Materials Transactions, Vol. 46, No. 12 (2005) pp. 2550 to 2553
Special Issue on Growth of Ecomaterials as a Key to Eco-Society II

RAPID PUBLICATION

Waste Input–Output Material Flow Analysis of Metals in the Japanese Economy

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This paper develops a theoretical model of material flow analysis (MFA) within the framework of the Waste Input–Output model (WIO) (Nakamura and Kondo). The model is developed based on two fundamental ingredients: yield ratios and the degree of fabrication. In manufacturing process, multiplication of physical inputs by the yield ratios gives the portion that enters physical outputs, with the rest being discarded as process waste without entering outputs. In input–output analysis, the degree of fabrication can be visualized as triangularity of the input coefficients matrix (goods of lower degree of fabrication can enter those of higher fabrication, but the reverse does not hold), which is known to emerge through an appropriate reordering of sectors. Application to the Japanese IO data indicates that the model can provide accurate estimates of the weight as well as the composition of metals (Fe, Cu, Pb, Zn, and Al) used in a passenger car. The model is also used to estimate the major final use categories (household consumption, public consumption, capital investment, inventory investment, and export) of metals.

(Received June 20, 2005; Accepted September 12, 2005; Published December 15, 2005)

Keywords: *material flow analysis, input–output analysis, triangularity*

1. Introduction

Material Flow Analysis (MFA) has been widely used to identify and trace the flow of materials/substances among different sectors of the economy. This paper develops a theoretical model of MFA within the framework of the waste input–output (WIO) model.[1)] The WIO is an extension of the conventional input–output analysis (IOA), which explicitly takes into account the flow of waste and the activity of waste management: the WIO thus provides an input–output methodology to consider the whole lifecycle of a product represented by production, use, and end-of-life, while the conventional IOA was not able to deal with the last phase. Integration of WIO with MFA would thus enable one to apply the whole battery of analytical tools of WIO/IOA to MFA.

In the WIO model, the extended parts referring to waste flow and waste management are measured in physical units, and are consistent with a mass balance condition. For each type of waste, the mass balance condition is satisfied, because the amount of its net generation (generation minus recycling) is equal to the amount of its treatment. For each waste treatment process, its feedstock is set equal to the amount of recovered waste materials and residues, and hence the mass balance condition is met. When it comes to the goods-producing sectors, however, the mass balance condition between inputs and outputs in physical terms (physical inputs = physical outputs + process waste) is not considered, because the flow of goods is measured in monetary units following the convention of IOA. Establishing the mass balance between input and output (or column-wise mass balance) is vital for integrating the WIO with MFA. This is a major concern of this paper.

Reordering of the sectors in the IO coefficients matrix can reveal a certain triangular structure that represents the hierarchical degree of fabrication among inputs.[2)] Exploiting the hierarchical structure that exists among resources (*e.g.* metal ores), materials (*e.g.* metals), and products (*e.g.* appliances, automobiles, buildings), we develop a new methodology, the WIO-MFA model, for generating a comprehensive flow of materials. The methodology is applied to the flow of base metals (iron, copper, lead, zinc and aluminum) in the Japanese economy.

2. The Model

Write $A = [a_{ij}]$ for an $n \times n$ matrix of input coefficients, the ith row jth column element of which refers to the input of i per unit of output j. We are interested in separating inputs between those that enter outputs and those that are discarded as process waste. This separation is done by the use of yield ratios, $\gamma_{ij} \in [0, 1]$, which refers to the ratio by which a physical input i becomes one element of the composition of physical output j. On the other hand, $1 - \gamma_{ij}$ refers to the ratio by which a physical input i is discarded as process waste without entering physical output j. Denote by $\Phi = [\phi_{ij}]$ an $n \times n$ matrix, the ith row jth column element of which is unity if output j is physical and input i physically enters j, and zero otherwise: multiplication of A by Φ removes non-physical flows from A (capital goods such as machines and buildings do not physically enter outputs, but provide services). Writing $\tilde{A}$ for the part of A that physically enters products, we then have:

$$\tilde{A} = \Gamma \odot \Phi \odot A \tag{1}$$

where $\Gamma = [\gamma_{ij}]$ and "$\odot$" refers to the element-wise multiplication of two matrices (the Hadamard product). The part of A that is discarded as process waste, $\check{A}$, is given by

$$\check{A} = (\iota\iota^{\top} - \Gamma) \odot \Phi \odot A, \tag{2}$$

where ι refers to an $n \times 1$ vector of unity, and $\iota^{\top}$ to its transpose.

The second ingredient of our theoretical model is based on the degree of fabrication among resources (R), materials (M), and products (P): before final products reach the consumers, resources have to be first processed into materials, and the materials thus obtained have to be further processed into products. By definition, the increase in the degree of fabrication occurs only in one direction (recycling of waste materials recovered from end-of-life products is consistent with this, because the latter has to be first reduced to materials before re-entering the production process). In input–output analysis, this one-directional increase in the degree of fabrication is known to impose a triangular structure on the matrix of input coefficients, which can emerge when the ordering of sectors is appropriately altered to reflect the degree of fabrication.[2)]

Divide n outputs into mutually exclusive and nonempty sets of R (n_R elements), M (n_M elements), and P (n_P elements) such that $\tilde{A}$ can be partitioned as follows

$$\tilde{A} = \begin{pmatrix} \tilde{A}_{PP} & \tilde{A}_{PM} & \tilde{A}_{PR} \\ \tilde{A}_{MP} & \tilde{A}_{MM} & \tilde{A}_{MR} \\ \tilde{A}_{RP} & \tilde{A}_{RM} & \tilde{A}_{RR} \end{pmatrix}. \quad (3)$$

We introduce the following set of assumptions with regard to the triangular structure:

(1) Resources are not produced but given from the environment: $\tilde{A}_{iR} = O$, $i \in \{P, M, R\}$, where O is a zero matrix of an appropriate order.

(2) Materials are made of resources: $\tilde{A}_{iM} = O$, $i \in \{P, M\}$.

(3) Products are made of products and materials: $\tilde{A}_{RP} = O$,

which implies

$$\tilde{A} = \begin{pmatrix} \tilde{A}_{PP} & O & O \\ \tilde{A}_{MP} & O & O \\ O & \tilde{A}_{RM} & O \end{pmatrix}, \quad (4)$$

It follows from (4) that any physical product can be reduced to elements in M, with its "M composition" being given by the column elements of the following $n_M \times n_P$ matrix:

$$\begin{aligned} C_{MP} &= \tilde{A}_{MP}(I + \tilde{A}_{PP} + \tilde{A}_{PP}^2 + \tilde{A}_{PP}^3 + \cdots) \\ &= \tilde{A}_{MP}(I - \tilde{A}_{PP})^{-1}, \end{aligned} \quad (5)$$

where I refers to an identity matrix of order n_P. The ith row jth column element of this matrix, say $C_{M_iP_j}$, gives the amount of material i that is contained in product j per unit. If all the materials are measured in a common physical unit, say kg, then $\sum_i C_{M_iP_j}$ gives the weight of a unit of j in kg, where the unit of j can be physical or monetary.

By use of C_{MP}, the flow of products can easily be converted into the corresponding flow of materials. Write $\tilde{X}_{PP}$ for the $n_P \times n_P$ matrix of the interindustry flow of products that physically enter outputs (formally, this can be given by $\tilde{A}_{PP}\,\mathrm{diag}(X_P)$, with $\mathrm{diag}(X_P)$ being the diagonal matrix of the n_P output vector of P), and $\tilde{X}_{P_kP_j}$ for its kth row jth column element, say the input of a motor that enters a passenger car. The amount of material i, say copper, that enters a passenger car (product j) in the form of a motor (product k) is then given by $C_{M_iP_k}\tilde{X}_{P_kP_j}$. An $n_P \times n_P$ matrix, the kth row jth column element of which is $C_{M_iP_k}\tilde{X}_{P_kP_j}$, then gives the flow of material i that is contained in $\tilde{X}_{PP}$, an formal expression of which is

$$\begin{aligned} &\mathrm{diag}(C_{M_iP}) \odot \tilde{X}_{PP} \\ &\quad = \mathrm{diag}(C_{M_iP}) \odot \tilde{A}_{PP}\,\mathrm{diag}(X_P), \quad i \in M, \end{aligned} \quad (6)$$

where C_{M_iP} refers to the ith row of C_{MP}. Write $\check{X}_{PP} = \check{A}_{PP}\,\mathrm{diag}(X_P)$ for the flow of produts that are discarded as process waste without entering products. Analogous to (6), the flow of material i that is contained in it is given by $\mathrm{diag}(C_{M_iP}) \odot \check{X}_{PP}$. Finally, write X_{PF} for an $n_P \times n_F$ matrix of the flow of products among n_F final demand categories such as household consumption, capital investment, and export. Its material component, or the the final use categories of materials, is given by

$$\mathrm{diag}(C_{M_iP}) \odot X_{PF}, \quad i \in M. \quad (7)$$

Our model can thus determine the use categories of materials. This is in sharp contrast to the usual practice of MFA studies, where they are a prior given from outside sources.[3)]

Before turning to application, a remark is due on the use of physical input that does not enter output, a typical example of which is catalyst metals. In the above model, Φ excludes the flow of catalyst metals from $\tilde{A}$. Consideration of this type of material flow belongs to a future topic of research.

3. Application and Results

The above methodology is applied to the flow of base metals in the Japanese economy. We consider 11 types of metals consisting of pig iron, ferroalloys, copper, lead, zinc, aluminum, and their scraps, except for ferroalloy, as materials (M). Henceforth, the term "iron" refers to pig iron, ferroalloys, and iron scraps. The Japanese IO table for the year 2000 is used as a major data source after having extended/modified it by use of detailed and mostly physical information on the production and supply of metals and related products.[5,6)] In particular, batteries were disaggregated into car batteries, bike batteries, and other batteries. The resulting IO table consists of 416 inputs, which include the 11 types of metals measured in weight (10^3 kg) and 10 resources (R: ores, stones including limestone, coal, petroleum and natural gas), and 407 endogenous sectors, of which 297 refer to sectors producing physical output (P) and the rest to services or energy sectors. The data on Γ for iron, copper, and aluminum were respectively taken from the physical flow data of the Japanese IO table, 7), and 8).

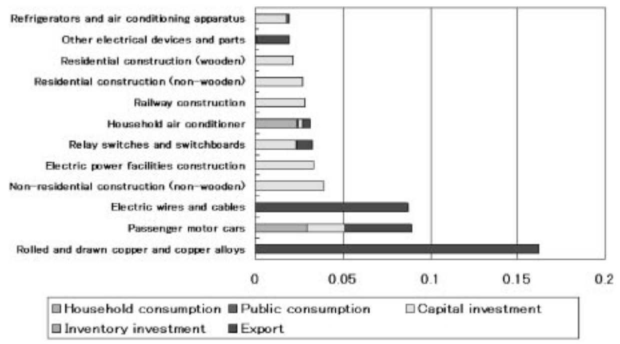
The column sum of C_{MP} gives the estimated metal weight of products per unit (10^3 kg for metal products such as steel products and one million yen for others). For a product for which both the weight and price are available, this feature of the model can be used to check its explanatory power. A good example for this purpose is a passenger car. It turned out that the estimated metal weight of a passenger car (776 kg = 536 kg/one million yen × 1.45 million yen/unit) compares well with the real weight.[9,10)] Furthermore, Table 1 indicates that the estimated metal composition reproduces the real composition of both 1997 and 2001 models[10)] fairly well.

An important task of MFA is to identify the location of

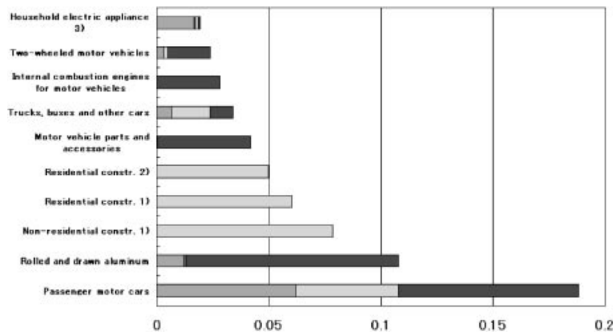
Table 1 The metal composition of a passenger car.

	Iron	Aluminum	Copper	Lead	Zinc
JAMA 1997	0.88	0.096	0.015	0.006	0.003
JAMA 2001	0.904	0.078	0.01	0.006	0.001
WIO-MFA	0.877	0.085	0.023	0.008	0.007

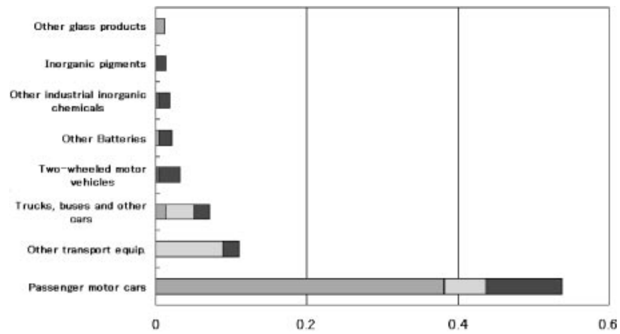
JAMA refers to the composition due to Ref. 10) of respective year, and WIO-MFA to the estimate due to C_{MP}.



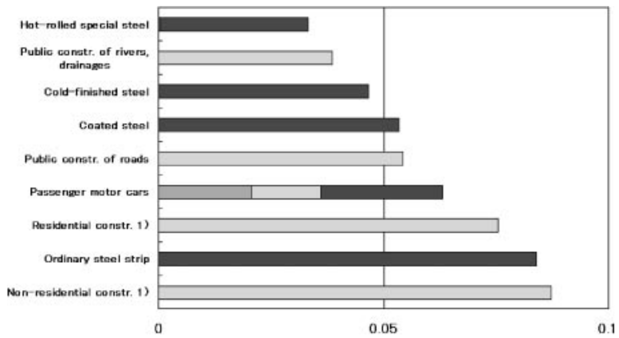
(a) Cu



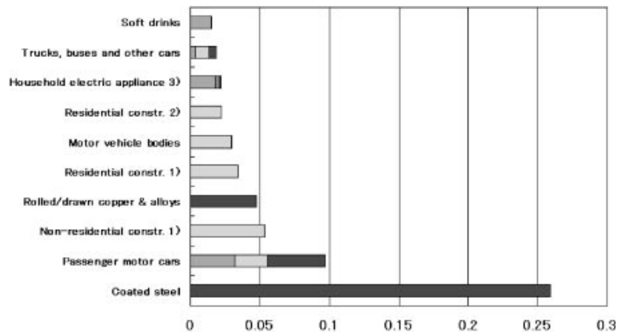
(d) Aluminum



(b) Pb



(e) Iron



(c) Zinc

Fig. 1 The distribution of metals among final products (continued): ((1) non-wooden, (2) wooden, (3) except air conditioners).

metals (or any substance of concern), or the way metals are distributed among different final products in the economy. Figure 1 shows the distribution of metals among major final products distinguished by five final demand categories (household consumption, public consumption, capital investment, inventory investment, and export) obtained by (7). Except for export in the form of intermediate inputs such as rolled and drawn copper or electric wires and cables, the majority of copper in the Japanese economy ends up in automobiles, construction, relay switches, and appliances. In particular, air conditioners and refrigerators constitute about 5% of the new addition to the domestic copper stock.

More than 70% of lead occurs in automobiles mostly in the form of car batteries. A non-negligible portion of lead also occurs in inorganic chemicals, pigments, and glass products. As for zinc, 25% goes to export in the form of coated steel, while automobiles and construction constitute its major domestic destination. The portion of containers (including those of soft drinks) and pigments is also non-negligible. Automobiles in the form of parts, accessories, and engines constitute about 20% of the total amount of aluminum embodied in products. The destination of iron has two distinguishing features. First, the share of the largest user (non-residential construction) is the smallest among all the metals considered here, which indicates the wide use of iron in the economy. The second point is the remarkably large share of export in the form of intermediate products, which amounts to more than 30% of the major users.

4. Discussion

A theoretical model of MFA has been presented, which is aimed at integrating the WIO with MFA. This model differs from conventional MFA studies such as[3] in two respects. First, it can deal with all the materials at the same time. Secondly, it can estimate the use categories of materials, whereas in conventional MFA studies they are given *a-priori* from other sources. Both characteristics result from the fact that our model is based on a solid theoretical foundation of IOA.

Finally, two future directions for research are pointed. First, the model should be extended in its coverage of materials to make it applicable to the management of resources. For instance, other metals such as rare metals and plastics should also be considered. Our model in this article has been a static one, which gives a snapshot of the material flow at a given moment of time. Its dynamic extension under consideration of the fact that products have different lives is another important direction for research.

Acknowledgments

This work has been supported by RISTEX of JST (Japan Science and Technology Agency). We would like to thank Shinsuke Murakami and Yasushi Kondo for helpful comments, and Anthony Newell for editing the English, while we alone are responsible for any errors.

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