Building the Material Flow Networks of Aluminum in the 2007 U.S. Economy

Wei-Qiang Chen,*[1,2] T.E. Graedel,[1] Philip Nuss,[1] and Hajime Ohno[1,3]

1. Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA

2. Institute of Urban Environment, Chinese Academy of Sciences, 1799 Jimei Road, Xiamen, Fujian 361021, P.R.China

3. Graduate School of Engineering, Tohoku University, 6-6-04, Aramaki Aza Aoba Aoba-ku, Sendai, Miyagi 980-8579, Japan

*Corresponding author: Wei-Qiang Chen, wqchen@iue.ac.cn, Phone: +86-592-619-0763. Fax: +86-592-619-0763

Please cite as:

Chen, W.-Q.; Graedel, T. E.; Nuss, P.; Ohno, H. Building the Material Flow Networks of Aluminum in the 2007 U.S. Economy. Environ. Sci. Technol. 2016, 50 (7), 3905–3912.

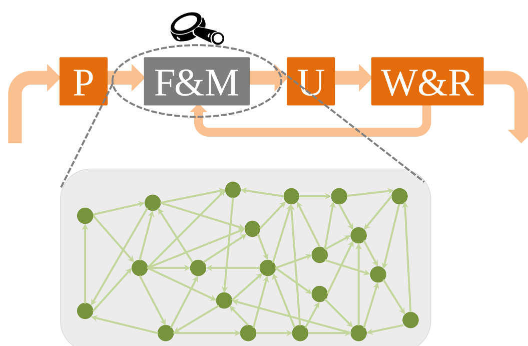
Building the Material Flow Networks of Aluminum in the 2007 U.S. Economy

Wei-Qiang Chen,*[1, 2] T.E. Graedel,[1] Philip Nuss,[1] and Hajime Ohno[1, 3]

1. Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA

2. Institute of Urban Environment, Chinese Academy of Sciences, 1799 Jimei Road, Xiamen, Fujian 361021, P.R.China

3. Graduate School of Engineering, Tohoku University, 6-6-04, Aramaki Aza Aoba Aoba-ku, Sendai, Miyagi 980-8579, Japan



Abstract: Based on the combination of the U.S. economic input-output table and the stocks and flows framework for characterizing anthropogenic metal cycles, this study presents a methodology for building material flow networks of bulk metals in the U.S. economy and applies it to aluminum. The results, which we term the Input-Output Material Flow Networks (IO-MFNs), achieve a complete picture of aluminum flow in the entire U.S. economy and for any chosen industrial sector (illustrated for the Automobile Manufacturing sector). The results are compared with information from our former study on U.S. aluminum stocks and flows to demonstrate the robustness and value of this new methodology. We find that the IO-MFN approach has the following advantages: (1) it helps to uncover the network of material flows in the manufacturing stage in the life cycle of metals; (2) it provides a method that may be less time-consuming but more complete and accurate in estimating new scrap generation, process loss, domestic final demand, and trade of final products of metals, than existing material flow analysis approaches; and, most importantly, (3) it enables the analysis of the material flows of metals in the U.S. economy from a network perspective, rather than merely that of a life cycle chain.

Keywords: material flow analysis, input-output analysis, complex network, industrial ecology

1 Introduction

An anthropogenic cycle is the quantitative characterization of the flows of a specific material into, within, and from a given anthropogenic system[1], and is usually also reported as material flow analysis (MFA) or substance flow analysis (SFA). One of the most widely used methods of characterizing anthropogenic metal cycles is the Stocks and Flows framework developed by the Yale Center for Industrial Ecology[1-5]. In this approach, the life cycle of a metal in the anthroposphere is divided into four principal life stages - production, fabrication and manufacturing, use, and waste management & recycling, each of which can be further divided into several sub-stages when necessary and appropriate. By using statistics mainly released by industries, this framework has been applied to characterize the anthropogenic cycles of many metals[4-12]. However, a significant challenge of such studies is that in almost all cases existing statistics cannot enable researchers to characterize elemental flows within the manufacturing stage at a level that is sufficiently detailed to identify flow magnitudes among manufactured products. For example, U.S. aluminum statistics[13] (which are believed to be more detailed than those of other economies) can only support the characterization of aluminum flows from eight semi-fabricated products to seven general end-use sectors[6], and there is a lack of data on aluminum flows (that are inferred to exist) among these seven end-use sectors.

Input-output analysis (IOA), a tool that has been widely used, provides monetary data on the inter-sectoral flows of goods and services within an anthropogenic system[14]. Compared to data that are from industrial statistics and are used in existing MFA/SFA studies to characterize metal flows in the manufacturing stage, data compiled in input-output (IO) tables have the great advantage that they are generally classified at quite high resolution. For example, the 2007 U.S. IO table includes 393 sectors, about 230 of which are categorized as manufacturing sectors[15].

Another advantage is that the IO tables provide information on monetary flows among all these sectors, as well as monetary value added to, and final demand for, all these sectors.

These features of IO tables enable researchers to analyze monetary flows and material flows (if they can be generated from the monetary flows) at a very detailed level and as a network (rather than as a life cycle chain in existing MFA/SFA studies). However, challenges exist when attempting to convert monetary flows in IO tables into material flows: (1) data in IO tables are only compiled using monetary metrics; (2) flows in IO tables are for all economic activities rather than just for activities involving physical flows; namely, they also include flows resulting from services (e.g., education or consultation) that do not correspond to any physical flows among sectors; (3) physical flows in an economy comprise not only commodity flows (each sector produces at least its own commodity, and possibly commodities of other industries, according to the commodity-by-industry approach[14, 15]) but also flows of material scrap and flows of material losses into the environment. However, data in IO tables capture only the commodity flows among sectors while ignore the flows of material scrap and losses, or treat scrap flows of all materials as a whole to the Scrap sector rather than as separate scrap flows (e.g., separate aluminum scrap and iron scrap flows).

By using a price homogeneity assumption, Nakamura and colleagues developed the WIO-MFA (waste input-output MFA) model[16, 17] and the UPIOM (Unit Physical Input-Output by Materials) model[18, 19] that can be used to estimate iron and other metals flows among IO sectors in Japan. The WIO-MFA and UPIOM models help to address the challenges of converting IO monetary flows into physical flows for materials such as iron, aluminum, and plastics for which there are relevant independent sectors in the Japanese IO tables. This means that if one were to apply the WIO-MFA and UPIOM approaches to the U.S. IO tables, bulk metals including iron, aluminum, and copper could be analyzed because U.S. IO tables have independent sectors for these three metals too. Thus, there is a significant potential to apply the WIO-MFA and UPIOM approaches in combination with existing MFA/SFA studies to characterize anthropogenic metal cycles at a highly detailed level in anthropogenic systems for which IO tables are available at fairly high resolution.

A further benefit of achieving detailed economy-wide characterization and quantification of material flows among sectors is that it creates a material-based version of an economic network that can be studied using complex network analysis (CNA) approaches[20]. CNA has been drawing increasing attention in the last two decades. However, few MFA/SFA studies have been analyzed using its tools. This is probably due to the fact that existing MFA/SFA studies supported by industrial statistics appear to be relatively simple systems. For example, there are typically less than twenty nodes in many MFA/SFA studies, and these studies are unable to explore inter-sectoral flows that would make the cycles look like a network rather than a life cycle chain. However, as mentioned above, if a MFA/SFA framework can be enhanced by transforming IO tables to provide a more detailed characterization of metal flows inside the manufacturing stage (meaning more nodes and inter-sectoral flows), it will be not only possible but also necessary to analyze the cycles using CNA tools and methods.

Thus, this study seeks to achieve the following goals using aluminum as the subject metal: 1) develop the method of building the IO-MFN (Input-Output Material Flow Network) for bulk metals in the entire U.S. economy, using data from a traditional MFA study[6] and the 2007 U.S. IO table[15]; 2) demonstrate how to build a detailed IO-MFN of the metal for specific IO sectors rather than for the entire U.S. economy, using the Automobile Manufacturing sector as an example; and 3) compare results generated from this study with those from a traditional MFA study[6] to demonstrate the robustness and value of the IO-MFN approach.

2 Methodology

A network consists of two basic components: nodes and links between those nodes (also termed “edges” in network analysis parlance). The magnitudes of the edges are the “edge strengths”. In the IO-MFNs, the nodes correspond to economic sectors while the links represent the physical exchange of metal (e.g., embodied in products) between nodes. The nodes and links of the material flow network of aluminum in the U.S. economy can be roughly grouped into two categories: (1) those determined by using the 2007 U.S. IO table (Figure 1, in green); and (2) those determined based on a traditional MFA study[6] (Figure 1, in purple).

2.1 Identifying Metal-Related Network Nodes

A commodity-by-commodity (C×C) IO table in the 2007 U.S economy was first generated by using the “after redefinition make and use tables” that was compiled and released by the U.S Bureau of Economic Analysis (BEA)[15]. Within this monetary IO table, there are three regions: (I) the inter-sectoral flow region that depicts monetary transactions among sectors; (II) the value added region depicting the contribution of employees, business owners and capital, and government to each sector; and (III) the final demand region depicting the final demand for commodities of each sector by net export, domestic personal consumption, domestic private investment, domestic government purchases, and change in domestic private inventories (Table S1 in Supporting Information 01 (SI-01)).

Theoretically, if one were to build a network of monetary transaction flows, each sector in Region I, Region II, and Region III can be a node in this network. However, the present study aims to build a material flow network of aluminum rather than one of monetary transactions, and wishes to make this network a harmonious part of the anthropogenic aluminum life cycle (Figure 1). From this perspective, we take the following steps to identify and define nodes for our network:

Step I: Nodes corresponding to sectors (Region II) contributing non-physical value added to sectors in Region I are ignored, because there is no material flows embedded in these monetary value-added flows.

Step II: Nodes corresponding to sectors or sector groups receiving final demands from sectors or sector groups in Region I are divided into two categories (No. 13 and 14, Table S2 in SI-01): trade nodes and domestic final demand nodes. There is one trade node and one domestic final demand node corresponding to each sector or sector group, and each sector's domestic final demand node is the combination of that sector's domestic personal consumption, domestic private investment, domestic government purchases, and change in domestic private inventories. Because final goods of aluminum are generally grouped into end-use sectors, we identify 15 end-use sectors (Table S3 in SI-01) according to a guide prepared by the Aluminum Association[21], and categorize all domestic final demand nodes into these 15 end-use nodes as appropriate.

Step III: Each sector in Region I is identified as a node, and all these 393 nodes are used to generate an inter-sectoral material flow network (Figure S1 in SI-01, excluding trade nodes and domestic final demand nodes). In order to make this network more tractable when visualizing them, sectors with similar features are grouped together when possible (Table S4 in SI-01). This simplification reduces the number of nodes from 393 to 99, each of which is given a label as demonstrated in Figure 3 and Table S4 in SI-01. For example, eleven vehicle component sectors are combined to generate a node called Motor Vehicle Parts, and twenty-four food sectors are combined to generate a node called Foods. These 99 nodes are then classified into 12 categories (No. 1-12, Table S2 in SI-01; Table S4 in SI-01) and are distributed in Figure 3 from left to right roughly according to their progression along the stages of manufacturing.

Step IV: Nine external nodes that are not based on the IO table (the purple nodes in Figure 1) are identified so that the whole anthropogenic aluminum life cycle can be included. Most of these are self-explanatory, but a few deserve comment. One issue is that the mining of bauxite is found together with several other minerals in the “Other Nonmetallic Minerals Mining and Quarrying” sector, while the production of alumina and the refining of alumina to produce aluminum are aggregated into a single sector in the IO tables, but these three steps can be distinguished on the basis of MFA information. Similarly, the transaction of aluminum scrap may be recorded in the flows from each sector to the Scrap sector, but these flows include scrap for all materials, making it impossible to estimate aluminum scrap flows using just the IO table data. Finally, loss and in-use stock of aluminum are not captured by IO tables so it is necessary to add an external node for each of them.

2.2 Determining Links to Connect Nodes

The links determined by using the 2007 IO table (Figure 1, in green) can be classified into five types: (1) aluminum flows among sectors; (2) aluminum contained in traded commodities; (3) domestic final demand of aluminum contained in domestically used commodities; (4) new aluminum scrap generated from each sector; and (5) aluminum loss from each sector. Note that data on these links are first estimated for each of the 393 sectors, and data on links for the 99 sector groups are then calculated for visualization in Figure 3. Links that are known to be relevant but which cannot be determined by using the 2007 IO table (Figure 1in purple) can be classified into two types: (1) links introducing aluminum into the inter-sectoral network; and (2) links used for closing the aluminum life cycle. The following steps describe details of determining data for these links.

Step I: Aluminum metal is introduced into the inter-sectoral network from three sources – domestic primary aluminum production, domestic secondary aluminum production, and net import of unwrought aluminum. The first of these requires special treatment because there is no IO sector specifically for bauxite mining, while alumina refining and primary aluminum smelting are integrated into one sector in the 2007 U.S. IO table. To address this issue, aluminum flows from bauxite mining to alumina refining and then to primary aluminum smelting compiled by a relevant MFA study[6] are used to introduce domestically-produced primary aluminum (2.5 million metric tons (MMTs)) into the network. We then create two external nodes, New Scrap and Old Scrap Preparation, to introduce both new and old scrap into the IO sector Secondary Smelting and Alloying of Aluminum (SSAA) that represents the production of secondary aluminum. The production of secondary aluminum from new and old scrap[6] is then used to introduce domestically-produced secondary aluminum (3.6 MMTs) from sector SSFA to the sector Aluminum Refining and Primary Aluminum Production (AR&PAP). Note that secondary aluminum is introduced into the network through the AR&PAP node because in the 2007 IO table all output of SSAA sector is reported to be sold to the AR&PAP sector. This means that the use of primary and secondary aluminum by the U.S. economy is reported together in the IO table rather than individually. Finally, U.S. net import of unwrought aluminum (2.6 MMTs), compiled by the relevant MFA study[6], is also introduced into the network through the node AR&PAP. The total of aluminum metal introduced into the U.S. economy in 2007 then becomes 8.7 MMTs.

Step II: Aluminum metal introduced into the inter-sectoral network is spread across the whole network node by node, starting from the AR&PAP node, according to the monetary distribution ratios recorded in the IO table. All monetary transactions are classified into five categories as demonstrated in Figure 2. Only when the monetary flows from a node (e.g., node a in Figure 2) belong to category I are the monetary IO values used to distribute aluminum to subsequent nodes. Otherwise, if monetary flows are from nodes of types d, e, and f (meaning flows belong to categories II, III, or IV), then no aluminum flows occur from one IO sector to another. In addition, we exclude all self-loop transaction flows (category V) because a sector does not use itself as a component. A binary matrix Φ (in which the element is 1 when the corresponding IO table's monetary transaction belongs to category I; otherwise the matrix element is 0) is then generated (Supporting Information 02 (SI-02)). Because new scrap is formed and metal loss occurs in every sector that processes aluminum or aluminum-containing products, a new scrap ratio matrix R^S and a loss ratio matrix R^L are also generated (Details are described in Section S2.2. of SI-01; the two matrices are provided in SI-02).

The monetary direct requirement coefficient matrix A is partitioned and reorganized as follows:

$$A = \begin{pmatrix} A_{MM} & A_{MP} \\ A_{PM} & A_{PP} \end{pmatrix} \tag{1}$$

where M indicates the studied material that is aluminum in this paper, P indicates products that include all other 392 sectors, A_{MP} is a 1×392 vector that represents the monetary distribution of aluminum from AR&PAP to all other sectors, and A_{PP} is a 392×392 matrix. The matrixes Φ, R^S, and R^L are partitioned and reorganized similarly.

A matrix that represents the distribution of aluminum among all sectors ($\tilde{A}_{PP}$) is then generated by the following equation:

$$\tilde{A}_{PP} = \Gamma_{PP} \otimes \Phi_{PP} \otimes A_{PP} \tag{2}$$

where $\otimes$ indicates the Hadamard product (the element wise product of two matrices). Γ_{PP} is the yield ratio matrix, which is given by:

$$\Gamma_{PP} = I - \mathrm{R}_{\mathrm{PP}}^{\mathrm{S}} - \mathrm{R}_{\mathrm{PP}}^{\mathrm{L}} \tag{3}$$

A 1×392 vector, C_{MP}, which represents the aluminum content in all sectors is then derived by formula (4)[18]:

$$C_{MP} = \tilde{A}_{MP}(I - \tilde{A}_{PP})^{-1} \tag{4}$$

where $\tilde{A}_{MP}$ represents the physical input coefficient of aluminum to other commodities and is given by

$$\tilde{A}_{MP} = \frac{T_{\mathrm{Al}}}{D_{\mathrm{Al}}^{\mathrm{Int}} + D_{\mathrm{Al}}^{\mathrm{Fnl}}} \cdot \Gamma_{\mathrm{MP}} \otimes A_{\mathrm{MP}} \tag{5}$$

where T_{Al} represents the metric tons of aluminum used by the entire U.S. economy in 2007 (i.e. T_{Al}=8.7 MMTs), $D_{\mathrm{Al}}^{\mathrm{Int}}$ and $D_{\mathrm{Al}}^{\mathrm{Fnl}}$ are the monetary intermediate use and the monetary domestic final demand of AR&PAP in the 2007 U.S. economy, respectively. Γ_{MP} is the yield ratio vector from AR&PAP to all other sectors, and is given by $I - \mathrm{R}_{\mathrm{MP}}^{\mathrm{S}} - \mathrm{R}_{\mathrm{MP}}^{\mathrm{L}}$.

A matrix U_{Al} representing the flows of aluminum among sectors then becomes:

$$U_{\mathrm{Al}} = \begin{pmatrix} \mathrm{diag}(C_{\mathrm{MP}})\tilde{A}_{\mathrm{PP}} \\ \tilde{A}_{\mathrm{MP}} \end{pmatrix} \mathrm{diag}(((I - \tilde{A}_{\mathrm{PP}})^{-1}) f_{\mathrm{P}}) \tag{6}$$

where f_{P} is the monetary final demand of all other 392 sectors in the 2007 U.S. economy. $(U_{\mathrm{Al}})_{i,j}$ represents the amount of aluminum sent from sector i to sector j, which will then be incorporated into the body of sector j.

Step III: Aluminum metal leaves the inter-sectoral network in four ways: (1) process loss and (2) new scrap generation occurring in each sector, and (3) net export and (4) domestic final demand of commodities generated by each sector. The loss and new scrap generation occurring in sector j are estimated by:

$$L_j = R_j^L \cdot \sum_i (U_{Al})_{i,j} \tag{7}$$

$$S_j = R_j^S \cdot \sum_i (U_{Al})_{i,j} \tag{8}$$

The aluminum embedded in final demand k for sector j is given by:

$$F_j^k = C_{\mathrm{MP}\,j} f_{P_j}^k \tag{9}$$

Then the five types of final demand are integrated into two groups: net export (import + export) and domestic final demand (personal consumption + private investment + government + change in private inventories).

Step IV: The life cycle of aluminum is closed by adding nodes for the in-use stocks, for the old scrap collection and preparation, and for the unidentified end-of-life aluminum (landfilled, exported as end-of-life products, or hibernating). From the life cycle perspective, the challenge of the inter-sectoral network built by this study is that it ends at the step where aluminum enters the in-use stock. Were similar studies to be done for a long-enough period before 2007, the historical flows of aluminum entering the in-use stock could be estimated sector by sector, and the historical sector-level end-of-life flows of aluminum from in-use stock could also be modeled using the dynamic lifespan modeling method[22, 23]. However, because only the 2007 analysis has been done to this point, we use data from a former study[6] in which the old scrap flows were provided as a sum of all commodities rather than sector by sector.

2.3 Building Sub-Networks for Sectors

The inter-sectoral network for which the data are generated by equation (6) represents the aluminum flow network for the entire U.S. economy. However, it is straightforward to generate data for sub-networks for either a certain sector or a certain group of sectors by replacing f_P in equation (6) by f_{P_n} or f_{P_g}, respectively, where f_{P_n} represents the final demand of a certain sector n and f_{P_g} represents the final demand of a certain group of sectors.

2.4 Validating the Approach

The validation of the IO-MFN approach was conducted by two methods: (1) by checking whether mass balance is achieved for each node and for the entire inter-sectoral network, and (2) by comparing data generated from this study with data that already exist or that were generated from a former study[6]. The comparison was done for the following four groups: (1) the MFA-based physical data for alumina and aluminum were multiplied by their prices to generate monetary data, which were then compared with the corresponding monetary data that already exist in the IO table (details in Table S6 in SI-01); (2) for the 15 end-use sectors (Table S3 in SI-01) that were further classified into seven end-use sectors identical to those used by the Aluminum Association[21], a new set of data on aluminum shipments to domestic markets by end-use sector (details in Section S4 in SI-01) was generated and compared with those estimated by the Aluminum Association[13]; (3) the modeled aluminum trade embedded in final products was grouped into the seven end-use sectors and compared with those estimated using physical data in our former study[6]; and finally, (4) the modeled new scrap generation from all sectors was totaled and then compared with statistics on new scrap use provided by the Aluminum Association[13].

2.5 Visualizing the Material Flow Networks

With all nodes and data for links among nodes determined, the material flow networks of aluminum were visualized using the open source software Gephi[24]. We did so for both (1) the network covering the whole economy and (2) the network for domestically producing automobiles in the United States (by assuming final demands for all other sectors are zero). For the automobile network, only the inter-sectoral nodes are shown (i.e., excluding those nodes and links for introducing aluminum into the network and for closing the life cycle) and nodes not connected to the automobile network are deleted (Figure S3 in SI-01).

3 Results

Figure 3 presents the material flow network of aluminum in the entire 2007 U.S. economy. It traces the flow of aluminum from alumina and scrap input through to final demands (divided into net export and domestic final demand), process loss, and new scrap generation. The life cycle is closed by using the in-use stock to link domestic final demands with old scrap collection and preparation. The width of each link in the network diagram is proportional to the material flow strength of aluminum along that link. (Note that the 393 sectors in the original input-output table have been categorized into 99 sector groups, and only these 99 nodes are shown in Figure 3 (Step III in section 2.1). Mass balance (input equals output) is achieved for each of the 393 sectors and the 99 sector groups, and for the whole of the 393 sectors in Region I. Two figures illustrating the inter-sectoral flows among the 393 sectors in Region I either as a network or as a 3-D matrix are provided in SI-01 (Figures S1 and S2). A comprehensive analysis of this inter-sectoral network is performed in a companion paper[20].

Using the Automobile Manufacturing sector as an example, Figure 4 demonstrates the material flow network of aluminum for domestically producing automobiles in the United States in 2007. It clearly shows the sectors that play roles in introducing aluminum step by step into automobiles, as well as the contribution of each sector to the network. Similar networks can be derived for other sectors as desired, such as Aircraft Manufacturing, Computer Manufacturing, Light Truck and Utility Vehicle Manufacturing, and so on.

A comparison between the monetary data compiled by the IO table and the monetary data estimated using the physical and price data for the sum of aluminum introduced into the inter-sectoral network shows that the difference between these two sets of data is less than 10% (Table S6 in the SI). Given the effects of price fluctuations, we regard this difference as reasonable, and regard the amount of aluminum (which is 8.7 MMTs) introduced into the network as reflecting the actual use of aluminum in the entire 2007 U.S. economy. Figure S4 in SI-01 demonstrates that the results estimated by this study are similar to the corresponding information provided by the Aluminum Association or estimated by our former MFA study. The total new scrap generation modeled by the current work is about 2.2 MMTs of aluminum metal, only about 5% less than the metal recovery from new scrap reported by the Aluminum Association (2.3 MMTs)[13].These comparisons help to further certify the robustness and reliability of the IO-MFN approach.

4 Discussion

By taking advantage of the combination of the U.S. economic input-output table and of physical data from an analogous MFA study, this paper uses aluminum as an example for a methodology of building material flow networks for bulk metals (iron, aluminum, and copper) in the U.S. economy. This methodology consists of two important aspects: (1) identifying nodes for the IO-

MFNs for metals; the whole collection of nodes represents the entire U.S. economy in which metals flow among sectors and all nodes are exclusive of one another; and (2) identifying the existence of links among nodes and determining data for these links. Using completely the same methodology and similar physical data, the IO-MFN for iron and copper in the 2007 U.S. economy can readily be built because the IO table has distinct sectors for those metals as well as for aluminum. The IO-MFN can also be built for other metals by additional manipulations and assumptions as reported in another companion paper[25]. A particular feature of this methodology is that IO-MFNs for only a single sector or a group of sectors can be built. If input-output tables in other economies are as detailed as that in the United States (e.g., Japan[26]), similar studies can be done for those economies.

Existing MFA studies for metals rely on information on the shipments of metal to the domestic market (reported as apparent consumption) by end-use sector to determine flows in the manufacturing and use stages, and the in-use stocks. However, there are several limitations for this end-use sector information: (1) the information is only for aggregated end-use sectors such as transportation or consumer durables rather than for specific products such as automobiles or refrigerators[23]; (2) the methods of classifying end-use sectors are material-specific and are generally inconsistent among metals; (3) for sectors that include many heterogeneous products, it is difficult to estimate a reasonable average product lifespan, therefore resulting in high uncertainties in estimation of in-use stocks; and (4) no information on flows among end-use sectors and especially among specific products, such as the use of electronics by automobiles, is reported. Because the U.S. input-output table enables us to analyze the aluminum flows among almost 400 sectors in this approach, these four limitations can be readily addressed by the approach developed in this study.

The IO-MFN approach helps to uncover the networks of material flows in the manufacturing stage of the life cycle of metals. It also enables us to estimate and visualize the new scrap generation and material loss of metals from each sector. (In contrast, the Aluminum Association reports only the new scrap generation of aluminum as a whole[13]). With the information on aluminum flows that is reported as part of final demands in the U.S. economy, the approach helps estimate the trade of aluminum contained in all kinds of final products. Compared to the MFA method using physical data from the UN Comtrade database and its respective aluminum content information[6], the present work provides a solution that is much less time-consuming and arguably more complete and accurate. Note from Figure S4(b) in SI-01 that this study provides results on the trade of aluminum contained in products in sectors such as Containers & Packaging and Others, which we found almost impossible to estimate using physical data. The final (and probably the most important) advantage of this approach is that it enables us to analyze the material flows of metals in the U.S. economy as a network, rather than merely a life cycle chain, so that we can draw on the indicators developed by complex network science to analyze the supply risk, the impacts of supply risk, and the criticality of metals[20].

There are several limitations to this approach that originate from either the limitations of the U.S. input-output data or from assumptions that are made when building the IO-MFNs. Because the U.S. input-output tables at the ≈400-sector level are compiled only at five year intervals (the most recent version is for 2007), the material flow networks can be made for only these years. This results in the challenge of lacking both annual and up-to-date information. In addition, the classification of the IO sectors was slightly changed from version to version of the IO tables. Therefore, if one were to apply the approach to derive historical input and output flows of the in-use stocks and to estimate the in-use stocks at the IO-sector level, suitable assumptions and adjustments of the data have to be made so that consecutive annual information for historically consistent sectors can be derived.

The process of building the IO-MFNs is not perfect, and is thus subject to further improvement. There are two types of assumptions that may result in challenges: (1) the values of elements in the matrixes Φ, R^S, and R^L are determined by the combination of data from various references and expert judgment; and (2) the distribution of aluminum from one node to those other nodes that purchase products from it is determined according to the distribution of monetary values among nodes, meaning that we apply the price homogeneity assumption as described in references[18, 27]. This assumption implies that every dollar of products sold from a particular IO sector contains the same amount of the studied metal, which may or may not be true (products sold to Scrap do not apply this assumption). Thus, if the aluminum content per dollar of products sold from one node to other nodes is heterogeneous, a skewed metal branching ratio will result, as illustrated in Figure S5 in SI-01. A possible solution for addressing this challenge resulting from the price homogeneity assumption is to get information on the price heterogeneity for each node, and to then generate a corresponding matrix H for adjusting the difference. However, getting the price heterogeneity information can be very time-consuming (or even impossible).

This challenge raises the question "What is represented by the numbers in the derived IO matrix, U_{Al}, for the IO-MFN?". In a traditional IO table the entries in each matrix element are the aggregated transactions between sectors of the economy, and are denominated in monetary units (dollars in the case of the U.S. IO table). In a derived IO matrix for IO-MFN, in contrast, the entries represent amounts of metal that are transferred from one sector of the economy to another. However, the correspondence between monetary units and metal units is not equivalent across the IO table, because monetary transactions in the metal IO table generally involve other metals and assemblages of the material as well. At the early stages of the aluminum cycle, the flows from the AR&PAP sector to initial customers are closely related to the amount of metal exchanging ownership. Subsequent transactions are less and less closely related to the pure metal for which the table was constructed, however, and are more accurately regarded as reflections of the metal-related value of the increasingly complex assemblages that are involved in product manufacturing processes. In place of the common but (in this case) inaccurate unit of metric tons, we term the aggregated quantities in the elements of a derived IO matrix for IO-MFN as "transformed metal unit (TMU)", and denominate them in "hektes". These are terms that parallel the economist's monetary units of dollars or yen. (The hekte, pronounced "hecktuh", is thought to have been the first metal coinage, used in Lydia [now Western Turkey] in the 7th century BPE[28]. The use of TMU and hektes remind us that TMU can be denominated, but not strictly in unit of either metric tons or dollars.

The methodology described above is able to generate a metal-based IO table from an economic IO table provided that a material flow analysis is available to supply nodes that are important to quantifying those ensemble metal flows that are extraneous to the economic IO table. Despite its limitations, we believe that the approach has been validated with satisfactory robustness and reliability. And, as suggested here but demonstrated more completely in two subsequent papers[20,25], the result meets all requirements to be regarded as a network. The network can then be analyzed by the tools of CNA[20] and similar networks for other metals can be built[25]. Accordingly, we term this methodology the IO-MFN approach to emphasize the integration of MFA, IOA, and CNA.

Supporting Information

Details on methodology, data compilation, and complementary figures are listed. This material is available free of charge via the Internet at http://pubs.acs.org.

Author Information

Corresponding Author

* E-mail: wqchen@iue.ac.cn; wqchen.thu@gmail.com. Tel. and Fax: +86-592-619-0763.

Notes

The authors declare no competing financial interest.

Acknowledgements

We thank Kenichi Nakajima, Shinichiro Nakamura, Marshall Jinlong Wang, the editor and the anonymous reviewers for providing relevant literature or for helpful comments.

References

1. Chen, W. Q.; Graedel, T. E., Anthropogenic Cycles of the Elements: A Critical Review. *Environmental Science & Technology* **2012,** 46, (16), 8574-8586.
2. Graedel, T. E.; Bertram, M.; Fuse, K.; Gordon, R. B.; Lifset, R.; Rechberger, H.; Spatari, S., The contemporary European copper cycle: The characterization of technological copper cycles. *Ecological Economics* **2002,** 42, (1-2), 9-26.
3. Spatari, S.; Bertram, M.; Fuse, K.; Graedel, T.; Rechberger, H., The contemporary European copper cycle: 1 year stocks and flows. *Ecological Economics* **2002,** 42, 27-42.
4. Wang, T.; Muller, D. B.; Graedel, T. E., Forging the anthropogenic iron cycle. *Environmental Science & Technology* **2007,** 41, (14), 5120-5129.
5. Reck, B. K.; Muller, D. B.; Rostkowski, K.; Graedel, T. E., Anthropogenic nickel cycle: Insights into use, trade, and recycling. *Environmental Science & Technology* **2008,** 42, (9), 3394-3400.
6. Chen, W. Q.; Graedel, T. E., Dynamic analysis of aluminum stocks and flows in the United States: 1900-2009. *Ecological Economics* **2012,** 81, 92-102.
7. Graedel, T. E.; van Beers, D.; Bertram, M.; Fuse, K.; Gordon, R. B.; Gritsinin, A.; Harper, E. M.; Kapur, A.; Klee, R. J.; Lifset, R.; Memon, L.; Spatari, S., The multilevel cycle of anthropogenic zinc. *Journal of Industrial Ecology* **2005,** 9, (3), 67-90.
8. Johnson, J.; Jirikowic, J.; Bertram, M.; Van Beers, D.; Gordon, R. B.; Henderson, K.; Klee, R. J.; Lanzano, T.; Lifset, R.; Oetjen, L.; Graedel, T. E., Contemporary anthropogenic silver cycle: A multilevel analysis. *Environmental Science & Technology* **2005,** 39, (12), 4655-4665.
9. Harper, E. M.; Graedel, T. E., Illuminating tungsten's life cycle in the United States: 1975-2000. *Environmental Science & Technology* **2008,** 42, (10), 3835-3842.
10. Du, X. Y.; Graedel, T. E., Uncovering the Global Life Cycles of the Rare Earth Elements. *Scientific Reports* **2011,** 1, 1-4.
11. Harper, E. M.; Kavlak, G.; Graedel, T. E., Tracking the Metal of the Goblins: Cobalt's Cycle of Use. *Environmental Science & Technology* **2012,** 46, (2), 1079-1086.
12. Chen, W.-Q.; Shi, L.; Qian, Y., Substance flow analysis of aluminium in mainland China for 2001, 2004 and 2007: Exploring its initial sources, eventual sinks and the pathways linking them. *Resources Conservation and Recycling* **2010,** 54, 557-570.
13. The Aluminum Association, Aluminum Statistical Review for 2009. In Arlington, VA, USA, 2010.
14. Miller, R. E.; Blair, P. D., *Input-Output Analysis: Foundations and Extensions*. 2 ed.; Cambridge University Press: 2009.
15. U.S. BEA Input-Output Accounts Data. http://www.bea.gov/industry/io_annual.htm#data. (April 1, 2015).
16. Nakamura, S.; Kondo, Y., Input-Output Analysis of Waste Management. *Journal of Industrial Ecology* **2002,** 6, (1), 39-63.
17. Nakamura, S.; Nakajima, K.; Kondo, Y.; Nagasaka, T., The waste input-output approach to materials flow analysis - Concepts and application to base metals. *Journal of Industrial Ecology* **2007,** 11, (4), 50-63.
18. Nakamura, S.; Kondo, Y.; Matsubae, K.; Nakajima, K.; Nagasaka, T., UPIOM: A New Tool of MFA and Its Application to the Flow of Iron and Steel Associated with Car Production. *Environmental Science & Technology* **2011,** 45, (3), 1114-1120.
19. Nakajima, K.; Ohno, H.; Kondo, Y.; Matsubae, K.; Takeda, O.; Miki, T.; Nakamura, S.; Nagasaka, T., Simultaneous Material Flow Analysis of Nickel, Chromium, and Molybdenum Used in Alloy Steel by Means of Input-Output Analysis. *Environmental Science & Technology* **2013,** 47, (9), 4653-4660.
20. Nuss, P.; Chen, W.-Q.; Ohno, H.; Graedel, T. E., Structural investigation of aluminum in the U.S. Economy using network analysis. *Environmental Science and Technology* **2015,** Under Review.

21. The Aluminum Association. *End Use Guide for Reporting Shipments of Semi-fabricated Aluminum Products*; Arlington, VA, USA, 2007.
22. Melo, M. T., Statistical analysis of metal scrap generation: the case of aluminium in Germany. *Resources Conservation and Recycling* **1999,** 26, (2), 91-113.
23. Chen, W. Q.; Graedel, T. E., Improved Alternatives for Estimating In-Use Material Stocks. *Environmental Science & Technology* **2015,** 49, (5), 3048-3055.
24. Gephi Team Gephi Makes Graphs Handy. https://gephi.github.io. (Jan. 1st, 2015).
25. Ohno, H.; Nuss, P.; Graedel, T. E.; Chen, W.-Q., Deriving the metal and alloy networks of modern technology. *Environmental Science and Technology* **2015,** Under Review.
26. Japanese Ministry of Internal Affairs and Communications Input-Output Tables for Japan. http://www.soumu.go.jp/english/dgpp_ss/data/io/index.htm. (Oct. 5, 2015).
27. Weisz, H.; Duchin, F., Physical and monetary input-output analysis: What makes the difference? *Ecological Economics* **2006,** 57, (3), 534-541.
28. Paszthory, E., Investigations of the early electrum coins of the Alyattes type. In *Metallurgy in Numismatics*, Metcalf; Oddy, Eds. Royal Numismatic Society: London, 1980; Vol. 1, p 151.

Figures

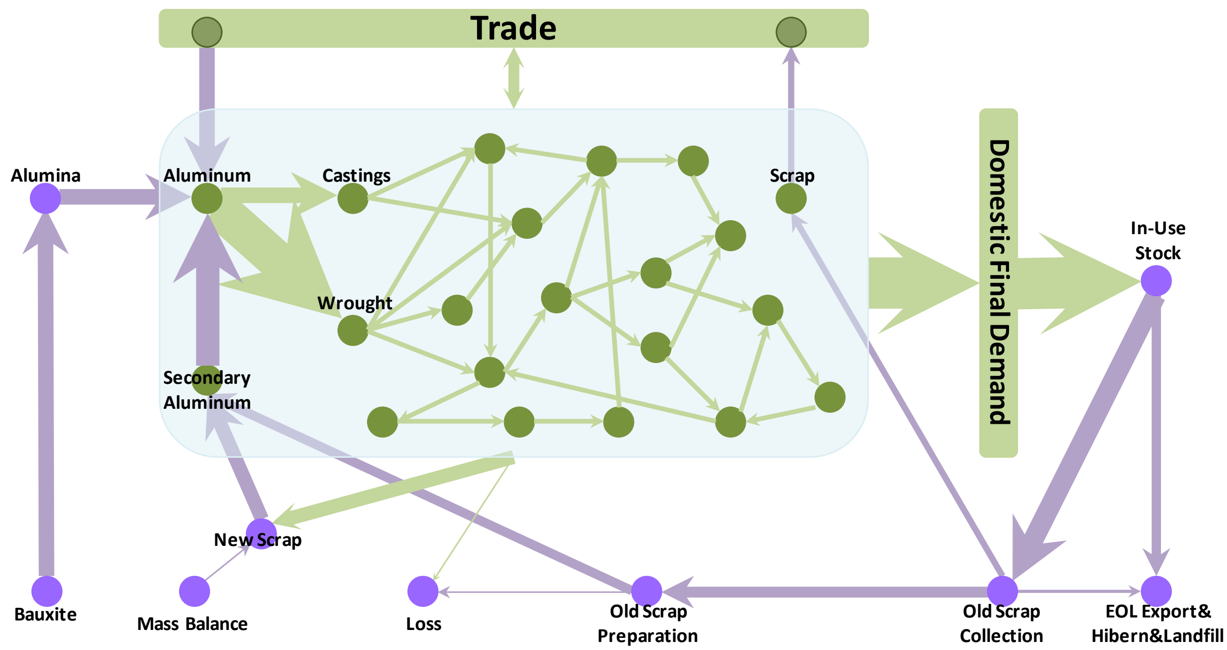
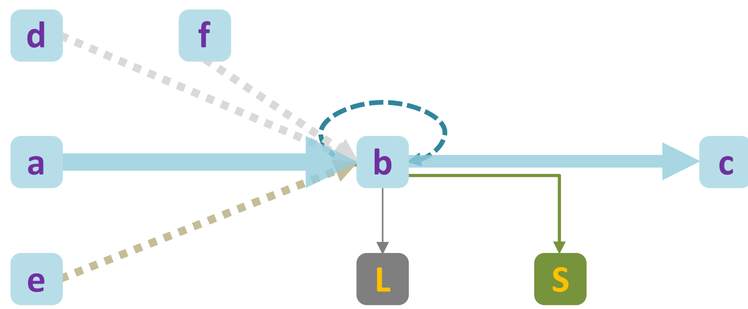


Figure 1 Schematic diagram demonstrating the embeddedness of the inter-sectoral material flow network of aluminum in the anthropogenic aluminum life cycle. Green nodes and links are determined using the U.S. input-output table (nodes for trade and domestic final demands are not shown), while purple nodes and links are determined based on a traditional MFA study[6] so as to demonstrate the whole aluminum life cycle.



Category	Flows	Flows Description
I	a-b, b-c	Physical flows with aluminum that will be integrated into commodities of sectors b and c, respectively
II	e-b	Monetary flow without physical flow
III	d-b	Physical flow without aluminum in it
IV	f-b	Physical flow with aluminum that is not integrated into commodities of sector b
V	b-b loop	Flow from an sector to itself
Loss	b-L	Aluminum loss from sector b
New Scrap	b-S	New scrap generated from sector b

Figure 2 Schematic diagram illustrating the heterogeneities of inter-sectoral flows of input-output tables when converting monetary flows into material flows of aluminum, as well as the loss and new scrap flows that are not captured by input-output tables. Each of the letters a-f represents a sector in the input-output table, while L and S indicate loss and new scrap, respectively.

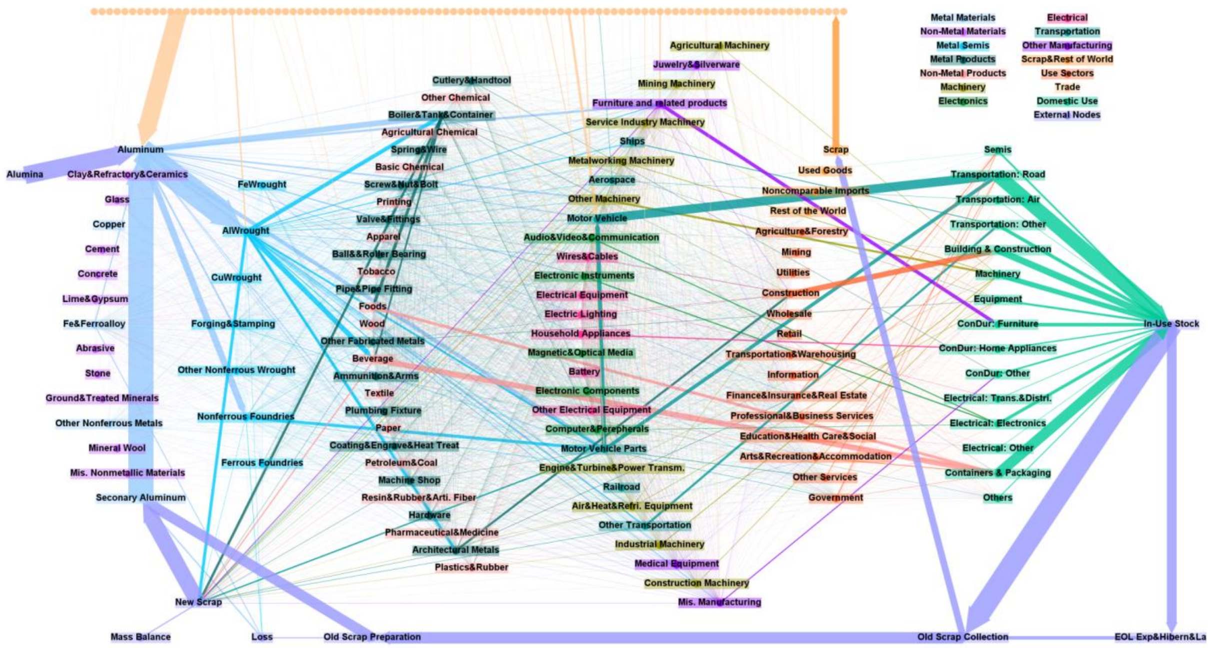


Figure 3 Material flow network of aluminum in the entire 2007 U.S. economy. The flow from bauxite to alumina is not shown for simplicity. Refer to Tables S2-S5 in the Supporting Information for the exact meaning of each node.

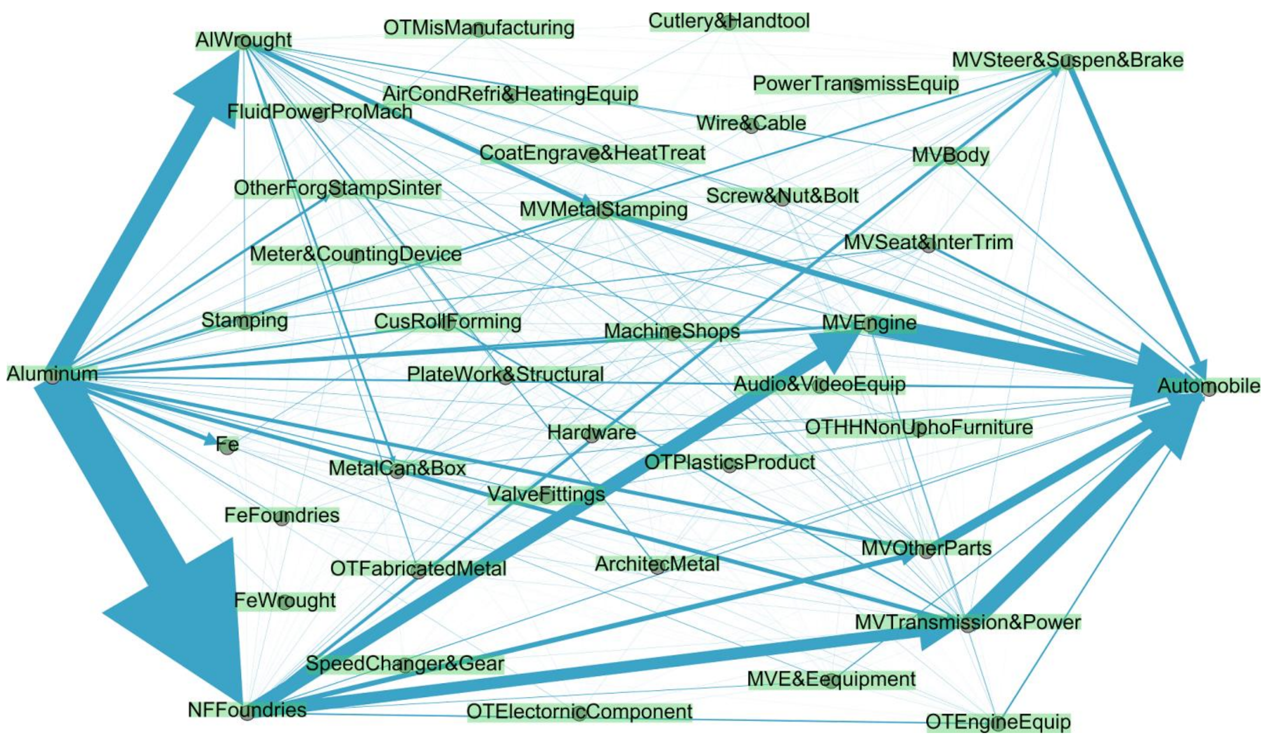


Figure 4 Material flow network of aluminum for producing automobiles in the United States in 2007. Refer to Tables S2-S5 in the Supporting Information for the exact meaning of each node.