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An Extended Model for Tracking Accumulation Pathways of Materials Using Input–Output Tables: Application to Copper Flows in Japan

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Abstract: Recycling has become increasingly important as a means to mitigate not only waste issues but also problems related to primary resource use, such as a decrease in resource availability. In order to promote and plan future recycling efficiently, detailed information on the material stock in society is important. For a detailed analysis of material stocks, quantitative information on flows of a material, such as its accumulation pathways, final destinations, and its processing forms, are required. This paper develops a model for tracking accumulation pathways of materials using input–output tables (IOTs). The main characteristics of the proposed model are as follows: (1) accumulations in sectors other than the final demand sectors (i.e., endogenous sectors) are explicitly evaluated, (2) accumulations as accompaniments to products, such as containers and packaging, are distinguished from the products, and (3) processing forms of materials are considered. The developed model is applied to analyze copper flows in Japan using the Japanese IOTs for the year 2011. The results show that accumulations of copper in endogenous sectors were not negligibly small (9.24% of the overall flow). Although accumulations of copper as accompaniments were very small, they may be larger for other materials that are largely used as containers or packaging. It was found that the destinations of copper showed different characteristics depending on the processing forms.

Keywords: material flow analysis; input–output table; accumulation; endogenous sector; accompaniment; processing form; copper

1. Introduction

Human life depends significantly on a variety of natural resources, including metals, and modern society consumes a large amount of resources [1]. Furthermore, the total demand for metals is expected to continue to increase in the future because of factors such as population growth and electronics revolution [2]. The use of primary resources will cause not only a decrease in resource availability but also the generation of environmental load and waste [3,4]. As a means to mitigate these problems, recycling has been of great interest. Although mineral resources including metals are non-renewable, they are "used but not consumed" [5]. They are accumulated in the economic sphere as "stock" and can be available as future secondary resources due to recycling unless they leave society in such a form that their functionality can no longer be restored (or dissipate) [6]. Substitution of a secondary resource (recycling material) for a primary resource can reduce the environmental impacts of metal production. In addition, "recycling a metal is generally much more energy-efficient than acquiring it from a mine" [7,8].

In order to discuss and develop a resource policy and holistic recycling strategy, we need to comprehend how much recyclable material exists in and exits the economic sphere [9,10]. Material flow analysis (MFA) can estimate the stock as well as the discarded flow of various materials [11,12]. There are two main approaches for estimating stocks: the bottom-up and the top-down approach [13,14]. The bottom-up approach quantifies the number of different products in society and the material contents of each product, and then directly estimates the stocks by combining those data. This approach can provide detailed information on stocks, such as the spatial distribution [15,16]. However, it often requires massive data and is not suitable for large-scale comprehensive analysis.

On the other hand, the top-down approach estimates the stocks by summing up the difference between the inflow (the amount of material entering the stock) and outflow (the amount of material leaving the stock) in each year. Generally, inflows are determined from the data of production and trade, and outflows are estimated by defining lifetime distribution [17]. This approach can provide a time-series estimation of not only stocks but also of discarded flows comprehensively. However, the classification of end use is not necessarily fine enough to conduct a detailed analysis [18–20].

From the viewpoint of the recycling of a specific material, it is important to obtain the information on both the volume of material stocks and on products in which the material is contained, sectors in which the products are accumulated (and eventually discarded), and processing forms of the material on which its recyclability depends [21,22]. This information is related to various factors, such as waste generation sources (municipal solid waste or industrial solid waste), relevant laws and regulations, and costs for recycling collection. Since the importance of the economic profitability of recycling has been often mentioned [3,23–25], more detailed analysis of material flow is required.

Recently, MFA utilizing input–output tables (IOTs) has been conducted. IOTs provide comprehensive information about intersectoral transactions in a specific economic system. Nakamura et al. [26] developed a waste input–output MFA (WIO-MFA) model based on IOTs. This model divides input from one sector to another sector in an IOT into primary input with mass, ancillary input with mass, and input without mass and traces the intersectoral material flows. It can estimate the material composition of a final product while avoiding double counting by partitioning sectors into resources, materials, and products based on the degree of fabrication. Using this model, the destinations of materials [27,28], the material flow related to a specific final product [29–32], the material flow embedded in international trade [33], and material flow networks [34,35] have been analyzed. In addition, novel models for tracing the fate of materials over time and across products and regions in open-loop recycling have been developed based on information about the material composition of a final product using WIO-MFA [36,37].

As described above, WIO-MFA has been applied in various studies as a useful tool for analyzing material flow between sectors and for final products. However, from the viewpoint of recycling collection, it is desirable to analyze more exhaustively the destinations of materials (i.e., in which sectors and how much of the target material is accumulated). WIO-MFA focuses mainly on the material composition of a final product and the destinations of the final product, whereas it lumps together inputs that do not constitute final products as waste. However, flows are forked and may be delivered to different sectors. In the Japanese IOTs, for example, some inputs accumulate in the final demand sectors but some also accumulate in intermediate industrial (i.e., endogenous) sectors (see Section 2.1.2). Thus, it is necessary to consider inputs that do not constitute final products. Furthermore, it is possible that a part of the output from one specific sector is accumulated in a different sector from the main output (e.g., packaging that accompanies the product; see Section 2.1.2), although one sector is assumed to produce only one output in the WIO-MFA model. What is more, the same material can be contained in products in different processing forms. Therefore, an extended model is needed to identify comprehensively the above-mentioned destinations of materials, particularly the accumulation pathways of materials that do not constitute final products, with the aim of contributing to a holistic recycling strategy.

On the basis of the existing study [26], this study develops an MFA model for tracking pathways of materials to their destinations, including three accumulation pathways, process waste, and dissipation for the purpose of quantitatively identifying how much, in which processing forms, and in which sectors materials accumulate in the economic sphere. For illustration, the proposed model is applied to the Japanese IOTs for the year 2011 to analyze comprehensively copper flows in Japan in 2011. Copper was chosen for the case study because the demand for copper is increasing due to its wide use across a variety of applications and because the ore grade is relatively low, making recycling important to reduce the environmental impact of copper production from ore [8,38,39].

2. Model and Methods

2.1. Model

2.1.1. Classification of Sectors

Some sectors of IOTs are aggregated to a square matrix. Letting n_E be the number of endogenous sectors (E denotes the set of them), and letting n_F be the number of final demand sectors (e.g., household consumption, fixed capital formations, and exports) (with F denoting the set of them), and letting n be the number of all sectors and with N denoting the set of them, we have ($N = E \cup F$, $n = n_E + n_F$) (Figure 1). Next, E is partitioned into mutually exclusive and nonempty sets of *products* (P) with n_P elements, *materials* (M) with n_M elements, *resources* (R) with n_R elements, and *services* (S) with n_S elements (Figure 1). This partition into *products*, *materials*, and *resources* is based on Nakamura et al. [26] and *services* correspond to the sectors without mass that are removed by the mass filter in Nakamura et al. [26]. That is, sectors with outputs without mass are classified as *services* in principle and sectors with outputs with mass are classified as *products*, *materials*, or *resources*. The objects of interest in the analysis are classified as *materials* and the classification of other sectors depends on which sectors are classified as *materials*. Sectors the degrees of fabrication of which are lower than those of *materials* (i.e., sectors that cannot be made of *materials*) are classified as *resources*, and sectors the degrees of fabrication of which are higher than those of *materials* (i.e., sectors that cannot be made into *materials*) are classified as *products*.

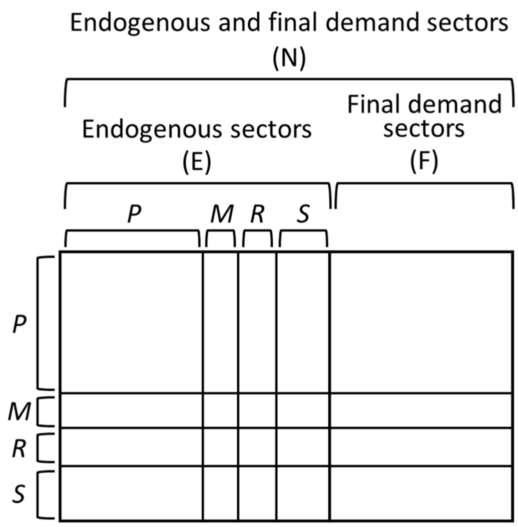


Figure 1. Classification of sectors. Note: P denotes *products*, M denotes *materials*, R denotes *resources*, and S denotes *services*.

2.1.2. Classification of Inputs

As mentioned in Section 1, a flow (input) from one sector to another sector can fork into different branches from its trunk. Input from sector $i \in P \cup M$ (input i) to sector $j \in E$ is classified into one trunk and four branches as illustrated in Figure 2. Here, sector $k \in N$.

Trunk: Input *i* constitutes the mass of output of sector *j* (output *j*).

This represents the case in which input *i* constitutes the mass of output *j* and then flows into another sector (*k*). For example, input from the "motor vehicle parts" sector to the "passenger motor cars" sector corresponds to this trunk. When sector *k* is a final demand sector, output *j* accumulates or dissipates in sector k. When sector *k* is an endogenous sector, the flow from sector *j* to sector *k* can fork into four branches. In this trunk, sector *j* consists of endogenous sectors with outputs the degrees of fabrication of which are higher than those of *materials* (i.e., *products*).

Branch 1: Input *i* is discarded as process waste in sector *j*.

Although input *i* flows into sector *j* to constitute the mass of output *j*, part of input *i* does not constitute the mass of output *j* but is discarded as process waste if the yield ratio is not 1. Such a case corresponds to this branch.

Branch 2: Input *i* accumulates in sector *j*.

This represents the case in which input *i* does not constitute the mass of output *j* but enters the stock at sector *j*. This covers the case in which input *i* is immediately discarded at sector *j*. It is different and should be distinguished from branch 1 in that input *i* cannot constitute the mass of output *j* (in branch 1, waste generation can be reduced by improving the yield ratio). In the case where input *i* accumulates in an industrial sector, conceptually it should be described as a flow from sector *i* to the final demand sector, such as a fixed capital formation sector. However, some inputs that would accumulate in industrial sectors are often counted as a part of the inputs to endogenous sectors in the actual IOTs. In the Japanese IOTs, specifically, the fixed capital formation sectors as final demand sectors basically cover "the transaction values of reproducible capital assets with a purchaser unit price of 100,000 yen or more and a utility duration of one year or longer" [40]. Thus, transactions values that do not fulfill the above conditions may be counted as the inputs to endogenous sectors, not final demand sectors. Most of the inputs from the "machine tools" sector or "cellular phones" sector to other sectors are examples of this branch.

Branch 3: Input *i* accompanies output *j*.

This represents the case in which input *i* accompanies output *j* and they flow into another sector (*k*) together. A typical example is a case in which input *i* is used as containers or packaging of output *j* (e.g., an input from the "plastic products" sector to the "beverages and foods" sectors used as plastic bottles). This should be distinguished from the trunk, because input *i* does not necessarily eventually accumulate in the same sector as the main output *j*. In this model, it is assumed that input *i* is an accompaniment to output *j*, flows into sector *k*, and accumulates in sector *k* regardless of whether the main output *j* accumulates in the same sector or a different sector. In this case, output *j* consists of endogenous sectors with outputs of mass (i.e., *products*, *materials*, or *resources*). As exceptional cases, some inputs to the *services* sectors can be classified into this branch. For example, input from the "plastic products" sector to the "retail trade" sector is assumed to flow into other sectors, such as the "household consumption" sector, as plastic bags. In this case, plastic bags accumulate (and they are eventually discarded) in not the "retail trade" sector but in the "household consumption" sector.

Branch 4: Input *i* dissipates at sector *j*.

This represents the case in which input *i* is dissipated at sector *j* in such a form that the recovery for recycling is almost impossible. This should be distinguished from the other branches because this type of input is outside the scope of recycling. It should be noted that this branch does not include the case in which materials are dissipated during their use (e.g., tire wear). This branch represents the case in which materials are dissipated immediately by their use (e.g., pesticides and fireworks).

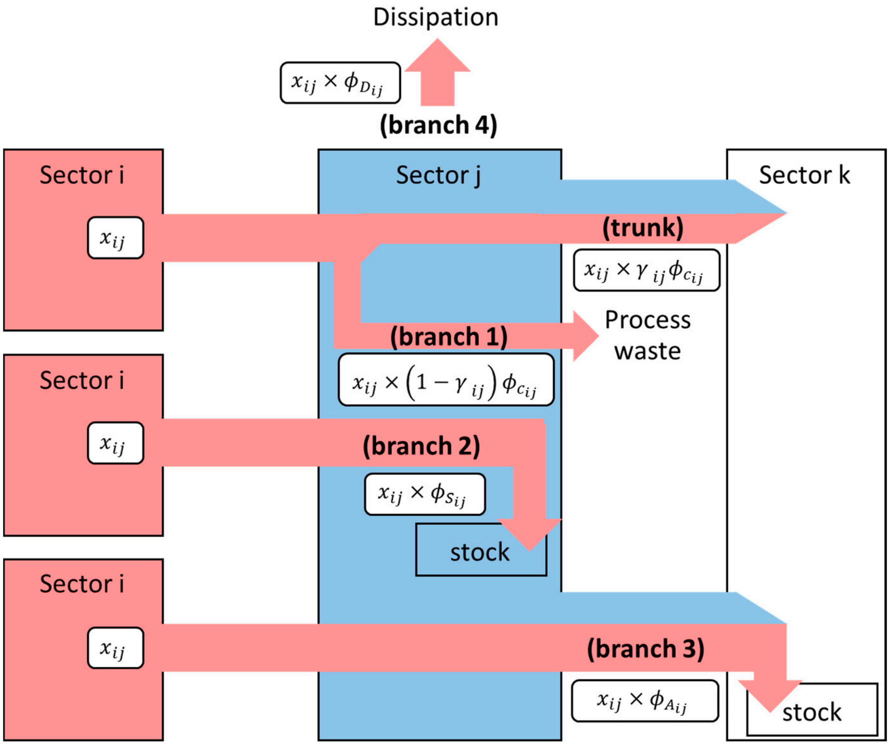


Figure 2. Classification of inputs. Note: x_{ij} is an input from sector i to sector j and γ_{ij} is the yield ratios. To the total input from sector i to sector j, $\phi_{C_{ij}}$ is the proportion of input i to constitute output j (trunk or branch 1), $\phi_{S_{ij}}$ is the proportion of input i to accumulate in sector j (branch 2), $\phi_{A_{ij}}$ is the proportion of input i to be used as accompaniments of output j (branch 3), and $\phi_{D_{ij}}$ is the proportion of dissipated input i in sector j (branch 4).

Next, we let $\Phi_C = \left[\phi_{C_{ij}}\right]$, $\Phi_S = \left[\phi_{S_{ij}}\right]$, $\Phi_A = \left[\phi_{A_{ij}}\right]$, and $\Phi_D = \left[\phi_{D_{ij}}\right]$ be $(n_P + n_M) \times n$ matrices, the ith row/jth column element of which is the portion of the input from sector i to sector j that corresponds to the trunk or branch 1, branch 2, branch 3, and branch 4, respectively (Figure 2). When sector j is a final demand sector, the case in which input i accumulates in sector j corresponds to $\phi_{S_{ij}}$, and the case in which input i dissipates in sector j corresponds to $\phi_{D_{ij}}$. These elements satisfy the following condition:

$$\phi_{C_{ij}} + \phi_{S_{ij}} + \phi_{A_{ij}} + \phi_{D_{ij}} = 1 \quad (1)$$

Φ_K $(K \in C,\ S,\ A,\ D)$ is partitioned into the parts for inputs from *products* to each sector group (e.g., $\Phi_{K(PE)}$) and inputs from *materials* to each sector group (e.g., $\Phi_{K(ME)}$):

$$\Phi_K = \begin{pmatrix} \Phi_{K(PN)} \\ \Phi_{K(MN)} \end{pmatrix} = \begin{pmatrix} \Phi_{K(PE)} & \Phi_{K(PF)} \\ \Phi_{K(ME)} & \Phi_{K(MF)} \end{pmatrix} = \begin{pmatrix} \Phi_{K(PP)} & \Phi_{K(PM)} & \Phi_{K(PR)} & \Phi_{K(PS)} & \Phi_{K(PF)} \\ \Phi_{K(MP)} & \Phi_{K(MM)} & \Phi_{K(MR)} & \Phi_{K(MS)} & \Phi_{K(MF)} \end{pmatrix},\ (K \in C,\ S,\ A,\ D) \quad (2)$$

2.1.3. Estimating the Destinations of Materials

Note that γ_{ij} is the yield ratio for the input from sector $i \in P \cup M$ to sector $j \in P$ that corresponds to the trunk or branch 1 (Figure 2). If the input from sector i to sector j does not correspond to either the trunk or branch 1, $\gamma_{ij} = 0$. Writing Γ for the $(n_P + n_M) \times n_P$ matrix of γ_{ij} (it is termed the yield matrix), Γ is partitioned into the part for inputs from *products* (Γ_{PP}) and inputs from *materials* (Γ_{MP}):

$$\Gamma = \begin{pmatrix} \Gamma_{PP} \\ \Gamma_{MP} \end{pmatrix}. \tag{3}$$

We then denote by A_{PP} and A_{MP} the matrices of input coefficients for the inputs from *products* and *materials* to *products*, respectively. Then, the parts of A_{PP} and A_{MP} that constitute the mass of outputs ($\widetilde{A}_{PP}$ and $\widetilde{A}_{MP}$) are given by the following equations:

$$\widetilde{A}_{PP} = \Gamma_{PP} \odot \left(\Phi_{C(PP)} \odot A_{PP}\right) \tag{4}$$

$$\widetilde{A}_{MP} = \Gamma_{MP} \odot \left(\Phi_{C(MP)} \odot A_{MP}\right) \tag{5}$$

where $\odot$ refers to the Hadamard product (the element-wise product of two matrices). We write V_{MN} for the $n_M \times n$ matrix, the elements of which refer to the reciprocal of the unit price of each *material* for inputs to each endogenous or final demand sector. V_{MN} is partitioned into the parts for inputs from *materials* to each sector group:

$$V_{MN} = \begin{pmatrix} V_{ME} & V_{MF} \end{pmatrix} = \begin{pmatrix} V_{MP} & V_{MM} & V_{MR} & V_{MS} & V_{MF} \end{pmatrix}. \tag{6}$$

Based on Nakamura et al. [26], the content of each *material* per unit of each *product* is given by the following matrix C_{MP}:

$$C_{MP} = V_{MP} \odot \left\{ \widetilde{A}_{MP} \left(I - \widetilde{A}_{PP}\right)^{-1} \right\} \tag{7}$$

where I is the unit matrix.

Writing $C_{M(m)P}$ for the row of C_{MP} that refers to the content of the specific *material m* per unit of each *product*, the destinations of *material m* embedded in each *product* are estimated with $C_{M(m)P}$. We then write X for the $(n_P + n_M) \times n$ matrix which refers to the flows from *products* and *materials* to endogenous and final demand sectors. X is partitioned into the parts for the flows from *products* to each sector group and inputs from *materials* to each sector group:

$$X = \begin{pmatrix} X_{PN} \\ X_{MN} \end{pmatrix} = \begin{pmatrix} X_{PE} & X_{PF} \\ X_{ME} & X_{MF} \end{pmatrix} = \begin{pmatrix} X_{PP} & X_{PM} & X_{PR} & X_{PS} & X_{PF} \\ X_{MP} & X_{MM} & X_{MR} & X_{MS} & X_{MF} \end{pmatrix}. \tag{8}$$

The amounts of *material m* in process waste generated in the production process in physical units (branch 1) are given by the following equation:

$$Process\ waste = diag\left(C_{M(m)P}\right)\left\{(U - \Gamma_{PP}) \odot \left(\Phi_{C(PP)} \odot X_{PP}\right)\right\} = diag\left(C_{M(m)P}\right) D_W \tag{9}$$

where $diag\left(C_{M(m)P}\right)$ refers to the diagonalized matrix of $C_{M(m)P}$, U to the matrix of unities of appropriate dimensions, and D_W to the flows of *products* that become process waste. The $(i,\ j)$-element of Equation (9) refers to the amount of *material m* in process waste generated from input i in the production process of sector j in physical units.

The accumulation of *material m* embedded in each *product* in the final demand sectors in physical units (trunk) is given by the following equation:

$$Accumulation\ in\ final\ demand\ sectors = diag\left(C_{M(m)P}\right)\left(\Phi_{S(PF)} \odot X_{PF}\right) = diag\left(C_{M(m)P}\right) D_{SF} \tag{10}$$

where D_{SF} refers to the accumulations of *products* in the final demand sectors. The $(i,\ j)$-element of Equation (10) refers to the accumulation of *material m* embedded in *product i* in sector j in physical units.

The accumulation of *material m* embedded in each *product* in the endogenous sectors in physical units (branch 2) is given by the following equation:

$$Accumulation\ in\ endogenous\ sectors = diag\left(C_{M(m)P}\right)\left(\Phi_{S(PE)} \bigodot X_{PE}\right) = diag\left(C_{M(m)P}\right)D_{SE} \quad (11)$$

where D_{SE} refers to the accumulations of *products* in the endogenous sectors. The $(i,\ j)$-element of Equation (11) refers to the accumulation of *material m* embedded in *product i* in sector *j* in physical units.

For estimating the destinations of the *material* as accompaniment, it is necessary to identify the destination of the accompaniment. When input *i* accompanies output *j*, it is assumed that the destination of input *i* depends on the flows from sector *j* to each sector in the model. First, we denote by x_{ij} the flow from sector $i \in E$ to sector $j \in E \cup F$ and by X_i the domestic production of sector $i \in E$. Next, we let *B* be an $n_E \times n$ matrix, the *i*th row/*j*th column element of which is x_{ij}/X_i. Then, the accumulation of *material m* as accompaniment in the endogenous and final demand sectors in physical units (branch 3) are given by the following equation:

$$Accumulation\ as\ accompaniment = diag\left(C_{M(m)P}\right)\left\{\left(\Phi_{A(PE)} \bigodot X_{PE}\right)B\right\} = diag\left(C_{M(m)P}\right)D_A \quad (12)$$

where D_A refers to the accumulations as accompaniment of *products* in the endogenous and final demand sectors. The $(i,\ j)$-element of Equation (12) refers to the accumulation of *material m* as the accompaniment *i* in sector *j* in physical units.

The dissipated amounts of *material m* embedded in each *product* in the endogenous and final demand sectors in physical units (trunk or branch 4) are given by the following equation:

$$Dissipation = diag\left(C_{M(m)P}\right)\left(\Phi_{D(PN)} \bigodot X_{PN}\right) = diag\left(C_{M(m)P}\right)D_D \quad (13)$$

where D_D refers to the flows of *products* dissipated in the endogenous and final demand sectors. The $(i,\ j)$-element of Equation (13) refers to the amount of *material m* dissipated in the flow from sector *i* to sector *j* in physical units.

The destinations of *materials* not embedded in any *product* can be estimated without C_{MP}. The amounts of each *material* in process waste generated from the input from the *material* in the production process of each *product* in physical units are given by:

$$V_{MP} \bigodot (U - \Gamma_{MP}) \bigodot \left(\Phi_{C(MP)} \bigodot X_{MP}\right) \quad (14)$$

the accumulation of each *material* not embedded in any *product* in the final demand sectors in physical units is given by:

$$V_{MF} \bigodot \left(\Phi_{S(MF)} \bigodot X_{MF}\right). \quad (15)$$

In addition, the accumulation of each *material* not embedded in any *product* in the endogenous sectors in physical units is given by:

$$V_{ME} \bigodot \left(\Phi_{S(ME)} \bigodot X_{ME}\right). \quad (16)$$

Next, the accumulation of each *material* not embedded in any *product* as accompaniment in the endogenous and final demand sectors in physical units is given by:

$$V_{MN} \bigodot \left\{\left(\Phi_{A(ME)} \bigodot X_{ME}\right)B\right\} \quad (17)$$

the dissipated amounts of each *material* not embedded in any *product* in the endogenous and final demand sectors in physical units are given by:

$$V_{MN} \bigodot \left(\Phi_{D(MN)} \bigodot X_{MN} \right). \tag{18}$$

2.1.4. The Destinations of Materials Considering the Processing Forms

From the viewpoint of recovery for recycling, it is desirable to estimate the destination of materials considering the processing forms. If all of the processing forms have the same degree of fabrication, the destination of materials by processing form can be estimated by defining the processing forms as *materials* in the model [26]. In reality, however, they are not necessarily the same. In this case, as the processing forms are defined as *products*, a different approach to estimate the destination by processing forms is required.

We let n_a be the number of *products* that become the processing forms of the specific *material m* and denote by $P_a = \{p_1,\ p_2,\ \cdots,\ p_{n_a}\}$ the set of them. Then, we let p_1 be the processing form (*product*) the degree of fabrication of which is the highest in P_a (i.e., even if p_1 constitutes the other *product*, it maintains its form). First, the destinations of *material m* in form p_1 are estimated.

Defining the $n_P \times (n_P + 3n)$ matrix D as Equation (19), Equations (9)–(13), which give the destinations of *material m* embedded in *products*, can be integrated into Equation (20):

$$D = \begin{pmatrix} D_W & D_{SF} & D_{SE} & D_A & D_D \end{pmatrix} \tag{19}$$

$$Destinations = diag\left(C_{M(m)P}\right)D. \tag{20}$$

Next, we let $\Phi_{PP(p_1)}$ and $\Phi_{MP(p_1)}$ be an $n_P \times n_P$ matrix and an $n_M \times n_P$ matrix, respectively, the ith row/jth column elements of which are zero if j corresponds to p_1 (otherwise they are unity). Then, the parts of $\widetilde{A}_{PP}$ and $\widetilde{A}_{MP}$ in which the inputs to the *product* p_1 are removed ($\widetilde{A}_{PP(\overline{p_1})}$ and $\widetilde{A}_{MP(\overline{p_1})}$) are given by the following equations:

$$\widetilde{A}_{PP(\overline{p_1})} = \Phi_{PP(p_1)} \bigodot \widetilde{A}_{PP} \tag{21}$$

$$\widetilde{A}_{MP(\overline{p_1})} = \Phi_{MP(p_1)} \bigodot \widetilde{A}_{MP}. \tag{22}$$

Replacing $\widetilde{A}_{PP}$ and $\widetilde{A}_{MP}$ in Equation (7) by $\widetilde{A}_{PP(\overline{p_1})}$ and $\widetilde{A}_{MP(\overline{p_1})}$, respectively, the content of each *material* in the forms other than p_1 per unit of each *product* is given by the following matrix $C_{MP(\overline{p_1})}$:

$$C_{MP(\overline{p_1})} = V_{MP} \bigodot \left\{ \widetilde{A}_{MP(\overline{p_1})} \left(I - \widetilde{A}_{PP(\overline{p_1})} \right)^{-1} \right\}. \tag{23}$$

Writing $C_{M(m)P(\overline{p_1})}$ for the row of $C_{MP(\overline{p_1})}$ which refers to the content of *material m*, the destinations of *material m* in form p_1 are given by:

$$diag\left(C_{M(m)P}\right)D - diag\left(C_{M(m)P(\overline{p_1})}\right)D. \tag{24}$$

Next, the destinations of *material m* in the processing form the degree of fabrication of which is the second highest in P_a (denoted by p_2) are estimated. The parts of $\widetilde{A}_{PP}$ and $\widetilde{A}_{MP}$ in which the inputs to the *product* p_1 or p_2 are removed ($\widetilde{A}_{PP(\overline{p_1 \cup p_2})}$ and $\widetilde{A}_{MP(\overline{p_1 \cup p_2})}$) are given by the following equations:

$$\widetilde{A}_{PP(\overline{p_1 \cup p_2})} = \Phi_{PP(p_2)} \bigodot \left(\Phi_{PP(p_1)} \bigodot \widetilde{A}_{PP} \right) \tag{25}$$

$$\widetilde{A}_{MP(\overline{p_1 \cup p_2})} = \Phi_{MP(p_2)} \bigodot \left(\Phi_{MP(p_1)} \bigodot \widetilde{A}_{MP} \right). \tag{26}$$

Replacing $\widetilde{A}_{PP(\overline{p_1})}$ and $\widetilde{A}_{MP(\overline{p_1})}$ in Equation (23) by $\widetilde{A}_{PP(\overline{p_1 \cup p_2})}$ and $\widetilde{A}_{MP(\overline{p_1 \cup p_2})}$, respectively, gives the matrix $C_{MP(\overline{p_1 \cup p_2})}$, which refers to the content of each material in the forms other than p_1 or p_2 per unit of each product. Writing $C_{M(m)P(\overline{p_1 \cup p_2})}$ for the row of $C_{MP(\overline{p_1 \cup p_2})}$ that refers to the content of material m, the destinations of material m in form p_2 are given by:

$$diag\left(C_{M(m)P(\overline{p_1})}\right)D - diag\left(C_{M(m)P(\overline{p_1 \cup p_2})}\right)D. \quad (27)$$

In a similar way, the destinations of *material m* in the other forms can be estimated sequentially.

2.2. Application of the Model to the Copper Flows in Japan

The proposed model is applied to analyze the copper flows in Japan. The Japanese IOT for the year 2011 [41], which is the latest version as of March 2018, is used for the analysis, and the "copper" sector is defined as *material*. In the Japanese IOT, flows from the endogenous sectors to each fixed capital formation sector are individually compiled as the fixed capital matrix, which is contained in one of the supplementary tables. In this study, the fixed capital formation sector as the final demand sector is disaggregated based on the fixed capital matrix.

Dissipated flows (sectors corresponding to branch 4) are defined based on Ciacci et al. [42]. Dissipative uses having a lifetime of less than one year as defined in Ciacci et al. [42] (i.e., pesticides, fertilizers, animal feed, and fireworks) are classified to branch 4. The data for the yield matrix Γ are taken from the Japan Copper and Brass Association [43]. The data on the unit price of copper for inputs to each sector for V_{MN} are taken from the table on value and quantity, which is contained in one of the supplementary tables of the Japanese IOT.

Copper is used mainly in the form of "electric wires and cables" or "rolled and drawn copper and copper alloys" [44]. In this study, the "electric wires and cables" sector, "rolled and drawn copper and copper alloys" sector, and "others" denote three different processing forms of copper. It is assumed that the "electric wires and cables" sector has the highest degree of fabrication (p_1), the "rolled and drawn copper and copper alloys" sector has the second highest (p_2), and the "others" represent the lowest (p_3). Copper not embedded in any *product* is included in the "others".

3. Results and Discussion

Figure 3 shows the overall results of the application of this model to copper flows in Japan. Figure 3 shows the accumulation in domestic demand sectors as products (trunk or branch 2), accumulation in domestic demand sectors as accompaniments (branch 3), process waste (branch 1), dissipation (trunk or branch 4), and exported flow (one of the final demand sectors) by the three processing forms. Since the exported flow does not enter the stock in Japan, it is distinguished from the other final demand sectors. The main final destinations of copper are export (51.1%), accumulation in domestic demand sectors (both in final and endogenous sectors) as products (41.1%), and process waste (7.61%). The accumulation in domestic demand sectors as accompaniments and dissipation is very small. Although the accumulation as accompaniments is very small for copper, it may not be negligible for other materials, such as plastic, because plastic is used as containers or packaging more than copper. Dissipation is very small partly because it does not include the case in which materials are dissipated during their use. Next to the exported flow, the largest flow of copper is accumulation in the domestic final demand sectors (31.9%). Accumulation in the endogenous sectors is not small and negligible (9.24%).

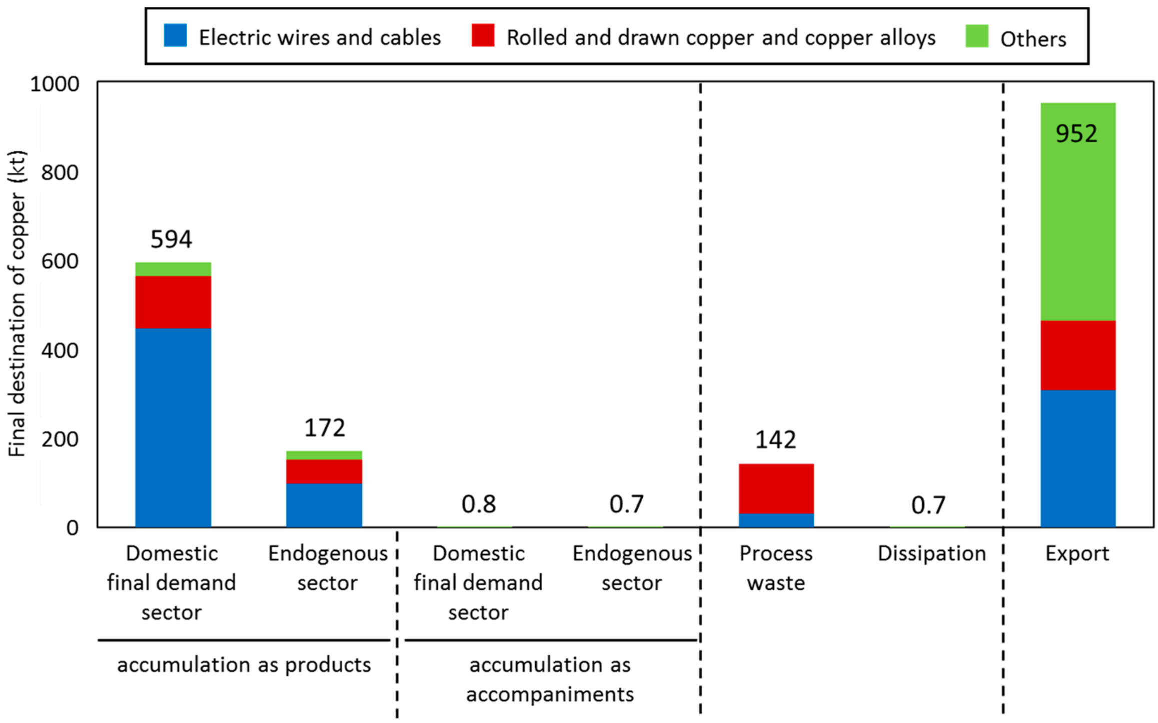


Figure 3. Final destination of copper by processing forms in Japan.

The most dominant processing form is the "electric wires and cables", and "others" is the second-most dominant processing form. The amount of copper flow in the form of "electric wires and cables" is about 884 (kt) and accounts for 47.5% of the overall flow. Most of the exported flow in the form of "others" is the export of "copper" itself. Although the amount of copper flow in the form of "rolled and drawn copper and copper alloys" is the smallest, it is dominant as the source of process waste. This is because the yield ratios for cases in which "rolled and drawn copper and copper alloys" are input tend to be smaller than those for the "electric wires and cables". For the accumulation, "electric wires and cables" is the most dominant processing form and "rolled and drawn copper and copper alloys" is the second-most dominant processing form.

Figure 4 shows the copper accumulations in each *product* by processing forms. In Figure 4, each value includes both accumulation as products and as accompaniments, and 256 *products* are aggregated into 16 *products*. The accumulation as "information and communication electronics equipment" is the largest, "electrical machinery" is the second-largest, and "other metal products" is the third-largest. These *products* are composed of all processing forms, whereas some *products*, including "electric wires and cables", "railway construction", and "electric power facilities construction", are mainly composed of "electric wire and cables".

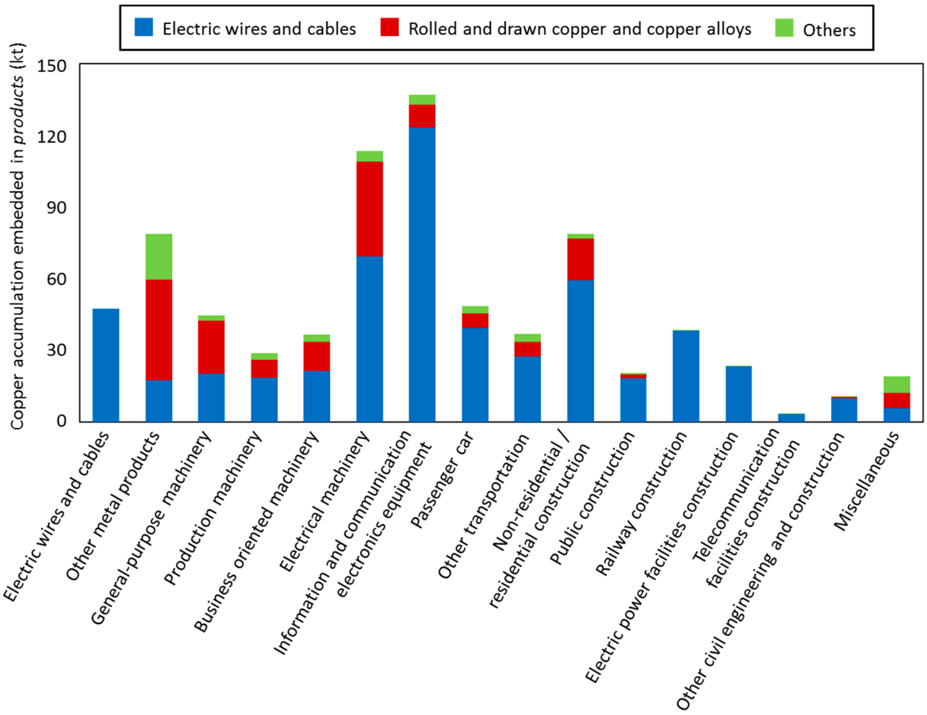
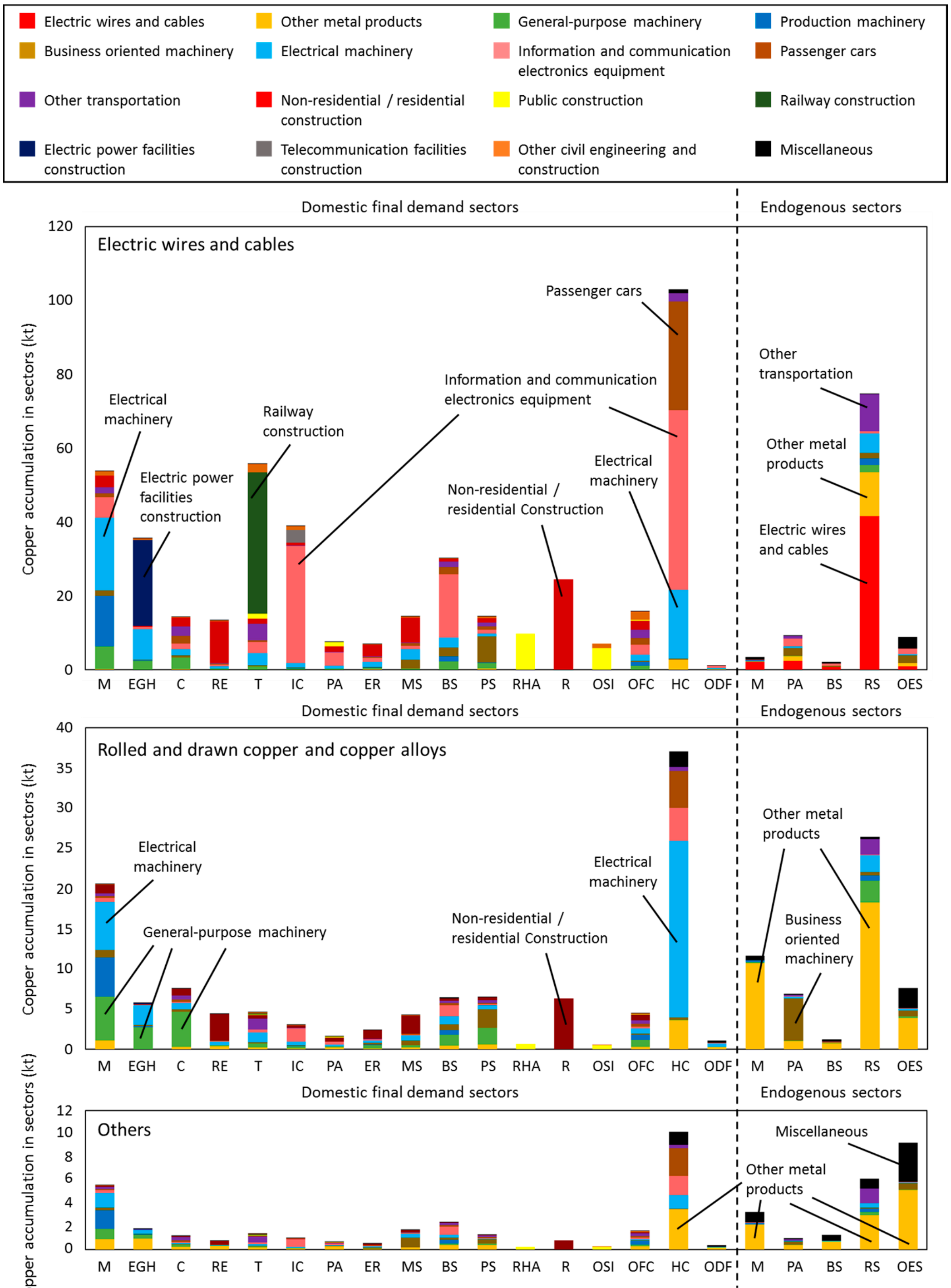


Figure 4. Copper accumulations embedded in each *product* by processing forms in Japan. Accumulations as products and accompaniments are summed up.

Figure 5 shows the copper accumulations in each sector embedded in each *product* in the form of "electric wire and cables", "rolled and drawn copper and copper alloys", and "others". In Figure 5, each value includes both accumulation as products and as accompaniments. In Figure 5, 62 domestic final demand sectors are aggregated into 17 sectors, 363 endogenous sectors into 5 sectors, and 256 *products* into 16 *products*. We can say that the *products* and sectors where copper enters are different depending on the processing forms.

The accumulation in the "household consumption" sector is the largest for all processing forms. For the form of "electric wire and cables", copper accumulates in the "household consumption" sector mainly as "information and communication electronics equipment" (e.g., cellular phones and radio communication equipment), "passenger cars", and "electrical machinery" (e.g., household electric appliances). On the other hand, for the form of "rolled and drawn copper and copper alloys", copper accumulates in the "household consumption" sector mainly as "electrical machinery". For the form of "others", copper accumulates in the "household consumption" sector mainly as "other metal products" (e.g., miscellaneous non-ferrous metals and miscellaneous manufacturing products) and "passenger cars". This result implies the importance of recovery of discarded products from households. Furthermore, products in a household often become "hibernating stock", which represents the material stock that has been used, is not now being used, and has not yet been discarded [45]. Hibernating stock attracts attention as an important potential secondary resource that can be recovered as needed [46]. For hibernating stock in a household, various studies have been conducted about cellular phones in Japan [47], televisions in the U.S. [48], and electrical and electronic equipment in the U.K. [49]. This model can be expected to contribute to the study of hibernating stock.



[Domestic final demand sectors]
M: Manufacturing; **EGH**: Electricity, gas, and heat supply; **C**: Commerce; **RS**: Real estate; **T**: Transport
IC: Information and communications; **PA**: Public administration; **ER**: Education and research; **MS**: Medical service
BS: Business services; **PS**: Personal services; **RHA**: Road, harbor, and airport; **R**: Residence; **OSI**: Other social infrastructure
OFC: Other fixed capital formation; **HC**: Household consumption; **ODF**: Other domestic final demand
[Endogenous sectors]
M: Manufacturing; **PA**: Public administration; **BS**: Business services; **RS**: Repair services; **OES**: Other endogenous sectors

Figure 5. Copper accumulations in final demand and endogenous sectors by *products* in the form of "electric wire and cables" (**top**), "rolled and drawn copper and copper alloys" (**middle**), and "others" (**bottom**) in Japan. Accumulations as products and accompaniments are summed up.

The second largest accumulation is the accumulation in the "repair services" sector. Input to the "repair services" sector includes the input of parts for repair and the input of tools used for repair. It should be noted that both of these inputs are considered as accumulations in the "repair services" sector in this study, and thus the result for the accumulation in the "repair services" sector in Figure 5 includes both values. The final destination of materials in the former input may change depending on which product the parts enter for repair. It is necessary to consider this point especially in applying this model to dynamic MFA (see Section 4). For the form of "electric wire and cables", copper accumulates in the "repair services" sector mainly as "electric wires and cables", "other metal products" (e.g., miscellaneous electronic components), and "other transportation" (e.g., motor vehicle parts and accessories). For the form of "rolled and drawn copper and copper alloys", copper accumulates in the "repair services" sector mainly as "other metal products" (e.g., rolled and drawn copper and copper alloys). For the form of "others", copper accumulates in the "repair services" sector mainly as "other metal products" (e.g., plumber's supplies, powder metallurgy products, and tools) and "other transportation".

Other characteristics of the destination of copper in the form of "electric wire and cables" are that accumulations in the "electricity, gas, and heat supply" sector as "electric power facilities construction", in the "transport" sector as "railway construction", and in the "information and communications" sector as "information and communication electronics equipment" (e.g., wired communication equipment and radio communication equipment) are relatively large. This means that most of the copper stocks in these sectors are stocks in the form of "electric wire and cables". The unique patterns of accumulation for the form of "electric wire and cables" can be seen in Figures 4 and 5.

4. Conclusions

In terms of recycling, this study proposes a model for tracking accumulation pathways of materials in detail considering the processing form of the material. The proposed model was applied to analyze copper flows in Japan for the year 2011. This study tracked the destination of copper for three processing forms (i.e., "electric wire and cables", "rolled and drawn copper and copper alloys", and "others") by the "product" in which materials are contained and the "sector" in which products accumulate.

The main characteristics of this model are as follows:

1. Accumulations in sectors other than final demand sectors (i.e., endogenous sectors) are explicitly evaluated.
2. Accumulations as accompaniments to products, such as containers and packaging, are distinguished from the products.
3. The processing forms of materials are considered.

For the first characteristic, application of the model revealed that accumulation of copper in endogenous sectors is not small and negligible (it accounts for 12.2% of the overall flow). For the second characteristic, accumulation of copper as accompaniments is very small. However, accumulation as accompaniments may be larger for other materials that are used more often as containers or packaging (e.g., plastic). This point is one of the possible future directions for research. For the third characteristic, the result of estimating the accumulation in the form of "electric wires and cables" showed that the characteristics could be different from those of other forms. This indicates the importance of analyzing material flows by considering the processing forms from the viewpoint of recycling.

It is necessary to mention the uncertainties and limitations of the model. This model utilizes IOTs, which provide comprehensive information and enable detailed analysis. However, as it is often discussed for analysis utilizing IOTs, some industry or commodity classifications are aggregated in IOTs and the level of resolution of them may be a source of uncertainty [50,51]. This uncertainty will be partly resolved with a hybrid approach, which combines other detailed data with input–output analysis [52]. For example, several studies have disaggregated the steel material sectors based on other data than IOTs for analysis utilizing WIO-MFA [28,30,31]. The hybrid approach will be also applicable to the extended model in this study. This is one of the future works for this model. Another source of uncertainty or limitation of the model is the estimation of the yield matrix (Γ). It determines the amounts of *material* in process waste and then effects the estimation of accumulation of *material*. As Γ is *material*-specific, the data availability for Γ is important and will be a limitation in applying the model.

Finally, we discuss the possible application of this model. While we applied the model to analyze the flow of materials for one year in this study, the model can be applied to the estimation of stock and discarded flow by dynamic MFA. Application to dynamic MFA is important because materials that are recovered for recycling in a given year are mainly discarded flow and hibernating stock in that year. A comprehensive analysis of material flow using the model will allow for a detailed dynamic MFA. Another possible application is the management of the release of hazardous substances. Detoxification of the industrial metabolism is one of the basic strategies for MFA [53]. Products such as electrical and electronic equipment contain a variety of substances that are potential environmental contaminants [54]. Since information on the amount and source of release of hazardous substances is important for managing them, tracking the flows of hazardous substances and/or their sources is highly beneficial. This model can contribute to the identification of the destination of hazardous substances.

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