrap generation can be modeled by end-use sectors, recycling rates of old scrap cannot be calculated on that basis because data on scrap recovery by sector do not exist except for aluminum cans (The Aluminum Association, 2010). Methods and results for recycling rates of aluminum varied substantially in previous studies (Global Aluminium Recycling Committee, 2006; Graedel et al., 2011; McMillan et al., 2010; Plunkert and Geological Survey (U.S.), 2005; Sibley, 2011). According to the modeling results in the present work, EOL collection rates of aluminum in the U.S. varied between 40% and 65%, and were very sensitive to the estimate of final products’ lifespans in the Use stage, the export of EOL products and old scrap, and the amount of EOL products entering hibernating stock. The loss rate of aluminum in the TS and MS processes for old scrap was about 8% and 5%, respectively, according to Wang (2011) and European Aluminum Association (2008).

Unlike Europe, where aluminum scrap consumers are generally categorized into two groups, refineries and remelters (European Aluminum Association, 2008), the Aluminum Association divides those in the United States into three kinds, secondary smelters, integrated producers,3 and other consumers (The Aluminum Association, 2010). From 1946 to about 1960, more than 70% of aluminum scrap in the United States was consumed by secondary smelters. However, during the periods increasing after 1980. More details about trade of final products are described in Section 3.1 and the Supplementary Material.

Output flows from the Use stage comprise two parts, the amount of aluminum contained in discarded EOL products and dissipative loss of aluminum in the Use stage. Total output from Use increased from 1900 to 2001. After a sudden decrease resulting from the C&P sector in 2002, it grew again until 2009, as illustrated by Fig. 6(b). The composition of these output flows is determined by both the composition of flows into Use and the average lifespans of different final products. Thus, the share of B&C sector in total scrap generation was relatively small (less than 10% before 2000 and about 14% in 2009) because of the several decades-long lifespan, while the share of the C&P sector has grown rapidly since 1960 because of its one-year lifespan. Note that the share of Trans has been increasing since 1990 and now is the biggest among all the seven sectors. Unlike China, where the output flow from aluminum deoxidizers in the steel industry became large after 2000 (Chen and Shi, 2012), the share of deoxidizer loss in total output flow in the U.S. was quite small compared to the level of scrap generation.

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3 The U.S. Geological Survey divides integrated producers into integrated aluminum companies, independent mill fabricators, and foundries in its annual Mineral Yearbooks on aluminum before 2005, while after 2006 integrated aluminum companies are integrated into independent mill fabricators (U.S. Geological Survey, 2010).
3.7. Aluminum Lost, Exported as EOL Products, or Entering Hibernating Stock

The difference between old scrap generation modeled by the top-down method and old scrap collection estimated according to the mass balance method at the WM&R stage is the uncollected EOL aluminum at the CES process. The magnitude of uncollected EOL aluminum, as indicated in Fig. 8 (EOL Products Lost, Exported, or Hibernating), increased quickly after 1960, and exceeded the sum of aluminum losses from all other processes after 1980. However, unlike aluminum losses from all other processes that are either returned to the environment or used for non-metallic or deoxidizer application, the destination of uncollected EOL aluminum is more difficult to identify. It should not be regarded entirely as losses, because part of it may be exported as EOL products and recycled outside the country, and part of it may enter hibernating stock with the potential for future recycling. Unfortunately, due to data unavailability, we cannot quantitatively separate the EOL aluminum exported as EOL products or entering hibernating stock from that lost back to the environment.

Excluding the uncollected EOL aluminum, aluminum losses are dominated by two flows that occur before aluminum is refined from chemical compound to metal single substance: losses into red mud at the aluminum refining process and bauxite or alumina used for non-metallic applications.

3.8. Input, Output and Accumulation of Aluminum in the U.S. Anthroposphere

In addition to Fig. 1, which illustrates historically cumulative aluminum cycles, Table 1 shows decade-by-decade flows of aluminum entering, leaving, and accumulating in the U.S. anthroposphere. Results show that from 1900 to 2009 total input of aluminum into the U.S. anthroposphere amounted to 438 Tg, with only 7% of it coming from domestic extraction and 93% coming from import, while total output amounted to 211 Tg (about 48% of total input), with 59% leaving the U.S. anthroposphere in the form of export, only 25% in the form of domestic loss back into the environment, and about 16% used in non-metallic applications such as refractory materials.

4. Results on Stocks

4.1. Total Domestic Stock and Its Distribution among Different Stocks

In 1900, before any significant processing and use of aluminum, the U.S. stock of aluminum was about 36 Tg, all in bauxite ore (Fig. 9). The situation was little changed until the 1940s, when significant use (and significant import) began. The result was that the domestic bauxite stock decreased, but the stock in use and in various loss reservoirs increased. In 2009, total stock was 316 Tg, about nine times of that in 1900, bauxite ore being only 2% of the total, while in-use stock comprised 48%. A consequence is that although the U.S. accounts for 5% and 11% of global primary aluminum production and consumption (Fig. 4), its domestic reserves of bauxite are less than 0.1% of global reserves (U.S. Geological Survey, 2011). This implies that in the future the U.S. will probably have easier access to secondary aluminum than to primary aluminum, unless it is able to continue importing large amounts of bauxite and alumina from other countries or to develop new technologies to replace bauxite by other raw materials such as alunite or anorthosite.

By 2009, more than 27% of aluminum having entered the U.S. anthroposphere during the period 1900-2009 had been lost, with about 10% in tailing ponds, 6% in slag repositories and landfills, and 10% used for non-metallic use; while about 23% were either lost into the obsolete stock, exported as EOL Products, or residing in hibernating stock. It is necessary to point out that it is difficult to determine the distribution among obsolete stock, exported EOL products, and hibernating stock, and it would be important to identify and quantify the amount and distribution among them because this aluminum

About 35% of total input was accumulated in domestic in-use stock, and the fate of the other 17% was unknown (either still residing in hibernating stock, lost, or exported in the form of EOL products).

Analysis of the distribution of each flow among the eleven decades, based on data listed in Table 2, shows that less than 5% of most flows took place before 1950 while more than 50% of them occurred in the last two decades. For example, import from 1900 to 1949 only accounted for 1% of historical cumulative import, while about 61% of historical cumulative import took place in the period 1990–2009 (35% after 2000). Also, for flows entering the Use stage only 3% took place in the period 1900-1949, while 52% occurred in the period 1990–2009 (27% after 2000). This reflects the continuous increase of many flows, including trade, consumption, and scrap generation, during the whole studied period.
The data used in this analysis is believed to be reasonably reliable but are known to have uncertainties, especially so far as losses, EOL recovery, and trade of final products are concerned. We are not able to estimate the reliability of information related to these parameters. Therefore, only uncertainties in different lifespan parameters in the top-down method are analyzed in this study. We employed normal distributions and midrange lifespan values, which we regard as the most reliable approach. In similar work, Chen and Shi (2012) show that scrap generation and in-use stock are not very sensitive to the differences of distribution models, but are sensitive to the mean values of lifespans. Figures illustrating the results of our own uncertainty analysis can be found in the Supplementary Material; they suggest that our conclusions are reasonably robust.

The results in this paper clearly illustrate the dramatic transition that has occurred in U.S. aluminum acquisition and use over slightly more than a century. Until the 1940s, aluminum was more a laboratory curiosity than an industrial metal. This changed rapidly in and after World War II, as an increasingly wealthy population employed aluminum in its many applications and by the 1990s had clearly entered into a decline, domestic depletion (Recalde et al., 2008). Meanwhile, aluminum losses to the environment had shifted from those only associated with ore processing to those related to unrecovered EOL aluminum-containing products.

The preceding paragraph demonstrates the benefits that can be derived by dynamic MFA analysis (i.e., MFA analysis over time). Such studies allow researchers to derive estimates of in-use stocks at any time within the analysis, to quantify losses to the environment, to reveal stocks and flows changes coincident with external events such as resource restrictions and political/energy/financial crises.

Table 1
Aluminum flows entering, leaving, and accumulating in the U.S. anthroposphere.

<table>
<thead>
<tr>
<th>Period</th>
<th>DOS</th>
<th>TI</th>
<th>TE</th>
<th>TNI</th>
<th>IPU</th>
<th>OPU</th>
<th>CIS</th>
<th>OHSE</th>
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<td>651</td>
<td>4351</td>
<td>2042</td>
<td>1966</td>
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<td>5321</td>
<td>8274</td>
<td>39109</td>
<td>30835</td>
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<td>17298</td>
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<td>8762</td>
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<td>6145</td>
<td>16948</td>
<td>64769</td>
<td>47821</td>
<td>39121</td>
<td>13709</td>
<td>25412</td>
<td>9779</td>
<td>10760</td>
<td>6084</td>
<td>1932</td>
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<tr>
<td>1980–1989</td>
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<td>19667</td>
<td>70004</td>
<td>50337</td>
<td>52085</td>
<td>26006</td>
<td>26079</td>
<td>14941</td>
<td>6491</td>
<td>4772</td>
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<td>32144</td>
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<td>64376</td>
<td>70304</td>
<td>35364</td>
<td>34940</td>
<td>18823</td>
<td>9718</td>
<td>6359</td>
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<tr>
<td>2000–2009</td>
<td>128</td>
<td>43492</td>
<td>116010</td>
<td>72517</td>
<td>76489</td>
<td>44846</td>
<td>31643</td>
<td>25967</td>
<td>9597</td>
<td>5908</td>
<td>−469</td>
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Total Net Import (TNI) = Total Import (TI) – Total Export (TE).
Change in In-use Stock (CIS) = Input into Use (IPU) – Output from Use (OPU).
OHSE: Obsolete and Hibernating Stocks Increase and Net Export of EOL Products.
and to study changes over time in such parameters as relative flows into use or import/export ratios. Notwithstanding this utility of method, dynamic MPAs are uncommon because of their extensive data requirements. In addition to the present work we cannot find similarly comprehensive dynamic stocks and flows analysis of metals except that for North American copper (Spatari et al., 2005), U.S. iron (Müller et al., 2006), Chinese aluminum (Chen and Shi, 2012) and another for U.S aluminum (Liu et al., 2011).

The absolute in-use stock for 2007 calculated by this study (149 Tg) is about 60% higher than the 93 Tg estimation of (McMillan et al., 2010) and about 6% higher than the 140 Tg estimation of (Hatayama et al., 2009) for the same year. These differences may be mainly a result of our much more complete analysis of trade of Final Products and longer lifespan estimates for some sectors. In contrast, the 127 Tg absolute in-use stock calculated by this study for 2001 is slightly less than the 139 Tg estimation for the same year by (Buckingham and Geological Survey (U.S.), 2006), despite the difference between our 40 Tg estimation of Trans stock and the 19 Tg estimation of automobile stock from (Buckingham and Geological Survey (U.S.), 2006) for the same year. We think the disparity in Trans stock is reasonable because the Trans sector in this study includes not only airplanes but also airplanes, trains, and marine vessels. However, as the methodology for accounting total in-use stock in (Buckingham and Geological Survey (U.S.), 2006) is unknown, we are unable to identify the reasons for the different estimates of total absolute stock. Finally, it is noted that our 146 Tg estimation of absolute in-use stock is the same as that calculated by a recent paper (Liu et al., 2011) which analyzes U.S. aluminum stocks and flows from 1900 to 2008. This dynamic analysis determines in-use stock as the cumulative difference between flows into and out of use (the “top-down” method). An alternative (“bottom-up”) method is to inventory all aluminum-containing final products at a given point in time, adding up the embodied aluminum in a given area. The latter approach was applied to the state of Connecticut by Recalde et al. (2008) and that determination and ours are compared in Table 2. We note that for the sectors of Trans and “B&C plus EE,” the national level of per-capita stock calculated by this study agrees rather well with the bottom-up estimate at the state level. However, for the other four sectors, the top-down results are higher than the bottom-up estimates. This is likely to be the result of (1) the bottom-up analysis could not cover all final products that are in use, especially in these four sectors, therefore it would inevitably underestimate the in-use stock (a similar result was found for China by Chen and Shi (2012), and (2) the national level per-capita stocks might really be higher than those in Connecticut, especially for the M&E sector, because Connecticut is less industrial than some other parts of the U.S.

If Fig. 10(b) in this paper is compared with Fig. 4 in Müller et al. (2011), we note that around 1980 the U.S. per-capita stock in use of iron starts to decline. In contrast, aluminum per-capita stock in use kept increasing until 2008. Sector-level comparison helps reveal that this phenomenon is the result of and perfectly reflects the light-weighting trend in the Road Transportation sector, namely the substitution of more and more aluminum for iron in automobiles.

A particularly interesting aspect of the results is the larger quantity of aluminum contained in U.S. in-use and obsolete or hibernating stocks, and the very small amounts in domestic ores. The potential for “urban mining” is thus quite large, but doing so efficiently will require social and governmental changes. The alternative is often to mine primary aluminum, invest the energy to turn it into products, and then use those products only once. Doing so cannot be regarded as good resource stewardship, and evolutionary approaches to resource reuse, guided by information such as that contained in the present work, is a necessary transformation if long-term sustainability is to be achieved.

6. Conclusions

This paper analyses the anthropogenic stocks and flows of aluminum in the U.S. from 1900 to 2009 by using time-series data for mining, production, fabrication, manufacturing, trade, and loss rates, and
by applying a dynamic top-down method to model scrap generation and in-use stock.

The main features for anthropogenic aluminum flows are as follows: (1) the U.S. has been a net importer of aluminum for more than a century, with aluminum imported first only in the form of Bauxite and Alumina, and then also in the form of unwrought aluminum after 1960, and finally as well as in the form of Final Products after mid 1980s; however, the U.S. was mainly a net exporter of aluminum scrap, especially after 2000; (2) the U.S. domestic production of bauxite, alumina, and primary aluminum, and the aluminum flows into fabrication, manufacturing, and use processes, as well as trade flows, were vulnerable to World War II, the three energy crises, and the 2008 financial crisis; basically, after each energy crisis the U.S. tended to produce less alumina, less primary aluminum, less semis, as well as less final products, and therefore import less bauxite and alumina but import more unwrought aluminum and final products; (3) before 1974, most of aluminum flows into fabrication process came from domestic primary aluminum production, while after 1974, more and more aluminum flows into fabrication process came from domestic production of secondary aluminum (due to increasing scrap generation) and the net import of unwrought aluminum; (4) both total input flows into manufacturing and Use processes increased continuously from 1900 to 2000 with the exception of three sudden decreases coinciding with the three energy crises, and then decreased in 2001 as well as from 2005 to 2009; (5) historically cumulative aluminum input into the U.S. anthroposphere amounts to 438 Tg, with about 35% of it accumulating in domestic in-use stock, about 48% exported or lost to the domestic environment, and the sink of the rest 17% obscure (exported as EOL product, lost, or entering the domestic hibernating stock).

Results on stock analysis indicate that total domestic stock of aluminum in the U.S. increased from 36 Tg in 1900 to 316 Tg in 2009, with only 2% residing in bauxite stock, 48% in in-use stock, and the remaining 50% in either tailing ponds, landfills, or hibernating stock. This fact implies that in the future the U.S. will probably have easier remaining 50% in either tailing ponds, landfills with only 2% residing in bauxite stock, 48% in in-use stock, and the rest 17% obscure (exported as EOL product, lost, or entering the domestic hibernating stock).

Acknowledgement

The research is funded by the Aluminum Association. We gratefully acknowledge Mr. Marshall Jilong Wang and Mr. Nicholas A. Adams for providing a lot of useful data and other information. However, the opinions expressed are ours and do not necessarily reflect those of the Aluminum Association.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eleconeco.2012.06.008.

References


