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Analysis

Quantifying U.S. aluminum in-use stocks and their relationship with economic output

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ABSTRACT

A dynamic material flow analysis model is developed to quantify aluminum in-use stocks and old scrap recycling and recovery in the United States for the period of 1900 to 2007. The total in-use aluminum stock in 2007 is estimated as 93 million metric tons, which represents approximately 34% of the cumulative apparent consumption since 1900. Alternately, since 1900 nearly 40% of the cumulative discarded aluminum has not been recycled for domestic use in the U.S. or for export to foreign consumers. Statistical time series analysis is used to explore the relationship between model results of in-use stocks and gross domestic product (GDP). Unlike most previous studies of material consumption and economic activity, which ignore the statistical properties of time series data to the detriment of model estimation and inference, data stationarity is explicitly evaluated through unit root testing and model specification is adjusted accordingly. The annual percentage change in GDP is found to have a large and significant association with the annual percentage change in net additions to in-use stocks. Model sensitivity and uncertainty are quantified through the application of the Fourier Amplitude Sensitivity Test and alternate specifications of product lifetime probability density functions.

1. Introduction

The demand for aluminum has grown tremendously since the mid-1800s and its worldwide use now is exceeded only by steel (IAI, 2009). The significance of aluminum as an industrial metal and climate change concerns have focused attention on the environmental impacts of aluminum production. While producing aluminum from mineral bauxite (i.e., primary production) is recognized for its large energy intensity and greenhouse gas (GHG) emissions, aluminum produced from recycled metal (i.e., secondary aluminum) is notable for its much lower environmental impact. Because of aluminum's nature as a lightweight metal and the large difference between primary and secondary aluminum, two potential emissions mitigation strategies are to use aluminum in reducing the mass of appropriate products such as automobiles and to substitute secondary aluminum for primary aluminum. However, these strategies would require changes in the consumption of primary and secondary aluminum. The assessment of their feasibility should include the analysis of where potentially-recoverable aluminum resides in the U.S. economy and what drives its accumulation.

Material flow analysis (MFA) is a method of quantifying the mass of a material or product of interest as it moves throughout specified temporal and economic or geographic boundaries. A MFA is essentially a mass balance whose results are used to estimate intensity of use, in-use stocks, material recovery rates, and other aspects of the flows and stocks of materials within the chosen boundary (Bringezu and Moriguchi, 2002). When applied to an entire economy, MFA can provide information on the structure and dynamics of physical metabolism and resource productivity (Giljum et al., 2009).

MFA models can be developed for a single year, providing a static snapshot, or over multiple years, creating a dynamic analysis. Numerous static MFA models have been developed for a variety of materials and products. Other MFA studies have utilized dynamic models to calculate the changes of flows and stocks over time. These include analyses of lead (Mao and Graedel, 2009), cement (Kapur et al., 2008), iron (Müller et al., 2006), and copper in the U.S. (Zeltner et al., 1999), iron and steel in the U.K. (Davis et al., 2007), and furniture in private households in Colombia (Binder et al., 2001). Assessment of the global industrial metabolism of metallic ores is included in work by Krausmann et al. (2009). Research has also been undertaken to forecast material flows in applications such as concrete in Dutch housing (Müller, 2006) and global production of silicon (Williams, 2003).

Most previous MFA models developed for aluminum in the U.S. have been constructed as single point estimates. Recalde et al. (2008) developed a model of aluminum stocks for the state of Connecticut in the year 2000. The authors utilized a bottom-up approach, gathering

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data on the aluminum composition of products consumed within the state. A summary of aluminum flows in the U.S. in 2000 was described by Plunkert (2006), and Sullivan (2005) estimated the amount of in-use aluminum stocks. While these estimates do provide an assessment of current conditions, they are unable to describe historical dynamics of growth or to forecast future scenarios.

A dynamic MFA approach was recently applied to the U.S., Japan, Europe, and China by Hatayama et al. (2009) to analyze aluminum recycling potential. The authors estimate the possible reduction in primary aluminum consumption in each country/region by forecasting stocks and flows and by accounting for the alloy composition of the aluminum consumed and scrapped. Forecasts of per capita in-use stock for each country/region are made by curve-fitting a logistic function to an assumed relationship between per capita in-use stocks and per capita GDP. This method explicitly assumes that there will be no future product breakthroughs that push per capita in-use stocks above their prior saturation level, an assumption that we show to be in contradiction to historical behavior of aluminum in the U.S.

One of the significant contributions of our work is the linking of MFA and statistical time series analysis. Dynamic MFA models estimate flows and stocks over time, making time series analysis a natural choice for additional study of model results. In particular, we use this approach to quantify the relationship between in-use stocks and economic output as measured by gross domestic product (GDP). This work also analyzes the time series properties of the material flow and economic data. These issues have frequently been ignored in previous studies of the relationships between economic output and material consumption. If appropriate corrections are not made to time series data, common regression techniques can yield results with serious weaknesses related to estimation and inference.

These modeling efforts provide a novel analysis of the behavior of in-use stocks and lay the foundation for future work in forecasting potentially-recoverable aluminum. Overall, we aim to improve the management of aluminum as both a non-renewable resource and as a potential means of reducing GHG emissions by increasing the understanding of the drivers and dynamics of U.S. aluminum in-use stocks.

2. Methods

This research first develops a dynamic MFA model of U.S. aluminum and then applies quantitative time series analysis to describe the relationship between in-use stocks and GDP. The MFA model utilizes a top-down approach to estimate the U.S. in-use stock and old scrap recycling and recovery of aluminum beginning in the year 1900 and ending in 2007. Discarded aluminum is collected in the form of new and old scrap. Old scrap is generated once a product reaches the end of its useful lifetime and is retired and disposed. New scrap is generated during the production of semi-fabricated and finished products. New scrap recovery is not explicitly estimated by the model, but the consumption of new scrap is implicitly included in the apparent consumption data. Apparent consumption serves as a metric of total metal demand and is calculated as domestic primary and secondary production plus imports minus exports and adjusted for inventory change. Because it is generally of a known and homogenous quality, nearly all new scrap is recycled and recovered soon after its generation. Data on the apparent consumption of aluminum by major end-use category (USGS, 2009) are used to calculate model results for the seven major end-use categories of construction, consumer durables, containers and packaging, electrical, machinery and equipment, transportation, and other. Model equations and detailed discussion of the model calculations are provided in the Supplemental material (SM).

Aluminum products are added to the existing U.S. in-use stock of aluminum when they are consumed in the economy. As these new products enter their use phase, others are retired and discarded when they reach the end of their useful lives. The cumulative in-use stock accounts for the flows of new and retired products. There are instances when products, such as buildings, reach retirement and are not immediately discarded. These are referred to as "hibernating stocks" (Bergbäck and Lohm, 1997) and their effect has not been included in this model due to a lack of data. Additionally, based on the major areas of consumption it is a reasonable assumption that most of the aluminum products enter the waste stream after they reach the end of their useful lives.

Annual product retirement flows are calculated for each end-use category using a probability density function estimated to be representative of each category's average product lifetime. Product lifetime probability density functions based on the normal, beta, and Weibull distributions were selected from Melo (1999) and are identified in the SM. These product lifetime distributions were developed by first identifying lifetime intervals for sub-categories of products. The lifetime interval for each average end-use sector was then calculated by taking the consumption weighted average of lifetime interval of the appropriate sub-categories. Although product lifetimes evolve over time, the subjective nature of estimating a lifetime range for even a current product makes this parameter uncertain. In order to address this uncertainty, we first quantify the sensitivity of this model parameter and utilize alternate estimates of product lifetimes as an uncertainty analysis. These alternate estimates are also included in the SM.

The nature of the model's top-down approach and use of apparent consumption data means that imports and exports of finished products containing aluminum are not included as input data. These indirect flows may represent significant sources of aluminum for the U.S. economy, as the U.S. is a net importer of many finished goods. Although no analysis has been published on mass of aluminum contained in the net trade of finished products for the U.S., Johnson and Graedel (2008) found that metal in traded products accounted for between 13% and 57% of total metal trade flows for copper, lead, zinc, chromium, and silver.

In order to increase the model's capture of U.S. aluminum consumption, the existing apparent consumption data are augmented with the data that are available on the net trade of aluminum products (i.e. doors and windows, household items, and motor cars and other motor vehicles) for the period of 1989 to 2007 (USITC, 2009). Although these data do not capture all of the aluminum contained in traded finished products, they do represent products that are part of the major end-use categories of aluminum consumption. Including these net trade data increases the model's capture of consumption by an average of 13% over the period, compared to USGS apparent consumption data, and provides a lower bound of estimated aluminum use. Details are included in the SM.

Statistical time series analysis is used to investigate and quantify the relationship between in-use stocks and GDP. Unit root testing is performed to determine covariance stationarity for each data series. Non-stationarity refers to the condition where the probability distributions of data are time-dependent. When data exhibit this property, the ordinary least squares (OLS) method results in a spurious regression, where the regression estimators are biased and inefficient and have biased standard errors. Under these conditions, the inference of statistical significance of the estimators is invalid (Granger and Newbold, 1974). Following unit root testing, non-stationary data are subjected to first-differencing or trend removal. The relationship between in-use stocks estimated by the MFA model and GDP is then statistically estimated using linear estimation methods.

MFA model parameter sensitivity is quantified using the Fourier Amplitude Sensitivity Test (FAST) method (Cukier et al., 1978). The FAST method provides a quantitative measure of input sensitivity expressed as the fraction of total model variance. It is capable of accounting for nonlinear and interaction effects of input parameters, unlike a sensitivity analysis technique such as perturbation analysis (Saltelli et al., 1999).

3. Results

3.1. In-use Stocks

Two distinct periods of logistic growth in aluminum in-use stocks are seen in Fig. 1. The first corresponds to the period between 1946 and 1986, when aluminum consumption was rapidly increasing in the construction and electrical sectors. Although there was growth in each of the end-use sectors as a result of overall economic expansion, consumption was largely driven by new product development and product substitution (Brubaker, 1967). The second period of logistic in-use stock growth occurs from 1986 to 2006 and unlike the first expansion, this was driven by consumption and substitution in the transportation sector. In particular, substitution occurred for many cast iron components of automobiles (Sheridan, 1996).

The U.S. in-use aluminum stock in 2007 is estimated as 91.1 million metric tons (Mt) assuming a beta distribution for product lifetimes, 97.6 Mt assuming a normal distribution, and 92.2 Mt assuming a Weibull distribution. On average, approximately 34% of the cumulative apparent consumption of aluminum is contained in in-use stocks. The construction and transportation sectors represent the largest components of in-use stock, a result of their large fraction of apparent consumption and the length of their average product lifetimes. The container and packaging sector is another large consumer of aluminum, but the short lifetimes of its products result in little accumulation. The model estimates that the total in-use stock decreased for the first time in the post-war period in 2007. A loss in the total in-use stock indicates that the mass of aluminum products retired exceeds the mass of aluminum products consumed. The average net stock loss across the three lifetime distributions in 2007 was 546,000 Mt.

Sullivan (2005) estimates the in-use stocks in 2002 as 142 Mt, a figure that is 56% larger than the average of our model results of 91.1 Mt for the same year. Unfortunately, essential model details are not published there and it is not possible to determine the reasons for the large difference between estimates. Hatayama et al. (2009) estimate U.S. in-use stocks in 2003 at 120 Mt, compared to our model estimate of 92.3 Mt. Although the two models rely on different data sources, the difference in in-use stock estimates is most likely due to the product lifetime and recovery assumptions made by each model. When the same product lifetimes are used, which is discussed in Section 4, our model estimates 2003 in-use stocks as 119 Mt.

3.2. Aluminum Recycling and Recovery

The model estimates the annual mass of aluminum collected from product retirement (i.e., aluminum recycling) and aluminum metal obtained from scrap remelting (i.e., aluminum recovery). Unless specifically stated, the estimates of aluminum recycling and recovery do not include scrap trade flows. Fig. 2 illustrates that the transportation and containers and packaging sectors contribute the vast majority of aluminum recovered from old scrap. These data are consistent with the fact that the sectors represent a large fraction of apparent aluminum consumption and have high recycling rates relative to the other end-use sectors. The model estimates that the construction sector contributes a much smaller fraction of the aluminum recovered from old scrap even though the sector represents the largest portion of in-use stock. This can be explained by the assumed low recycling rate and the long product lifetimes of the sector. The accumulated unrecovered aluminum in the U.S. is estimated to be 107 Mt in 2007, which is equal to approximately 39% of the cumulative apparent consumption since 1900. This mass represents the material that was not collected for recycling in the U.S. and was therefore not made available for domestic consumption or for export to foreign markets.

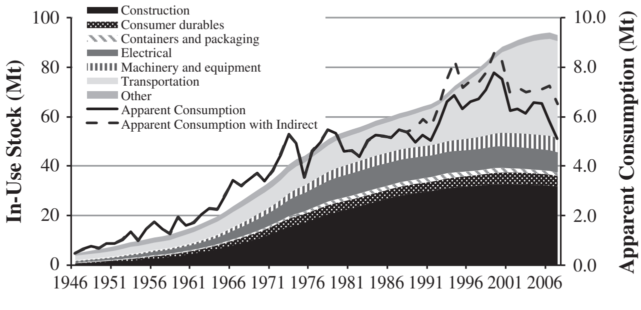

Fig. 1. U.S. estimated in-use aluminum stocks (average across distributions), apparent consumption (USGS, 2009), and apparent consumption including indirect flows.

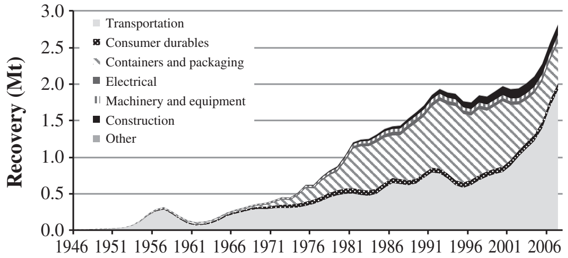

Fig. 2. Domestic recovery of aluminum from old scrap by end-use sector (average across distributions).

Additional information on U.S. aluminum is revealed by estimating the annual percentage of total aluminum collected for recycling by the domestic economy. This metric is calculated by dividing the mass of old scrap recycled domestically by the total mass of aluminum retired for that year based on model estimates of the annual amount of aluminum entering the waste stream.[1] To provide such a measure, it is necessary to first estimate the annual amount of old scrap that is collected domestically. USGS data on old scrap consumption do not represent domestic collection of old scrap because they include net scrap trade. As a result, data on scrap imports are subtracted and data on scrap exports are added, which leaves the mass of scrap recycled by the U.S. for consumption domestically or abroad.

Estimation of an overall recycling rate can be further improved by correcting for the consumption of aluminum beverage cans. Since the widespread adoption of aluminum beverage cans in the mid-1970s, the total recycling and recovery of aluminum has been largely driven by the collection of used beverage cans (UBCs). Yet, UBCs are part of the closed-loop system of aluminum beverage cans, whereby UBCs are collected for remelting into new cans. Due to this closed-loop system, the mass of UBCs collected does not provide the best indication of the amount of scrap available for producers of products other than beverage cans. Removing data on the consumption, disposal, and collection of aluminum beverage cans develops a more appropriate metric of old scrap recycling rate. Additional discussion is provided in the SM.

Without including UBCs, the highest recycling rate during 1972–2007 was approximately 37% in 2007. Preceding this peak was a period of gradually decreasing recycling rate, which concluded with a value of 13% in 2004. An earlier peak in recycling occurred in 1990 when approximately 29% of the aluminum from waste streams was recycled.

Even if aluminum is collected for recycling in the U.S., it is not necessarily consumed within the domestic economy. Because of its

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[1] Model estimates of old scrap recycling rely on assumptions of constant recycling rate, with the exception of the containers and packaging sector. Results of this calculation would reflect changes in the fraction of aluminum consumed by each sector and not changes in the recycling rate.

large endowment of in-use stocks, the U.S. has become a significant exporter of old scrap to the rest of the world. Using data available for UBCs beginning in 1989 (USITC, 2009), it is possible to estimate the percentage of U.S. recycled non-UBC scrap that is consumed domestically. Adjusting for UBC scrap lowers the rate of domestic old scrap consumption by as much as 50 percentage points; it is estimated that in 2004 only 2% of non-UBC old scrap that was recycled from U.S. waste streams was consumed domestically. Data used for this analysis, as well as an accompanying figure, are included in the SM.

3.3. Net Additions to In-Use Stock

Net additions to in-use stock (NAS) are calculated as the difference between annual aluminum consumption and retirement; this is equivalent to the annual net consumption of aluminum. The basic underlying thought is that periods of economic growth will lead to positive NAS. NAS peaked in 1973 at an average of 3.5 Mt then fell, likely due to a combination of the economic disruptions of the same year (e.g., stock market crash, first oil crisis) and a saturation of aluminum products in the construction market, as shown in Fig. 3. Although the NAS of the subsequent years remained positive, the growth trend experienced from 1946 to 1973 was not matched until the large expansion of the early 1990s when consumption in the transportation sector increased. The decreasing NAS since 2001 appears to have been first precipitated by a recession and then maintained by flattening consumption and growing product retirement in the transportation market.

3.4. Quantitative Analysis of Aluminum Stocks and GDP

One popular framework for analyzing metals use in an economy is the intensity of use hypothesis (International Iron and Steel Institute, 1972; Malenbaum, 1975). A type of environmental Kuznets curve (EKC) (Selden and Song, 1994; Grossman and Krueger, 1995), the intensity of use hypothesis asserts that metal consumption expressed on the basis of a per capita measure of gross economic output follows an inverted U-shape. As an economy first develops and expands its industrial base and infrastructure, it experiences an increasing intensity of use. The increase then slows and finally decreases as the economy matures and transitions from manufacturing to less resource-intensive activities. A comprehensive review of intensity of use and dematerialization studies is provided by Cleveland and Ruth (1999).

One purpose of this paper is to illustrate a number of potential metrics for evaluating the economy's in-use stocks. The focus of our analysis is the relationship between in-use stocks, population, and GDP. Fig. 4a presents indices of in-use aluminum stock per GDP, per capita, and per GDP/capita for 1946–2007. In-use stocks on a per GDP basis reveal a distinct plateau between 1975 and 1984, followed by a decrease of 18% from 1984 to 2007. Unless aluminum consumption increases on a large-scale relative to GDP growth, it appears that the U.S. aluminum in-use stock per GDP peaked at 10.6 Mt aluminum per million US$ GDP in 1982.

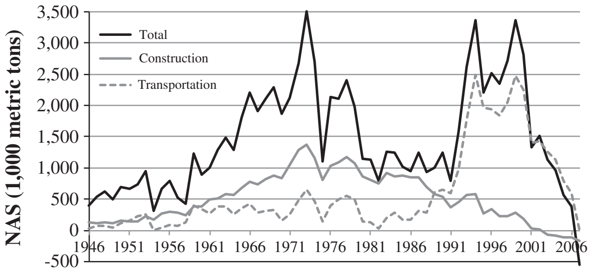

Fig. 3. Net additions to in-use stock, average across end-of-life (EOL) distributions.

Instead of in-use stocks, a more appropriate approach under the EKC framework is to analyze GDP with NAS, which, like GDP, is a flow variable. Fig. 4b depicts indices of NAS per GDP, per capita, and per GDP/capita for 1947–2007. With the exception of the early 1990s, which experienced a positive surge in NAS in the transportation sector, there is a distinct downward trend since 1973 for all three indices. This trend likely reflects the service sector's increasing share of GDP over the same period. In fact, the service sector share of GDP grew at an annual rate from 1973 to 2007 that was nearly twice as fast as its annual rate from 1947 to 1973 (BEA, 2010a).

We further analyze NAS per GDP and per GDP/capita by disaggregating the underlying NAS data by end-use sector. Data for the construction and transportation sectors, which represent the two largest components of total in-use stock, are presented as Fig. 5. The disaggregated data reveal that the NAS of nearly all the end-use sectors peaked by 1980, with the transportation sector the only exception. As was identified previously, the sector has experienced a surge in consumption since the early 1990s when large-scale substitution for cast iron components intensified in automobiles. NAS in the transportation sector have grown so quickly relative to GDP that they have largely offset the declines seen in the remaining end-use sectors. Fig. 5, together with Fig. 3, hint at an impending saturation in this market, an observation supported by the technical and economic difficulties associated with moving beyond cast components and producing vehicles with aluminum body panels and structural elements (Schatzberg, 2003).

We also analyze NAS on the basis of first difference of natural logs ($\Delta\ln$), which approximates the annual percentage change for small changes in data. Visual inspection of these data, shown in Fig. 6, indicates that there is some correlation between the $\Delta\ln$ GDP and $\Delta\ln$ NAS. This potential relationship is explored in detail in Section 3.4.1.

3.4.1. Stationarity Testing of Net Additions to In-Use Stock and GDP

The graphical analysis discussed in the beginning of Section 3.4 lends support to the existence of a systematic relationship between NAS and GDP. As a result, a statistical analysis was undertaken to develop a quantitative model for the period from 1948 to 2006.[2] Model parameters are chosen based on quantitative measures rather than on assumptions of their behavior, providing a more statistically rigorous approach than what is utilized by Hatayama et al. (2009). By analyzing time series data of NAS and GDP, we take a different approach than what has been used previously for cross-sectional studies of copper and zinc flows and stocks (Binder et al., 2006; Reck et al., 2006) and the largely cross-sectional analysis of European material and waste flows (Andersen et al., 2007).

Non-stationarity of time series data, defined as data having a time-dependent probability distribution, is a common condition and the appropriate testing and adjustments to model specification must be undertaken to obtain valid regression results. Previous econometric models utilizing OLS regressions of metal stocks data have neither acknowledged nor accounted for the possibility of non-stationary data. Consequently, these may represent instances of spurious regression. The most recent examples include models of Western European secondary aluminum production (Blomberg and Söderholm, 2009; Blomberg and Hellmer, 2000) and of the influence of old scrap flows and stocks on secondary copper production (Gómez et al., 2007). EKC analysis is also subject to the problems of non-stationary data, as discussed by Perman and Stern (2003). While some (e.g., Iriarte-Goñi and Ayuda, 2008; Friedl and Getzner, 2003) have addressed the time series properties of data, discussion and

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[2] The time period was chosen to correspond with the years subsequent to the end of the Second World War. Based on the use of first-differenced and lag values, 1948 is the starting year.

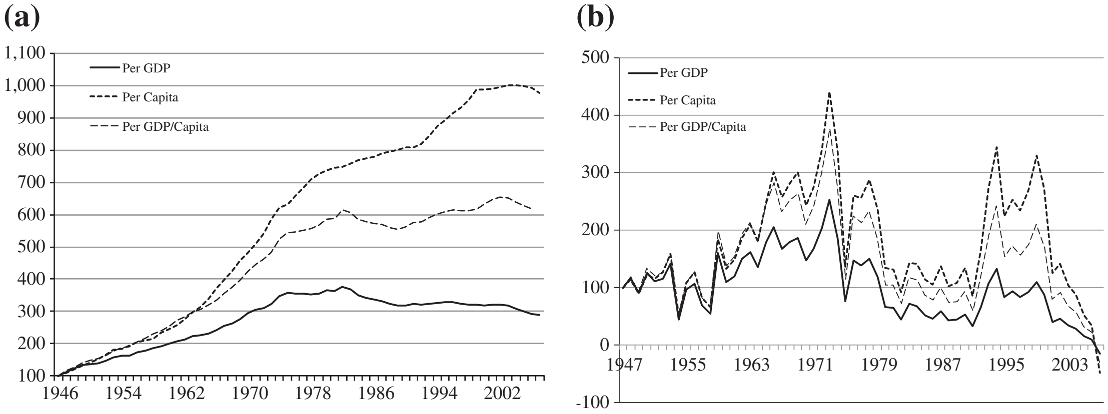

Fig. 4. Indices of (a) in-use stock (rebased, 1946 = 100) and (b) net additions to in-use stock (rebased, 1947 = 100).

testing of data stationarity remain absent in other studies of dematerialization and material intensity of use (e.g., Vehmas et al., 2007; Canas et al., 2003).

Stationarity testing of all data series were performed using the one- and two-break minimum Lagrange multiplier (LM) unit root tests of Amsler and Lee (1995) and Lee and Strazicich (2003), respectively. Initial testing was performed on the data in levels, which concluded that the GDP series contains a unit root. In order to have balanced equations where the data series are integrated of the same order, the data were then transformed by natural log and first-differenced to remove this unit root. Unit root testing results for all data are presented in Table 1. The two-break test was used first to identify the number of structural breaks in intercept and slope for each data series. In the instances where the LM unit root tests did not reveal a structural break significant at the 5% level, such as the disaggregate GDP data for durable manufacturing — motor vehicles, the Phillips and Perron (1988) and Kwiatkowski et al. (1992) tests were used. Data series were then detrended based on the identified structural break.

3.4.2. Model Estimation of Net Additions to Stock and Gross Domestic Product

The relationship between NAS and GDP is estimated for aggregate and disaggregate data series. The aggregate data includes estimation of the NAS calculated by the alternative lifetime distribution assumptions and NAS and GDP per capita. OLS is used to estimate the aggregate model for the period of 1948–2006 based on the specification

$$y_t = \alpha + \beta_1 y_{t-1} + \beta_2 x_t + \varepsilon_t \qquad (1)$$

where α is the intercept term, y_{t-1} is the one-year lag Δln NAS, x_t is Δln GDP, and ε_t is the random disturbance term.[3] Regression results are presented in Table 2, with t-statistics shown in parenthesis. The Breusch–Pagan and Breusch–Godfrey tests were used to test for the presence of heteroskedascitity and serially-correlated errors of the first order, respectively. Results of these tests indicate that their null hypotheses of no heteroskedasticity and no serial correlation cannot be rejected below the 16% level.

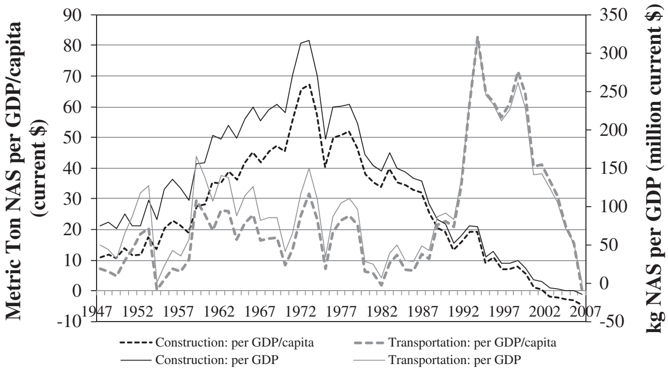

Fig. 5. Disaggregated construction and transportation net additions to stock per GDP.

The parameter coefficients in each model are interpreted as a percentage point change in Δln NAS that is associated with a one percentage point change in a regressor. For example, the regression estimates for Δln NAS indicate that each one percentage point increase in last year's Δln NAS and current Δln GDP is associated, *ceteris paribus*, with a change in current Δln NAS of −0.196 percentage points and 10.6 percentage points, respectively. Overall, the model results indicate that large, statistically significant changes in NAS are associated with changes in economic output as measured by GDP. These results are nearly the same using data measured on a per capita basis.

Model estimation for construction and transportation NAS included the effect of changes in GDP value added in the construction and durable goods — motor vehicles categories (BEA, 2010b), in addition to aggregate GDP. These were chosen because they represent a large fraction of apparent aluminum consumption and have significant economic importance. NAS data from the alternate product lifetime distribution assumptions were not included in the model estimation efforts. Initial regression using OLS revealed non-normally distributed residuals and as a result the models were estimated using maximum likelihood MM-regression estimators (Yohai, 1987).

Results of the model estimation reveal that changes in GDP by industry are associated with much smaller and mostly insignificant changes in Δln NAS for both the construction and transportation sectors than aggregate GDP. Additionally, changes in aggregate GDP were associated with much larger changes in Δln NAS for transportation than for construction. A detailed summary of model estimation and results is provided in the SM.

4. Sensitivity and Uncertainty Analysis

The product lifetime probability distribution, recycling rate, and recovery rate were subjected to the FAST method and results are presented in Table 3. Separate results are shown for the containers and packaging category because product retirement is assumed to be a simple one-year lag, which does not follow any statistical

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[3] Additional analysis was performed to test for a quadratic EKC relationship between in-use stocks and GDP. No statistically significant evidence for an EKC for Δln NAS was found. Results are provided in the SM.

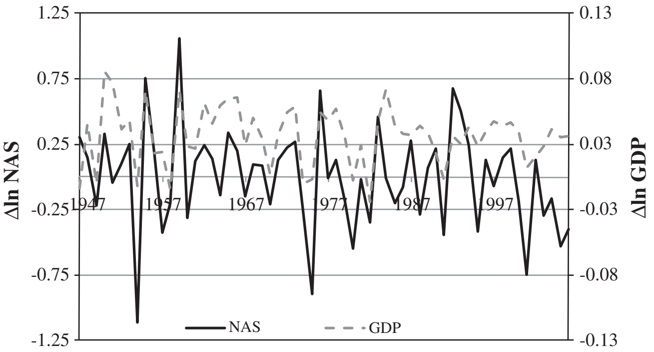

Fig. 6. First-differenced natural log of NAS and GDP.

distribution. Results show the largest sensitivity in the lifetime distribution and recycling percentage parameters for all end-use categories but containers and packaging. The recycling rate has the largest sensitivity for the containers and packaging category.

A successful application of the FAST method results in the summation of input sensitivity equal to unity. The results shown in Table 3 sum to approximately 0.83, indicating that 17% of the total model variance is not captured by the three selected parameters.

The uncertainty analysis of the model focuses on the lifetime distributions assumed for each product category. Additional normal and Weibull lifetime distributions were calculated based on product lifetimes provided in Müller et al. (2006) and are provided in the SM. Although these product lifetimes were originally applied to ferrous products in the U.S. market, aluminum is similarly used in many markets and it can be assumed that the aluminum products share the same product lifetime characteristics.

The largest difference between the product lifetimes provided by the studies of Müller et al. and Melo occurs in the construction end-use category. Melo assumes an average construction product lifetime of 31.5 years under a normal distribution. Müller et al. utilize a more comprehensive analytical methodology and develop a normally distributed average product lifetime of 75 years. Because the sector consumes a significant fraction of aluminum in the U.S., such a large disparity of when products are retired has major implications for the results of the model. In addition to longer product lifetimes, the alternate distributions have slightly different shapes than developed by Melo, which also affects the estimates of product retirement.

The general effect of increased estimates of product lifetimes is to increase current in-use stocks and shift old scrap availability into the future. Due to the timing of consumption growth, differences in model results for in-use stocks emerge toward the end of the period. On average, the product lifetimes from Müller et al. result in in-use stock estimates that are 14% higher and recovery estimates that are 24% lower than when using Melo. Additionally, the average domestic recycling rate (inclusive of UBCs) during 1972–2007 is on average seven percentage points higher using lifetime estimates from Müller et al.

5. Summary and Conclusions

U.S. aluminum consumption and in-use stocks have grown enormously since the beginning of the 20th century and by 2007 in-use stocks represented 34% of the cumulative aluminum consumption since 1900. Aluminum recovery has also dramatically increased, although the average recycling rate from 1972 to 2007 including UBCs is estimated as 25%. As a result, nearly 40% of cumulative apparent consumption was not removed from the waste stream for recycling. Additional significant losses of aluminum by the domestic economy have recently occurred due to scrap exports. These conditions represent significant opportunities for the U.S. domestic market to increase its recycling and recovery of aluminum from old scrap and indicate the need for more aggressive recycling policies. One option would be to explore the use of extended producer responsibility (EPR), or take-back, programs such as Europe's Waste Electrical and Electronic Equipment (WEEE), End-of-Life Vehicle, and Packaging Waste Directives (Tojo and Hansson, 2004).

The exponential increases in aluminum in-use stocks have historically been the result of a combination of new product development and substitution and economic growth; however, most of the aluminum end-use sectors have become saturated as measured by their mass of in-use stock per GDP and per GDP/capita. Our graphical and quantitative analyses of in-use stocks provide an increased understanding of where and why potentially-recoverable aluminum accumulates in the U.S. economy.

Table 1
Unit root testing results for data as first-differenced natural log and in levels (where noted).

Data series	Period	Break point(s)	Critical value at 5%	Test statistic	Unit root?
Aggregate data					
NAS	1948–2006	1973	−4.5	−9.58	No
NAS (level)	1948–2006	1972, 1990	−5.7	−6.57	No
NAS per capita	1948–2006	1973	−4.5	−9.57	No
NAS per capita (level)	1948–2006	1966, 1990	−5.7	−5.79	No
NAS alternative	1948–2006	1973	−4.5	−9.84	No
NAS alternative (level)	1948–2006	1977, 1990	−5.7	−5.80	No
NAS per capita alternative	1948–2006	1973	−4.5	−9.81	No
NAS per capita alternative (level)	1948–2006	1966, 1990	−5.7	−6.03	No
GDP	1948–2006	1970	−4.5	−7.32	No
GDP (level)	1948–2006	1980	−4.5	−3.37	Yes
GDP per capita	1948–2006	1970	−4.5	−7.38	No
GDP per capita (level)	1948–2006	1970	−4.5	−3.84	Yes
Data disaggregated by sector					
NAS (construction)	1948–2002	1993	−4.5	−6.75	No
NAS per capita (construction)	1948–2002	1994	−4.5	−6.79	No
NAS (transportation)	1948–2006	2000	−4.5	−9.56	No
NAS per capita (transportation)	1948–2006	2000	−4.5	−9.56	No
GDP (construction)	1948–2006	1957	−4.5	−5.75	No
GDP per capita (construction)	1948–2006	1957	−4.5	−5.70	No
GDP (motor vehicles)	1978–2006	na	PP: −2.97 KPSS: 0.463	PP: −4.99 KPSS: 0.227	No
GDP per capita (motor vehicles	1978–2006	na	PP: −2.97 KPSS: 0.463	PP: −4.97 KPSS: 0.229	No

Note: "Alternative" refers to NAS calculated using alternative product lifetime assumptions.

Table 2
Regression results for first-differenced total net additions to stock ($\Delta \ln$ NAS).

Regressors	$\Delta \ln$ NAS	$\Delta \ln$ NAS per capita	$\Delta \ln$ NAS (alternative)	$\Delta \ln$ NAS per capita (alternative)
Intercept	-0.361^{**} (-5.23)	-0.241^{**} (-4.51)	-0.241^{**} (-5.74)	-0.154^{**} (-4.74)
L.$\Delta \ln$ NAS	-0.196^{*} (-1.94)	–	–	–
L.$\Delta \ln$ NAS per capita	–	-0.184^{*} (-1.81)	–	–
L.$\Delta \ln$ NAS (alternative)	–	–	-0.251^{**} (-2.86)	–
L.$\Delta \ln$ NAS per capita (alternative)	–	–	–	-0.239^{**} (-2.69)
$\Delta \ln$ GDP	10.6^{**} (6.22)	–	8.19^{**} (7.90)	–
$\Delta \ln$ GDP per capita	–	10.4^{**} (6.04)	–	8.11^{**} (7.73)
R^2	0.437	0.424	0.562	0.552
Breusch–Pagan	0.910 *p*-value = 0.635	0.829 *p*-value = 0.661	1.82 *p*-value = 0.404	1.65 *p*-value = 0.439
Breusch–Godfrey (order 1)	1.83 *p*-value = 0.176	1.95 *p*-value = 0.163	0.0271 *p*-value = 0.869	0.0026 *p*-value = 0.959

Notes: "Alternative" refers to NAS calculated using alternative product lifetime assumptions. "L" refers to the 1-year lag of the variable. The *t*-statistics of regression estimates are in parenthesis. * denotes significance at the 5% level; ** denotes significance at the 1% level.

We have demonstrated the potential of time series analysis and other econometric techniques in building quantitative, explanatory models of MFA data. This work also highlights the importance of stationarity testing of MFA data, a consideration that has largely been ignored by the MFA community. The quantification of a relationship between the annual percentage changes in NAS and GDP leads to a better understanding of the extent to which economic output drives U.S. aluminum use. Due to the success of this methodology in analyzing a complex system like aluminum, we expect that the approach could be widely applied to other metals and material commodities.

One avenue for future research involves additional time series modeling. Testing for a cointegrating relationship between NAS and GDP data and then developing error correction models based on the cointegration results could provide further enhancements to the analysis. A second avenue is to investigate further the influence of economic activity on aluminum use. Variables could be constructed for the disaggregated components of GDP – final consumption, investment, government purchases, and net exports – to develop a richer analysis of the relationship between economic output and NAS of aluminum. As demonstrated in the paper, such an analysis would be complicated by the need for unit root testing of the individual variables as a precursor to estimating a regression model.

Although it was not in the scope of this research, it would be possible to use results of the model to forecast old scrap availability based on existing GDP forecasts. Estimating the future changes to in-use stocks and old scrap availability would aid both the evaluation of potential GHG mitigation strategies involving aluminum substitution and the management of aluminum as a non-renewable resource. For example, forecasts could provide planning agencies with metrics to help match recycling infrastructure capacity with anticipated flows of discarded aluminum products. More effective aluminum management could be a relatively inexpensive approach to GHG mitigation.

Table 3
FAST results for recovery model: contribution to model variance.

Parameter	Containers and packaging	All other end-use categories
Lifetime distribution	0.01	0.4
Recycling rate	0.8	0.4
Metallic recovery	0.03	0.02

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.ecolecon.2010.08.005.

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