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

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Abstract

This paper develops a theoretical model of 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. 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, 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 used in a passenger car. The model is also used to estimate the major final use categories of quantity metals.

keywords: MFA, input-output analysis, triangularity, base metals, yield ratios

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/SFA within the framework of the waste input-output (WIO) model [3]. 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/SFA would thus enable one to apply the whole battery of analytical tools of WIO/IOA to MFA/SFA.

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/SFA. This is a major concern of this paper.

It is known in the literature that reordering of the sectors in the IO coefficients matrix can reveal a certain triangular structure that represents the hierarchical degree of fabrication among inputs [4]. 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. Furthermore, we divide n outputs into mutually exclusive and nonempty sets of resources (n_R elements, denoted by R), materials (n_M elements, denoted by M), and products (n_P elements, denoted by P) such that $n = n_P + n_M + n_R$. Writing $\widetilde{A}$ for the part of A that physically enters products, we then obtain:

$$\Gamma \odot \Phi \odot A = \widetilde{A} = \begin{pmatrix} \widetilde{A}_{PP} & \widetilde{A}_{PM} & \widetilde{A}_{PR} \\ \widetilde{A}_{MP} & \widetilde{A}_{MM} & \widetilde{A}_{MR} \\ \widetilde{A}_{RP} & \widetilde{A}_{RM} & \widetilde{A}_{RR} \end{pmatrix}, \tag{1}$$

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 [4].

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

1. Resources are not produced but given from the environment: $\widetilde{A}_{iR} = O$, $i \in \{P, M, R\}$.

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

3. Products are made of products and materials: $\widetilde{A}_{RP} = O$,

which implies

$$\widetilde{A} = \begin{pmatrix} \widetilde{A}_{PP} & O & O \\ \widetilde{A}_{MP} & O & O \\ O & \widetilde{A}_{RM} & O \end{pmatrix}, \tag{3}$$

where O is a zero matrix of an appropriate order. It follows from (3) that any physical product can be reduced to materials, with its "material composition" being given by the column elements of the following matrix:

$$C_{MP} = \widetilde{A}_{MP} \left(I - \widetilde{A}_{PP} \right)^{-1}. \tag{4}$$

If all the materials are measured in a common physical unit, then the column sum of C_{MP} gives the weight of products in that unit.

By use of C_{MP}, the flow of products can easily be converted into the corresponding flow of materials. Write C_{M_iP} for the ith row of C_{MP}, X_P for the $n_P \times 1$ vector of the output of products, and X_{Pf} for the final demand for the products. Table 1 showss the way to convert the input-output matrix into the flow matrix of materials. For instance, $\mathrm{diag}(C_{M_iP}) \odot \widetilde{A}_{PP}\ \mathrm{diag}(X_P)$ gives the part of the intermediate flow of material i that physically enters products, while $\mathrm{diag}(C_{M_iP}) \odot \breve{A}_{PP}\ \mathrm{diag}(X_P)$ gives the part of the flow that is discarded as process waste.

Of special interest is the expression $\mathrm{diag}(C_{M_iP}) \odot X_{PF}$. This gives the component of material i in the final demand for products, or the final use categories of material i: our model can determine the use categories of materials. This is in sharp contrast to the usual practice of MFA studies, where the use categories of materials are a prior given from outside sources [2][5].

3 Application and Results

3.1 Data

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). We use the Japanese IO table for the year 2000 [6] 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 [7][8]. 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 (10^3kg) and 10 resource sectors (ores, stones including limestone, coal, petroleum and natural gas), and 407 endogenous sectors, of which 297 refer to sectors producing physical output 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, [10], and [11].

3.2 Testing the accuracy of the model

The column sum of C_{MP} gives the estimated metal weight of products per unit (10^3kg 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, we can use this result to check the accuracy of the model. This was the case for a passenger car, among others: 821kg and 1.45 million yen per unit [9][6][12] . It turned out that the estimated metal weight of a passenger car (776 kg $=$ 536kg/one million yen $\times$ 1.45 million yen/unit) compares well with the real weight of a representative compact car (821 kg).

We now turn to the testing of the model with regard to the metal composition of a passenger car. Figure 1 compares the estimated metal composition of a passenger car with the real composition of both 1997 and 2001 models [12]. It is found that the estimated shares of major metals reproduce the real shares fairly well. In interpreting Figure 1, a remark seems due on the difference in the definition of metal categories between [12] and our model (WIO-MFA). The iron composition in [12] includes Zn contained in coated steel, while in our model this is not the case: our estimate of Zn contained in a passenger car includes, besides that used in coated steel, that which is used as an additive to tires, pigments, and inorganic chemicals.

3.3 Destination of metals

An important task of MFA/SFA is to identify the location of metals (or any substance of concern), or the way metals are distributed among different final products in the economy. As mentioned above, a distinguishing feature of WIO-MFA consists in that it can estimate the final use categories of materials, whereas in usual MFA studies it is given *a-priori* from outside sources. Figures 2 to 6 show the distribution of metals among major final products, which constitute more than 60% of the total amount that enters products, distinguished by five final demand categories (household consumption, public consumption, capital investment, inventory investment, and export).

Figure 2 indicates that 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.

Figure 3 indicates that while more than 70% of lead occurs in automobiles, a non-negligible portion occurs in inorganic chemicals, pigments, and glass products. The recycling of car batteries is thus vital for managing lead in the economy.

Figure 4 shows that while 25% of zinc is exported in the form of coated steel, automobiles and construction constitute its major domestic destination. Also noteworthy is the fact that a non-negligible portion goes to containers (including those of soft drinks) and pigments.

Figure 5 shows that while automobiles constitute about 20% of the total amount of aluminum embodied in products, the share of the export of parts and engines amounts to more than 6%, which indicates the importance of these intermediate products in the use of aluminum. It then follows that a siginificant amount of aluminum enters automobiles in the form of parts, accessories, and engines.

Finally, Figure 6 shows the destination of iron. Two distinguishing features can be pointed out. 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, the WIO-MFA model, has been presented. This model differs from conventional MFA studies such as [5] 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 input-output analysis (IOA). In contrast, examples of MFA studies base on the theory of input-output analysis are extremely rare ([2] is a minor exception) notwithstanding the occasional mention of a close relationship between MFA and IOA [15].

With regard to the objective of developing a physical input-output model, our model has much in common with physical input-output tables (PIOTs) [13]. However, our model differs significantly from PIOTs at least in two respects. First, our model is based on two theoretical ingredients, yield ratios and triangularity, which is not the case for PIOTs. PIOTs have mostly been developed by extending accounting systems, while our model starts from basic theoretical considerations within the framework of IOA. Because of this feature, our model is fully consistent with the concepts of the monetary input-output table (MIOT), which is not the case for PIOTs [14]. This feature of PIOTs has been criticized by Helga Weisz and Faye Duchin [14] because of the "lack of standardization for physical input-output accounting". Due to its full consistency with IOA, our model escapes such criticism.

We finish our theoretical discussion by mentioning an important study by Shinsuke Murakami [2], a rare example of an extensive MFA study of 19 types of metals, including both base and rare metals based on IOA. Three distinguishing points can be mentioned with regard to its theoretical features. First, in [2] the generation of process waste is not considered: yield ratios of unity are assumed. Secondly, it does not use the concept of triangularity or the degree of fabrication. Thirdly, the use categories of metals are given *a-priori* from other sources. The last two points indicate that [2] has much in common with conventional MFA studies.

We close this article by briefly pointing out two future directions for research. 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. Dynamic extension of the model under consideration of the fact that products have different lives can be mentioned as another important direction for research.

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Table 1: The flow of material i in the input-output matrix

Intermediate flow	Final demand
Entering outputs:	
$\mathrm{diag}(C_{M_iP}) \odot \widetilde{A}_{PP}\ \mathrm{diag}(X_P)$	$\mathrm{diag}(C_{M_iP}) \odot X_{PF}$
Discarded as process waste:	
$\mathrm{diag}(C_{M_iP}) \odot \breve{A}_{PP}\ \mathrm{diag}(X_P)$	

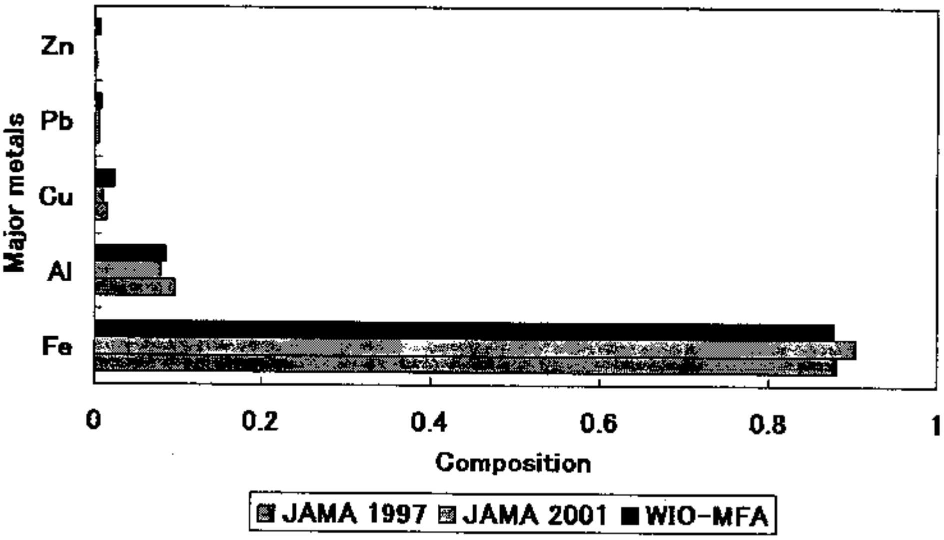

Figure 1: The metal composition of a passenger car. JAMAxxxx refers to the metal composition of a representative passenger car of year xxxx taken from [12]. WIO-MFA refers to the composition estimated by our model.

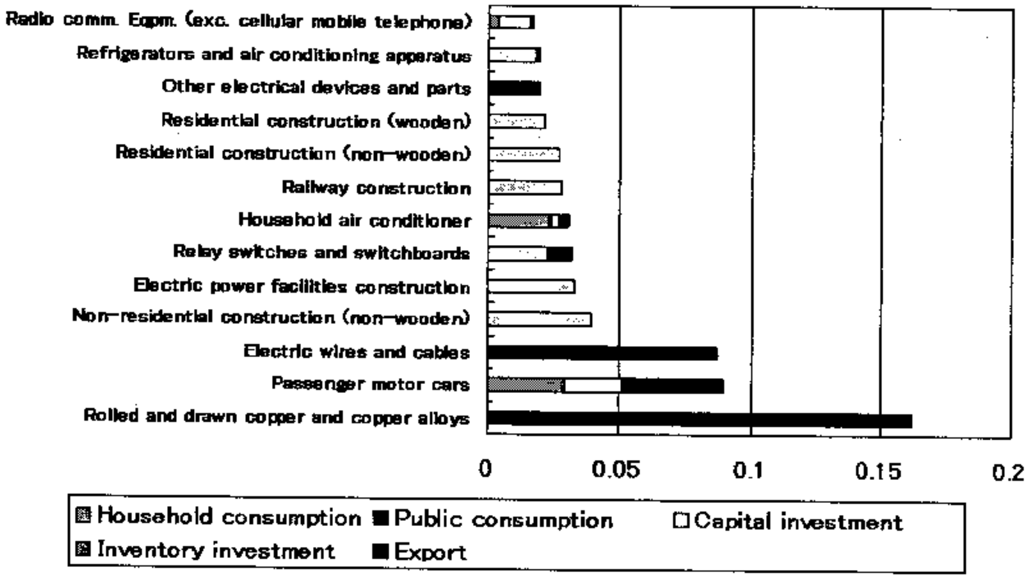

Figure 2: The distribution of Cu among final products.

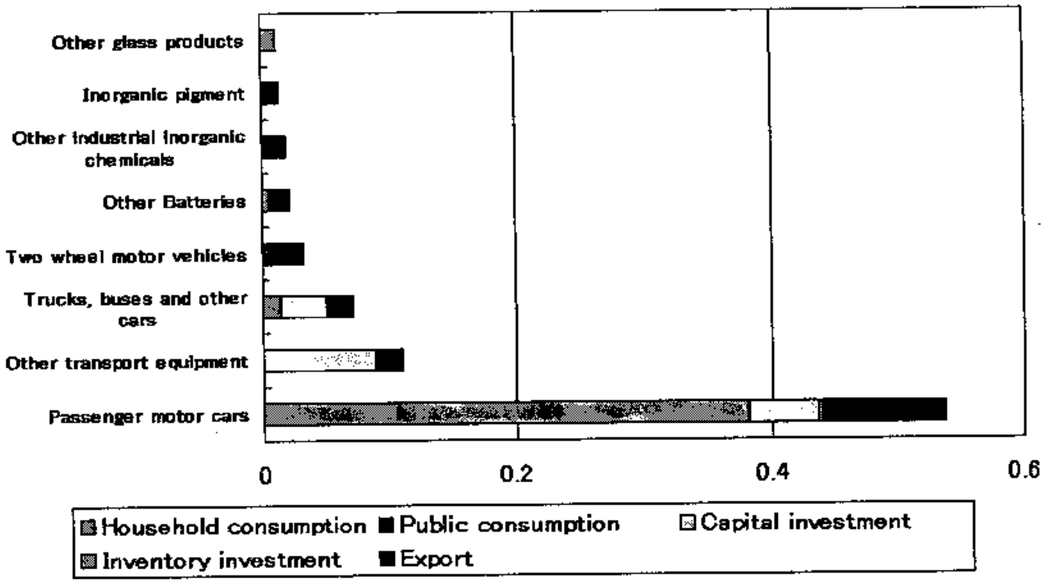

Figure 3: The distribution of Pb among final products.

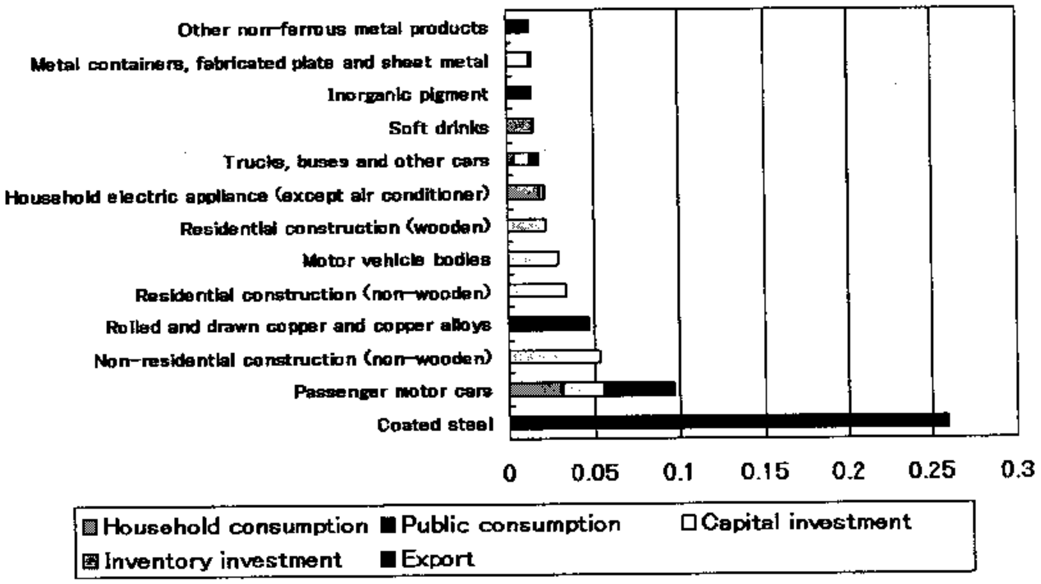

Figure 4: The distribution of Zn among final products.

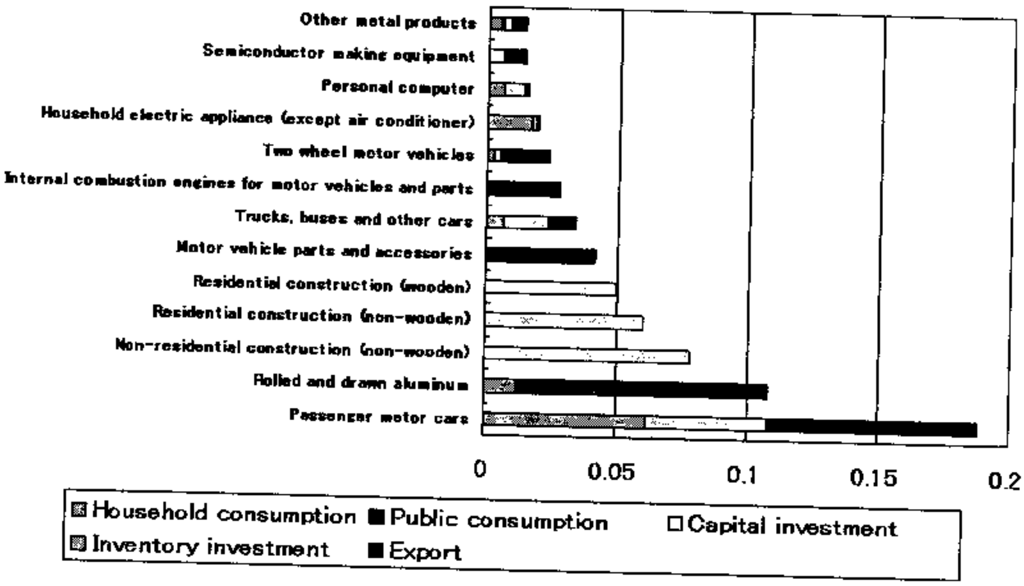

Figure 5: The distribution of Al among final products.

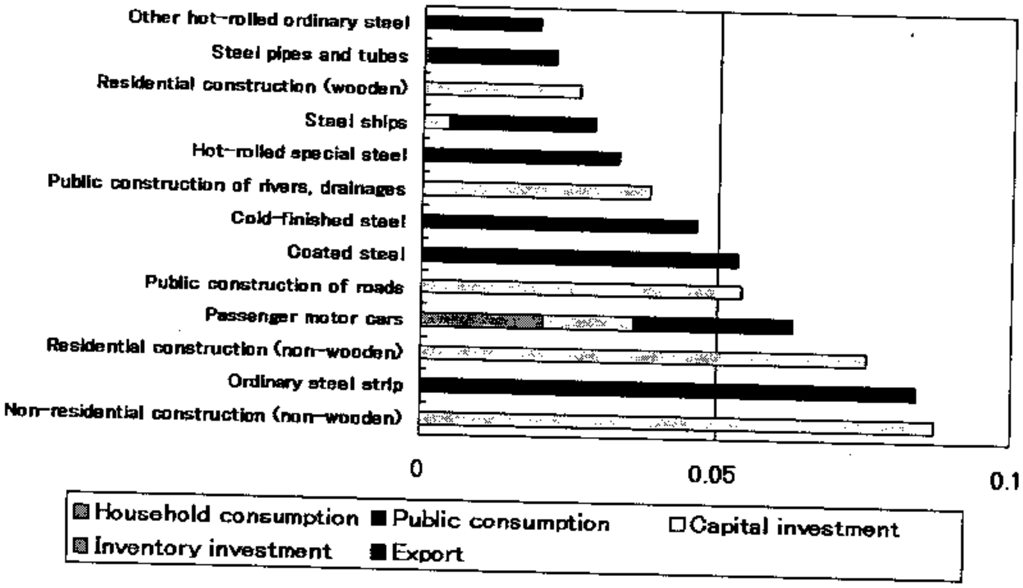

Figure 6: The distribution of Fe among final products.