The development of an enterprise input output model and its application to industrial environmental management

By

Mitsutaka MATSUMOTO* and Jun FUJIMOTO**

Abstract

In this paper, we present an enterprise input-output (EIO) model and apply it to an industrial environmental management. We present two versions of the model: a "micro EIO model" describing production within an enterprise, and a "macro EIO model" describing production across a broader range, such as in a nation. We discuss that the CO_2 emissions calculated using the models provide a metrics for companies to assess environmental management within the companies. We applied the model to a group of companies in the Japanese electronics industrial sector. We discuss the implications of the model results on the corporate environmental management.

1 Introduction

Climate change is a major global concern that requires a multifaceted solution. Effective responses to the climate change problem need to be adopted by corporations because a substantial proportion of global CO_2 emissions is produced by the industrial sector, and environmental impact assessment of product manufacturing processes are therefore necessary for improving the energy efficiency of this sector. In addition, the increased energy used by information and communication technology (ICT) products is becoming a concern (Huber and Mills, 1999; Kawamoto et al., 2002; METI, 2008; Plepys, 2000). In 2006, 230 million of personal computers (PCs) were sold worldwide. As we review in Section 2.2, energy consumption by ICT products is estimated to be 2-8% of the total electricity used in developed countries (Huber and Mills, 1999; Kawamoto et al., 2002; METI, 2008). Energy consumption by the ICT sector occurs during manufacturing process, as well when the products are used. We focus on energy flow during the manufacturing process of ICT products using the framework of the input-output model (IO model). The IO has been traditionally used to analyze mone-

* Center for Service Research, National Institute of Advanced Industrial Science and Technology (AIST), Japan.
Postal address: 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
E-mail address: matsumoto-mi@aist.go.jp

** Research Center for Advanced Science & Technology, The University of Tokyo
Postal address: 4-6-1 Komaba, Meguro, Tokyo 153-8904, Japan

tary flow in nations or regions (Leontief, 1936; Isard and Kuenne, 1953; Miller, 1957). The model has also been applied to energy flow analyses within nations (Leontief et al., 1970; Wyckoff and Roof, 1994).

The IO model described here is intended for application to the corporate level and is therefore referred to as an enterprise input-output model (EIO model), several applications of which have been described previously (Albino et al., 2003; Albino et al., 2008; Grubbstrom et al., 2000; Lin and Polenske, 1998; Marangoni et al., 2004; Polenske 1997; Polenske and McMichael, 2002). Lin and Polenske, for example, applied the model to corporate environmental management (Lin and Polenske, 1998). They discussed that we can quantify the waste disposal costs, identify factors that influence waste generation, and evaluate alternative options to comply with regulations, using the model. In this paper, we focus on corporate environmental management for CO_2 abatement and discuss the application of the EIO model to provide a metrics for the management. We define two versions of CO_2 emissions of in-company sectors: the "direct CO_2 emissions" representing the emissions in the sector, and the "sales-based CO_2 emissions" representing the emissions in the company to produce the products that are sold externally from the sector. We discuss the usage of the sales-based CO_2 emissions for corporate environmental management.

One major obstacle to effective corporate environmental management is that the organizational structure of a company changes frequently. When the organizational structure changes, for example, a manufacturing process of an in-company sector move to other sector, if other conditions are same, CO_2 emissions in the sector from which a process moves out will decrease, and the emissions in the sector to which the process comes in will increase. In such cases, CO_2 emissions of the sectors before and after the move can not be simply compared. It makes companies difficult to set CO_2 abatement goal to in-company sectors and to evaluate the effectiveness of environmental management of sectors. An effective metrics to evaluate environmental management is required. In this paper, we discuss that the sales-based CO_2 emissions can be a metrics.

Manufacturing processes are moved not only within a company but also to outside the company. It is called *outsourcing*. We formulate the "macro EIO model" which describes productions in a broader range than in a company, such as in a nation. In the model, an enterprise is embedded explicitly in the range. We discuss that the sales-based CO_2 emissions calculated using a macro EIO model provide a metrics in cases in which a process is outsourced outside the company. An analogy is that, in international climate change politics, an effective metrics for national CO_2 emissions is required. The emissions of a country can seemingly decrease when energy intensive industries are transferred to abroad.

We applied the models to a group of electronics companies in Japan. The group consists of several tens of companies and has totally several ten thousands of employees. We divided the group into 10 in-company (in-group) sectors and built the EIO table for the group. Using the EIO table, we calculated the direct and sales-based CO_2 emissions of the in-company sectors. We also built the macro EIO table for the group by integrating the (micro) EIO table with the Japanese national IO table. We calculated the sales-based CO_2 emissions using the table and analyzed the breakdowns. We present the results and discuss the implications.

The present paper is organized as follows: Section 2 outlines the previous studies on EIO models and introduces the studies on the impact of ICT on energy consumption. In Section 3, formulation of the EIO model is presented. We formulate two versions of the model, with the former used as the IO model for individual companies and the latter for companies that are explicitly linked to a national IO model. In Section 4, we apply the models to the analysis of energy flow within companies. We present the mathematical formulation of the sales-based CO_2 emissions. In Section 5, we present the findings obtained using actual data. We applied the model and methods to a group of Japanese electronics companies and discuss the implication of the model results on corporate environmental management. Finally, our conclusions are presented in Section 6 and recommends future research.

2.1 Enterprise input-output model

Input-output analysis (IO analysis) is an analytical framework for economics originally developed by Leontief (Leontief, 1936). The model provides a consistent method for ascertaining the flows from suppliers to users within a nation. In addition to the national level, considerable IO activities occur at a variety of levels; whether it is for a group of nations, a county, or a metropolitan area. Regional IO models deal with a single region or with two or more regions and their interconnections. Examples of the earliest attempts of quantifying single-region IO tables can be found in (Isard and Kuenne, 1953; Miller, 1957).

Researchers in countries, such as Belgium, Italy and China, have developed enterprise input-output (EIO) models (Albino et al., 2003; Albino et al., 2008; Grubbstrom et al., 2000; Lin and Polenske, 1998; Marangoni et al., 2004; Polenske 1997; Polenske and McMichael, 2002). The basic units of the EIO model are typically products and branches within a company, which are in many cases treated in the same way as the sectors in national IO tables. EIO models were proposed to support corporate management accounting system and were used for a variety of analytical tasks in the firm. Their applications to corporate environmental management were also proposed. In particular, Lin and Polenske built a specific IO model for a steel plant, and presented the methods to investigate the energy intensity of the plant (Lin and Polenske, 1998). Polenske and McMichael built an IO model for a cokemaking plant and assessed the economic and energy requirements of using alternative cokemaking technologies (Polenske and McMichael, 2002). Using a similar approach, Albino et al. have formulated models that analyze logistics flows in industrial clusters (Albino et al., 2008). In this paper, we apply the EIO model to support corporate environmental management to abate the CO_2 emissions in companies. CO_2 emission abatement is a pressing issue for companies today. Also, we apply the methods to a group of Japanese electronics companies. EIO models have not been applied to recent ICT product manufacturing companies nor were they used in Japanese companies.

2.2 Environmental impacts of ICT

Increased energy use by ICT products is a concern (Huber and Mills, 1999; Kawamoto et al., 2002; METI, 2008; Plepys, 2000). In 2006, 230 millions of PCs, and 1 billion of cellular phones were sold in the world. In addition, the number of servers and wireless base-stations that support both internet and telecommunication systems also increased. According to previous studies, ICT products consume 3 to 8% of all the electricity in U.S. (Huber and Mills, 1999; Kawamoto et al., 2002; METI, 2008). In Japan also, IT-related energy consumption has been rapidly increasing. According to the Japan Ministry of Economy, Trade and Industry (METI), 50 TWh of electricity was used in 2006 to run all the servers and PCs in the country (METI, 2008). That represents about 5 percent of all electricity use nationwide. METI estimated that ICT products consume over 20% of electricity in 2025 (METI, 2008).

It is important to remember that energy consumption occurs during the manufacturing process of the product, as well as when the product is used. While the findings of life cycle assessment (LCA) studies are different[1], the energy use in manufacturing processes of products is not negligible. The approaches for assessing energy use during the manufacturing phase are categorized as two types: process-analysis assessments and national-IO-based assessments. For the former type, energy use in the manufacturing processes is assessed in detail, while for the latter type, national IO tables are used to estimate the total energy multipliers that describe energy per unit of consumption for producing commodities. While process-analysis-based assessments are generally more accurate, it is difficult to obtain all the necessary data for the analysis. Conversely, IO-based-assessments use data that can be accessed with relative ease; however, the accuracy is lower. To optimize the potential associated with both approaches, a hybrid method is frequently used (Bullard et al., 1978; Joshi, 2001). In this method, the process-analysis- based assessment methodology is used for the data is available, and the IO-based assessment methodology is applied for the remaining instances when the data is not available.

The EIO model could further complement such an assessment as the EIO model uses data that is more readily available (company accounting data) compared to the data that is required for process-analysis-based assessments. In addition, the EIO model uses data that is more specific to the targeted manufacturing process than the data used for national-IO-based assessment.

3 Enterprise input-output table

The IO tables have been formulated for a variety of levels, ranging from nations, to groups of nations, regions within nations, cities, etc. Enterprise input-output (EIO) tables are IO tables that apply to a company or a group companies[2], and which describe

[1] Energy use in manufacturing phase has been analyzed in LCA studies. However, the assessed results are divisive. Tekawa et al., for example, reported that the ratio of energy use in manufacturing phase and usage phase is 2:8 in the case of desktop PC (Tekawa et al., 1997). Williams reported the ratio is 8:2. The difference largely comes from the estimate for energy consumption in semi-conductor material manufacturing process (Williams, 2003). The process is placed in chemical industry sector in national IO table and not in electronics industry sector.

[2] Although the focus of EIO model is “a company”, it could be “a group of companies”.

the flow of commodities within a company. We represent this flow using monetary units because the national IO tables usually use monetary units and we incorporate EIO tables with the national IO tables.

We formulate two versions of EIO tables: one is what we refer to as a "micro EIO table", and the other is a "macro EIO table". A micro EIO table is analogous to a national IO table. It contains the IO data for a specific company. A macro EIO table is analogous to a multi-regional IO table. It represents IO data for a nation and is comprised of both company and national data from which the company data is excluded. Such a table is formulated by integrating a micro EIO table and a national IO table.

3.1 Micro EIO table

Micro EIO tables are analogous to national or single-region IO tables. We divide a company into sectors and products manufactured by each intra-company (in-company hereinafter) sector are regarded as distinct products. It is a general assumption in IO tables.

Table 1 shows the outline of a typical micro EIO table. The table consists of following components.

$\{S_1, \ldots, S_n\}$ set, in-company sectors;
$\{P_1, \ldots, P_n\}$ set, products of in-company sectors;
$\{E_1, \ldots, E_m\}$ set, externally procured products;
$\{VA_1, \ldots, VA_q\}$ set, primary inputs;
X matrix, intermediate inputs of in-company produced products;
X_{ij} , input of product P_i in sector S_j
Y matrix, inputs of externally procured products;
Y_{ij} , input of product E_i in sector S_j
V matrix, primary inputs;
V_{ij} , input of primary input VA_i in sector S_j
T vector, total outputs;
T_i , total output (production) of sector S_i
IV vector, investment;
IV_i^p , investment of product P_i in the company
IV_i^e , investment of product E_i in the company
EX vector, external sales of products;
EX_i , external sales of product P_i from the company
IM vector, external procurement;
IM_i , external procurement of product E_i of the company

To illustrate the model, consider a hypothetical computer equipment company that sells 50 million dollars of hard disk drive (HDD) and 100 million dollars of computer a year, as shown in Table 2.

Each column of Table 2 provides information on the inputs used and outputs generated in each in-company sector. The inputs include those produced by the company, those purchased externally, and primary inputs (such as labor, capital, and land). We use the computer sector (column 2) as an example. To produce 100 million dollars of computers, the sector used 50 million dollars of HDD, 10 million dollars of parts and 20 million dollars of energy, and required 10 million dollars of capital and 10 million dollars of labor wages. Consumption of 20 million dollars of energy produced 40 thousand tons of CO_2.

When each element in a column of Table 2 is divided by the total output of the sector, we obtain the input or technical coefficients matrix. Each coefficient shows the amount of input required for each unit of output.

Mathematically, the input coefficients are obtained as

$$a_{ij}^S = X_{ij} / T_i$$

$$a_{ij}^e = Y_{ij} / T_i \, . \qquad (1)$$

Each row in the table describes the use of a commodity or input. For example, the first row (Hard Disk row) of Table 2 shows that 100 million dollars of HDD were produced by the corporation, of which 50 million dollars were used in the production of computers and the remaining 50 million dollars were sold to external customers. The forth row (Energy row) indicates the energy-use pattern in the company: 30 million dollars used for HDD producing and 20 million dollars in the computer producing operations. The total energy input was 50 million dollars a year.

The row of the input-output table, therefore, provides a statistical account of input -output flows in the corporation. These flows must be balanced, as follows:

$$X_{i1} + X_{i2} + \ldots + X_{in} + IV_i^p + EX_i = T_i$$
$$Y_{i1} + Y_{i2} + \ldots + Y_{in} + IV_i^e - IM_i = 0 \qquad (2)$$

Table 1: Structure of micro enterprise input-output tables

		In-Company Sectors				Invest-ment	External sales	External procurement	Total Output
		S_1	S_2	・・・	S_n				
Products of In-Company Sectors	P_1	X_{11}	X_{12}		$X_{1,n}$	IV_1^p	EX_1	0	T_1
	P_2	X_{21}	X_{22}		$X_{2,n}$	IV_2^p	EX_2	0	T_2
	P_3	X_{31}	X_{32}		$X_{3,n}$	IV_3^p	EX_3	0	T_3
	:	:	:		:	:	:	:	:
	P_n	X_n	$X_{n,2}$		$X_{n,n}$	IV_n^p	EX_n	0	T_n
External Procure-ment	E_1	Y_{11}	Y_{12}		$Y_{1,n}$	IV_1^e	0	$-IM_1$	0
	E_2	Y_{21}	Y_{22}		$Y_{2,n}$	IV_2^e	0	$-IM_2$	0
	:	:	:		:	:	:	:	:
	:	:	:		:	:	:	:	:
	:	:	:		:	:	:	:	:
	E_m	$Y_{m,1}$	$Y_{m,2}$		$Y_{m,n}$	IV_m^e	0	$-IM_m$	0
Primary Inputs	VA_1	V_{11}	V_{12}		$V_{1,n}$				
	:	:	:		:				
	VA_q	$V_{q,1}$	$V_{q,2}$		$V_{q,n}$				
Total Output		T_1	T_2		T_n				

Table 2: Micro enterprise input-output table: hypothetical hard disk drive (HDD) and computer company

(unit: million dollars)

	HDD Sector	Computer Sector	Invest-ment	External Sales	Procure-ment	Output
HDD	0	50	0	50	0	100
Computer	0	0	0	100	0	100
Parts	50	10	0	0	-60	0
Energy	30	20				
(CO_2)	(60K ton)	(40K ton)	0	0	-50	0
Capital	10	10				
Labor	10	10				
Output	100	100				

In matrix notation, it is expressed as follows:

$$AT + F - M = T \tag{3}$$

Or,

$$T = (I - A)^{-1}(F - M) \tag{4}$$

where,

$$T = \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_n \\ 0 \\ \vdots \\ 0 \end{bmatrix}, A = \begin{bmatrix} a^s_{11} & \cdots & a^s_{1n} & 0 & \cdots & 0 \\ a^s_{21} & \cdots & a^s_{2n} & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a^s_{n1} & \cdots & a^s_{nn} & 0 & \cdots & 0 \\ a^e_{11} & \cdots & a^e_{1n} & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a^e_{m1} & \cdots & a^e_{mn} & 0 & \cdots & 0 \end{bmatrix}, F = \begin{bmatrix} IV^p_1 + EX_1 \\ IV^p_2 + EX_2 \\ \vdots \\ IV^p_n + EX_n \\ IV^e_1 \\ \vdots \\ IV^e_m \end{bmatrix}, M = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ IM_1 \\ \vdots \\ IM_m \end{bmatrix} \tag{5}$$

The formula (4) clarifies the relationship between total outputs (T_1, T_2, ...) and final demands ($IV^p_1 + EX_1$, $IV^p_2 + EX_2$, ...).

3.2 Macro EIO table

Macro EIO tables are analogous to multi-regional IO tables which deal with two or more regions and their interconnections[3] and are formulated by integrating a micro EIO table and a national IO table. The boundary associated with a macro EIO table is same as that of national IO table in that it covers an entire nation. In an EIO table, the company and the rest of the nation are explicitly distinguished. Table 3 outlines the structure of a macro EIO table. In Table 3, the column "Company" under "Intermediate Demand" is identical to the data in the micro EIO table compiled for the company. The

[3] Multi-regional IO tables were proposed by Isard in 1951.

Table 3: Structure of macro enterprise input-output tables

	Intermediate Demand		Final Demand		Import	Total Output
	Company	Nation (besides the company)	Nation Investment + Consumption	Export		
Company	In-company product flow	Domestic sales (1)	Domestic sales (2)	Foreign sales		
Nation (besides the company)	Procurement for production	(National IO)	(National IO)	(National IO)		
Primary Inputs						
Total Output						

row "Company" in Table 3 contains more information than the data shown in the micro EIO table. The cells "Domestic sales (1)", "Domestic sales (2)" and "Foreign sales" in Table 3 specify which sectors the company sells its products to, but these are not specified in the micro EIO. The cells in the "National IO" column in Table 3 are populated with values derived from the data of the national IO table.

The mathematical expressions for the macro EIO tables are the same as those employed for micro EIO tables. The matrix A has more columns and rows because it also contains the columns and rows that correspond to the sectors and products of "Nation". Similarly, vectors T, M *and* F have more elements. The elements of F are the sum of the values for the columns of "Company", "Nation" and "Export" under "Final Demand" in Table 3.

4 Enterprise input-output analyses

4.1 Micro EIO analysis

4.1.1 Direct CO_2 emissions and sales-based CO_2 emissions

We define two types of CO_2 emissions in in-company sectors: direct CO_2 emissions and sales-based CO_2 emissions. Both emissions can be calculated using an EIO table. We discuss the application of the analysis to corporate environmental management.

One of the difficulties in corporate environmental management is that the organizational structure of a company changes frequently. When the organizational structure changes, the CO_2 emissions of the in-company sectors before and after the change can not be simply compared. This makes it difficult for companies to set CO_2 abatement goals for in-company sectors and to evaluate the effectiveness of environmental management of the sectors by comparing the emission amounts at different times. In other words, an effective metrics for comparison or evaluation is needed. We define the sales -based CO_2 emissions and insist that they can be used as a metrics.

The sales-based CO_2 emissions of an in-company sector are defined as: the amount of CO_2 emissions induced by energy use in the company to produce products that are sold externally from the sector. Figure 1 illustrates the company of Table 2. Suppose that the company emits 100 thousand ton of CO_2 a year and that the direct CO_2 emission of hard disk drive (HDD) sector and computer sector are 60 thousand tons and 40 thousand tons, respectively. Table 2 and Figure 1 show that a half of HDD produced in HDD sector is for external sales and that another half is used by the computer sector as intermediate input. We regard that a half of the direct CO_2 emissions in HDD sector are the sales-based CO_2 emissions of computer sector. Consequently, the sales-based CO_2 emissions of HDD sector are 30 thousand tons and those for computer sector are 70 (= 40+60/2) thousand tons.

Figure 2 shows an example of organizational restructuring from Figure 1. For simplicity, suppose that the company has two HDD manufacturing factories, and that one

Figure 1: Illustration of the direct and sales-based CO_2 emissions

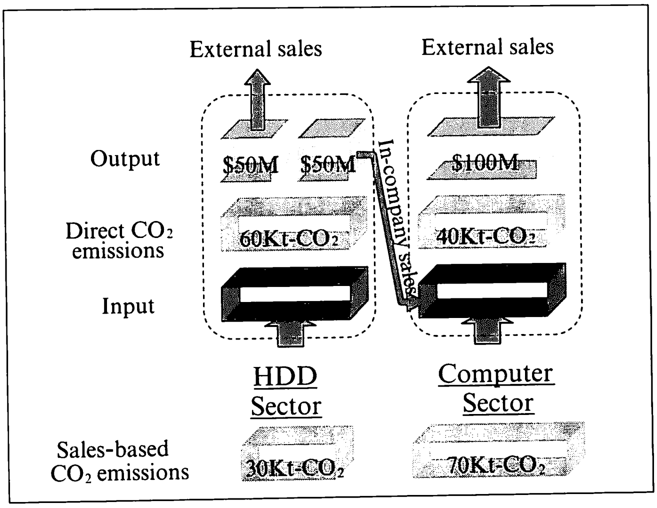
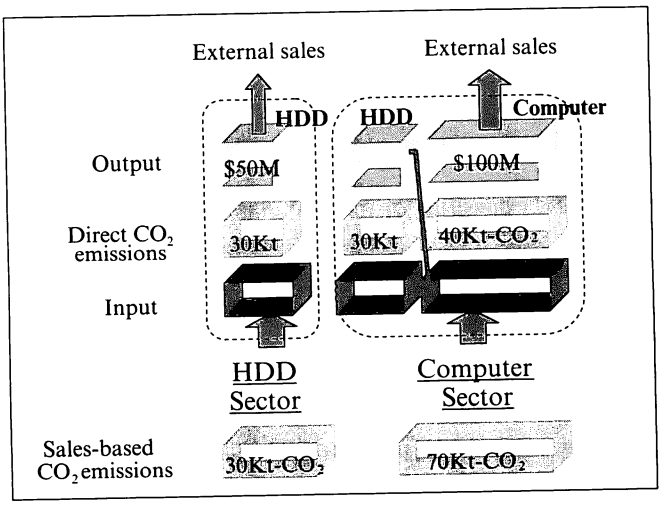


Figure 2: An example of organizational restructuring (from Figure 1)



factory (factory A) manufactures HDD for external sales and the other factory (factory B) manufactures HDD for computer sector. While in Figure 1, both factories belong to HDD sector, as the result of organizational restructuring, in Figure 2, factory B belongs to computer sector. As the result of the restructuring, while the direct CO_2 emissions of the sectors change (in Figure 1, 60 thousand ton and 40 thousand ton for HDD and computer sectors, respectively; in Figure 2, 30 thousand ton and 70 thousand ton for HDD and computer sectors, respectively), the sales-based CO_2 emissions do not change (both in Figure 1 and 2, 30 thousand ton for HDD sector and 70 thousand ton for computer sector).

It indicates that the sales-based CO_2 emissions can be used as a metrics to compare the CO_2 impacts of the in-company sectors at different times and, accordingly, to evaluate the environmental management of the sectors. The mathematical formulation of the sales-based CO_2 emissions and a numerical example are presented in next sections.

4.1.2 Mathematical formulation of sales-based CO_2 emissions

Sales-based CO_2 emissions can be calculated using micro EIO tables. In addition to the definitions in (3) in 3.1, we define T^i, F^i and e as follows:

$$T^i = \begin{bmatrix} T_1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & T_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & T_n & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix}, F^i = \begin{bmatrix} F_1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & F_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & F_n & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \end{bmatrix},$$

$$e = (e_1\ e_2\ \cdots\ e_{n+m}) \tag{6}$$

where e_i is the CO_2 coefficient of the i th commodity (goods), which is nonzero for energy goods such as oil, and represents the CO_2 emissions associated with the unit input of the energy goods (ton-CO_2 per dollar).

The direct CO_2 emissions of in-company sectors can be calculated using the expression

$$eAT^i \tag{7}$$

while the sales-based CO_2 emissions of in-company sectors are calculated using

$$e(I - A)^{-1}F^i \tag{8}$$

The sales-based CO_2 emissions of a sector are comprised of the direct emissions in the sector and indirect emissions in other sectors. In Figure 1, for example, the sales -based CO_2 emissions of the computer sector (70 thousand ton) are comprised of the direct emissions in the sector (40 thousand ton) and indirect emissions (30 thousand ton) which were directly made in HDD sector. The direct CO_2 emissions in sales-based CO_2 emissions (intersection of the direct CO_2 and the sales-based CO_2) can be calculated using

$$eAF^i \tag{9}$$

4.1.3 Numerical example

We present the numerical examples of EIO analysis for the example company of Figure 1 (Table 2) and Figure 2. The EIO matrix and vectors for the company of Figure 1 (Table 2) are as follows.

$$A = \begin{bmatrix} 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0.3 & 0.2 & 0 & 0 \\ 0.5 & 0.1 & 0 & 0 \end{bmatrix}, F = \begin{bmatrix} 50 \\ 100 \\ 0 \\ 0 \end{bmatrix}, M = \begin{bmatrix} 0 \\ 0 \\ 50 \\ 60 \end{bmatrix}, T = \begin{bmatrix} 100 \\ 100 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

We assume that the third row in the table represents energy goods such as oil and that its CO_2 coefficient is 2 (thousand ton-CO_2 per million dollar). The other products do not emit CO_2 directly and their CO_2 coefficients are 0. Accordingly, vector e is:

$$e = (0 \;\; 0 \;\; 2 \;\; 0) \tag{11}$$

From the description in (7), we can obtain the following

$$AT^i = \begin{bmatrix} 0 & 50 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 30 & 20 & 0 & 0 \\ 50 & 10 & 0 & 0 \end{bmatrix}, (I - A)^{-1} = \begin{bmatrix} 1 & 0.5 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0.3 & 0.35 & 1 & 0 \\ 0.5 & 0.35 & 0 & 1 \end{bmatrix},$$

$$(I - A)^{-1}F^i = \begin{bmatrix} 50 & 50 & 0 & 0 \\ 0 & 100 & 0 & 0 \\ 15 & 35 & 0 & 0 \\ 25 & 35 & 0 & 0 \end{bmatrix} \tag{12}$$

From these, we obtain

$$eAT^i = (60 \;\; 40 \;\; 0 \;\; 0),\ e(I - A)^{-1}F^i = (30 \;\; 70 \;\; 0 \;\; 0),$$
$$\text{and } eAF^i = (30 \;\; 40 \;\; 0 \;\; 0) \tag{13}$$

Direct CO_2 emissions of the sectors are 60 and 40 thousand tons, respectively, and the sales-based CO_2 emissions are 30 and 70 thousand tons, respectively. The direct CO_2 in the sales-based CO_2 emissions are 30 and 40 thousand tons, respectively.

Next, we calculate the CO_2 emissions for the company of Figure 2 --- an organizational restructuring was made from Figure 1. The EIO matrix and vectors are

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0.3 & 0.35 & 0 & 0 \\ 0.5 & 0.35 & 0 & 0 \end{bmatrix}, F = \begin{bmatrix} 50 \\ 100 \\ 0 \\ 0 \end{bmatrix}, M = \begin{bmatrix} 0 \\ 0 \\ 50 \\ 60 \end{bmatrix}, T = \begin{bmatrix} 50 \\ 100 \\ 0 \\ 0 \end{bmatrix} \tag{14}$$

The calculation results are:

$$eAT^{i} = (30\ \ 70\ \ 0\ \ 0),\ e(I - A)^{-1}F^{i} = (30\ \ 70\ \ 0\ \ 0),$$
$$\text{and } eAF^{i} = (30\ \ 70\ \ 0\ \ 0) \quad (15)$$

While the direct CO_2 emissions changed as the result of the restructuring, the sales-based CO_2 emissions did not change. Production of HDD for external sales induced 30 thousand ton of CO_2 emissions to the company (sales-based CO_2) and production of computers induced 70 thousand ton of the CO_2 emissions to the company.

4.2 Macro Enterprise Input-Output Analysis

4.2.1 Macro EIO analysis

The macro EIO table describes the productions in wider range such as in a nation, and in the model, a company (micro EIO table) is embedded explicitly in the range. Using the macro EIO, not only the CO_2 emissions within the company but also the emissions in their upstream industries outside the company are analyzed. For example, if a computer manufacturing company procures parts from other company (upstream company), the CO_2 emissions to produce the parts are counted. We call the sales-based CO_2 emissions including the emissions in upstream industries as "the macro sales-based CO_2 emissions". In analysis, we use formula (6) using the macro EIO values instead of micro EIO values.

We propose two applications of the macro sales-based CO_2 emissions to corporate environmental management. One application is, again, to use as a metrics. Suppose that a company outsources a process to other company. By outsourcing a process, the CO_2 emissions in the company also decrease. However, as the macro sales-based CO_2 emissions include both the emissions within a company and those in upstream companies, the CO_2 impacts before and after the outsourcing can be compared by using the macro sales-based CO_2 emissions. If the CO_2 efficiency for the process in the company is better than that in outside the company, the macro sales-based CO_2 emissions will increase (the metrics gets worse).

Another application is analysis of the ratio of CO_2 emissions for product manufacturing. By calculating the macro sales-based CO_2 emissions, and the direct and sales-based CO_2 emissions using the micro EIO model, we can compare: 1) the direct CO_2 emissions in in-company sector which sells the products, 2) CO_2 emissions in other in-company sectors to produce the products, and 3) CO_2 emissions outside the company (in upstream company). From the analysis, implications for an effective corporate environmental management are available. For example, if the direct CO_2 emissions in the in-company sectors are relatively large, energy efficiency improvement in the sector is substantial. Or, if the CO_2 emissions in upstream company are relatively large, green procurement is effective to abate CO_2 impacts.

4.2.2 Mathematical formulation

The macro sales-based CO_2 emissions of in-company sectors are calculated using following expression.

$$e(I - B)^{-1}F^{i} \quad (16)$$

where B is the input coefficient matrix for the macro EIO table, and e, F and F^{i} are the same as in the micro EIO analysis (e is the CO_2 coefficient vector, F is the external sales vector).

The CO_2 emission ratio is analyzed by comparing, 1) the macro sales-base CO_2 emissions which are calculated by the above formula, 2) the CO_2 emissions within the company total which are calculated by formula (8), and 3) the CO_2 emissions within the in-company sectors which are calculated by formula (9).

4.2.3 Numerical Example

Table 4 presents an example macro EIO table for the company of Figure 1.

We apply the formula (6) using the following matrix and vectors:

$$B = \begin{bmatrix} 0 & 0.5 & 0 & 0.01 & 0.005 \\ 0 & 0 & 0 & 0.01 & 0.005 \\ 0 & 0 & 0 & 0 & 0 \\ 0.3 & 0.2 & 0.3 & 0.05 & 0.25 \\ 0.5 & 0.1 & 0.5 & 0.14 & 0.45 \end{bmatrix}, F = \begin{bmatrix} 50 \\ 100 \\ 0 \\ 0 \\ 0 \end{bmatrix}, e = (0 \;\; 0 \;\; 2 \;\; 0 \;\; 0) \tag{17}$$

We obtain the macro sales-based CO_2 emissions of the in-company sectors as follows.

$$e(I - B)^{-1}F^{i} = (60.8 \;\; 117.2 \;\; 0 \;\; 0 \;\; 0) \tag{18}$$

In the macro EIO table (Table 4), we assumed that the CO_2 efficiencies in the in-company HDD sector and the external HDD sector are identical. Suppose that the company outsources the production of HDD which are used in computer sector to an external HDD company, the coefficient matrix becomes as follows.

Table 4: Example of macro EIO table

(unit: million dollars)

		Intermediate Input					Final Demand			Import	Total Output	External Sales
		Company		Nation			Nation					
		HDD	Computer	HDD	Energy	Other	Invest	Consumption	Export			
Company	HDD	0	50	0	10	10	0	30	0	0	100	50
	Computer	0	0	0	10	10	0	80	0	0	100	100
Nation	HDD	0	0	0	0	0	0	200	0	0	200	
	Energy	30	20	60	50	500	0	400	0	0	1000	
	Other	50	10	100	140	900	0	900	0	0	2000	
Primary Inputs		20	20	40	790	580						
Total Output		100	100	200	1000	2000						

Table 5: Energy flow analysis using macro EIO

(unit: thousand ton)

	Before outsourcing		After outsourcing	
	HDD	Computer	HDD	Computer
Macro sales-based CO2 emissions (thousand ton)	60.8	117.2	60.8	117.2
CO2 in the sector	30	40	30	40
CO2 in other in-company sector	0	30	0	0
CO2 in outside the company	30.8	47.2	30.8	77.2
Direct CO2 emissions	60	40	30	40

$$B' = \begin{bmatrix} 0 & 0 & 0 & 0.01 & 0.005 \\ 0 & 0 & 0 & 0.01 & 0.005 \\ 0 & 0.5 & 0 & 0 & 0 \\ 0.3 & 0.2 & 0.3 & 0.05 & 0.25 \\ 0.5 & 0.1 & 0.5 & 0.14 & 0.45 \end{bmatrix} \tag{19}$$

The macro sales-based CO_2 emissions obtained are same as those before the outsourcing.
We calculated the CO_2 emissions in in-company sectors and in company total in Section 4.1.3. The ratio of the CO_2 emissions of the company of Table 5 is summarized in Table 6.

4.2.4 Application to Life Cycle Assessment (LCA)

The idea of macro sales-based CO_2 emissions has a common with life cycle assessment (LCA) and with carbon footprints. They differ in the boundaries for assessments. LCA counts the environmental (CO_2) impacts in production, distribution, usage, and end-of-life phases of products. Carbon footprint generally counts the CO_2 impacts until the point of consumer's receiving products (production and distribution phases). The macro sales-based CO_2 emissions count the CO_2 impacts until the point of products' going out the company. Accordingly, the macro sales-based CO_2 emissions consists a part of LCA and carbon footprints. In LCA studies, CO_2 impacts are investigated by process analysis, and when process analysis data is not available, data is supplemented by national IO-based IO analysis (Bullard et al., 1978; Joshi, 2001). As an EIO model contains company-specific energy flow data, the EIO analysis provides an easy and more precise CO_2 impact assessment method.

5 EIO model applied to group of Japanese electronics companies

5.1 EIO Table

5.1.1 EIO Table Construction

We applied the model to a group of Japanese electronics companies. The group included thirty companies with a total of fifty thousands of employees. The companies produce electronic devices, information and communication technology (ICT) hardware and ICT services. Using corporate accounting data for fiscal year (FY) 2001, we generated an EIO table for the group. The total sales of the group in the year were 25.5 billion U.S. dollars (2.55 trillion Japanese Yen).

The accounting data records documented the data on: 1) the products and expenses that each division procured from inside and outside the group (the products were categorized into approximately two thousand categories), 2) the products and revenues that each division sold to inside and outside the group, and 3) each division's expenses on wages, facility depreciation, and land rents.

We defined the table components that we specified in section 3.1 as follows.

- In-company sectors $\{S_i\}$: The group includes 20 business divisions operating during FY 2001. The divisions correspond to 10 sectors represented in the Japanese national IO table (categorization of the divisions was more refined than that of the national IO table). We reclassified the business divisions to be consistent with the 10 sectors. The 10 in-company sectors represent three electronic device production sectors: 1) semiconductor devices, 2) electronic devices, and 3) display devices; four ICT hardware sectors: 4) computers, 5) radio communication equipment, 6) wired communication equipment, and 7) computer accessory equipment; and three ICT service sectors: 8) information service, 9) telecommunication service, and 10) software service. In addition, the companies all have headquarters-divisions and the monetary flows within these divisions are considerable. In the table, instead of defining each of the divisions as an independent in-company sector, the divisions' monetary flows were allocated to the 10 in-company sectors in proportional to division sales.
- Products $\{P_i\}$: We defined the products that are produced in sector S_i as P_i. Using this definition for P_i, by-products do not appear in the table. Different divisions within the group rarely sell identical products. Consequently, a one-to-one correspondence between sector and product does not cause problems.
- Externally procured products $\{E_i\}$: Using the accounting data, products procured from outside the group were categorized into approximately two thousand categories. We aggregated the categories and aligned them with those in the Japanese national IO table (the national table has approximately 500 products in total). The products procured by the group from external sources FY 2001 were categorized into 63 product types.
- Intermediate inputs of in-company produced products $\{X_i\}$: Accounting records document trades within the group. Based on the records, we can determine the internal inputs $\{X_{ij}\}$.
- Inputs of externally procured products $\{Y_{ij}\}$ and external procurements $\{IM_i\}$: Accounting data records document external procurements. The inputs of externally procured products $\{Y_{ij}\}$ and $\{IM_i\}$ were set based on the accounting records.
- Investment $\{IV_i\}$: The accounting data records did not contain data for large invest-

[4] In real world scenarios, energy use for such construction of new plants should also be considered in corporate energy analyses.

ments such as expenses for new plant construction. Therefore, in the table, we set the values for IV_i^p and IV_i^e as zero[4]

- External sales $\{EX_{ij}\}$ and total outputs $\{T_i\}$: The accounting data records document external sales of products for each sectors (EX_{ij}). By adding the amount of trade within the group (X_{ij}) to the external sales amount, we determine the total sector output (T_i).
- Primary inputs $\{VA_{ij}\}$: The accounting data records document labor wages, facility depreciation, and land rents for the companies. We set the amounts as VA_{ij}.
- CO_2 coefficient vector e : For fossil fuel (oil and gas) use and electricity, we apply a non-zero CO_2 coefficient vector e. Although electricity is technically not a CO_2 emitting commodity (because CO_2 is directly emitted by the electricity generation industry and not by the companies that use the electricity), as most companies determine their CO_2 emissions based on their fossil fuel consumption and electricity use, we treated electricity as a direct CO_2 emitting commodity. We set the CO_2 coefficient for oil, gas, and electricity in FY 2001 as 10.4, 2.9 and 3.5 kg-CO_2 per dollar, respectively, based on the CO_2 intensities of the energies and the prices in the year.

5.1.2 EIO Table Overview

Table 6 shows the micro EIO table for the group.

The total external sales of the group were 25.5 billion U.S. dollars. The three large sectors in terms of external sales were: 1) radio communication equipment sector (23% of the group total), 2) computer sector (23% of the group total), and 3) semiconductor device sector (18% of the group total).

The total output of the group was amounted to 42.7 billion dollars. The total output is equivalent to the sum of external sales and intra-group sales. The ratio of external sales to intra-group sales was 3:2 (25.5 and 17.2 billion dollars, respectively), which indicates 40% of the group output was used within group (40% was intermediate commodities in the group).

The total output is also equivalent to the sum of intra-group procurement (= intra-group sales), external procurement, and the value added. The share of the three items was 40:32:28. The external procurement and the value added were 13.5 and 12.0 billion dollars, respectively.

The CO_2 emissions of the group were calculated as 502 thousand ton-CO_2. The direct CO_2 emissions of the sectors calculated with formula (7) are shown in the table. In the group, the semiconductor device sector was the most energy consuming sector. The sector emitted over 60% of the group total CO_2 emissions.

5.2 Micro EIO analysis

Based on the micro EIO analysis framework described in Section 4.1, we calculated the sales-based CO_2 emissions for the 10 in-company sectors. We calculated the direct and sales-based CO_2 emissions for the 10 in-company sectors. As shown in Figure 1, the sectors whose sales-based CO_2 emissions are greater than direct CO_2 emissions are downstream sectors in terms of CO_2 flows (the "computer" sector in the example), and vice versa. If the differences between the two emissions total is large, the interdepend-

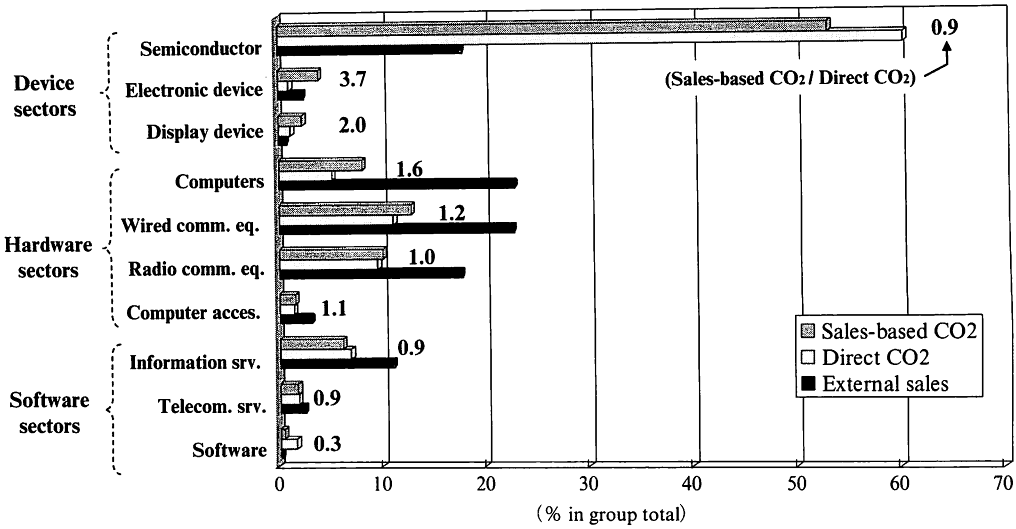
Table 6: Micro EIO table

(Unit: million U.S. dollars (1 dollar = 100 Japanese Yen))

		In-company sectors										Sub-total	Invest-ment	External sales	External procure.	Total output
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10					
Products of in-company sectors	1 Semiconductor	2450	98	300	131	128	84	7	2	0	4	3204	0	4511	0	7715
	2 Electronic device	12	19	7	6	6	2	1	2	0	0	54		175		230
	3 Display device	74	51	0	4	5	1	1	0	0	0	137		587		734
	4 Computers	54	4	5	3169	189	125	257	964	238	4	5009		5773		10782
	5 Wired comm. eq.	73	4	6	218	2924	767	22	78	15	2	4110		4475		8585
	6 Radio comm. eq.	23	1	1	93	310	708	9	21	3	2	1171		5802		6973
	7 Computer acces.	3	0	0	351	13	7	17	84	13	0	488		760		1248
	8 Information serv.	61	4	6	1068	96	78	118	839	182	9	2461		2791		5253
	9 Telecomm. serv.	36	2	4	125	75	61	14	73	73	1	464		594		1058
	10 Software	20	3	2	9	10	10	3	5	1	2	66		24		90
	Total Internal Proc	2805	188	331	5178	3755	1842	448	2068	525	26	17166	Total:	25502	Total:	42668
External procurement	Material (*1)	482	8	8	274	161	99	64	58	13	5	1172	0	0	-1172	0
	Parts (*2)	1198	44	254	1226	892	2429	194	151	15	6	6409			-6409	
	Services (*3)	138	8	8	449	1109	622	58	853	43	14	3302			-3302	
	Others (*4)	151	5	20	1243	409	234	143	238	65	7	2516			-2516	
	Oil	5.0	0.02	0.05	1.9	1.2	0.5	0.2	1.0	0.1	0.01	10			-10	
	Gas	7.5	0.3	0.2	0.9	1.5	0.8	0.1	0.4	0.08	0.4	12			-12	
	Electricity	70.1	1.5	1.3	10.0	9.6	5.7	1.4	6.9	2.3	2.1	111			-111	
	(CO2 (K-ton-CO2))	(316)	(6)	(5)	(57)	(50)	(27)	(7)	(36)	(10)	(8)	(502)				
	Total External Proc.	2052	67	292	3204	2583	3390	461	1308	138	35	13531		Total:	-13531	
Value added		2858	-26	111	2399	2247	1741	339	1876	395	29	11971				
Total Output		7715	230	734	10782	8585	6973	1248	5253	1058	90	42668				

A1: Semiconductor device, A2: Electronic device, A3: Display device, A4: Computers, A5: Wired communication equipment,
A6: Radio communication equipment, A7: Computer accessory equipment, A8: Information service, A9: Telecommunication service, A10: Software
*1: Material products (total of 32 type products); *2: Parts products (12 type products); *3: Services (7 types); *4: Other products (9 type products)

Figure 3: Sales-based CO_2 emissions, direct CO_2 emissions, and external sales of ten sectors (% in group total);
The numbers are the ratio of the sales-based CO_2 to the direct CO_2 emissions (sales-based CO_2 emissions / direct CO_2 emissions)



encies among in-company sectors is greater.

Figure 3 shows the sales-based CO_2 emissions, the direct CO_2 emissions, and the external sales, for each of the 10 sectors. The amounts are presented as the shares (%) in the group. The numbers in Figure 3 show the ratio of the sales-based CO_5 emissions to direct CO_2 emissions of the sectors.

In the group, the sectors --- electronic device, display device, and the four hardware sectors were in the downstream. The interdependencies of the electronic device, display device and software service sectors to other sectors were high. In the case of electronic device and display device sectors, they used devices produced in the semiconductor device sector. In such cases, the two sectors might be better to support abating CO_2 emissions at the semiconductor sector (the upstream sector) rather than to make efforts to abate direct CO_2 emissions in the own sector, in order to abate the total CO_2 emissions in the group.

As we discussed in Section 4.1, the sales-based CO_2 emissions can be used as a metrics to set up intra-company environmental management goals or to evaluate the in-company sectors' environmental management performance. Even if organizational restructuring is undertaken within the group, the CO_2 impacts of in-company sectors, or those of their externally sold products, can be compared using the metrics for before and after the reorganization.

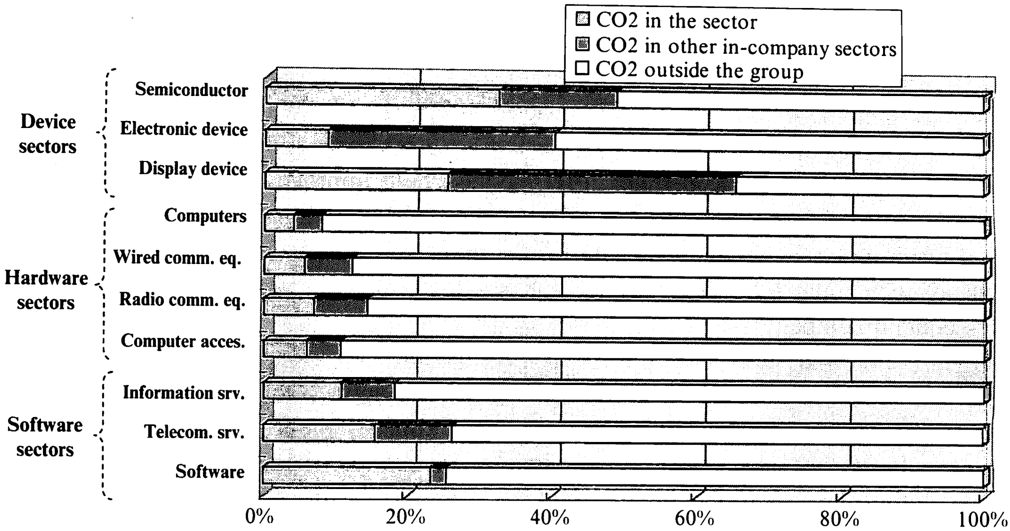
5.3 Macro EIO analysis

We generated a macro EIO table for the group by integrating the micro EIO table with

---

[5] http://www.stat.go.jp/english/data/io/index.htm

Figure 4: Breakdown of the macro sales-based CO_2 emissions



the Japanese national IO table[5]. The group represented approximately 0.3% of the national economy based on total output.

We calculated the macro sales-based CO_2 emissions of the in-company sectors. The macro sales-based CO_2 emissions of an in-company sector are the amount of CO_2 emissions caused by production of products or services that are sold externally from the sector (see Section 4.2 and Table 4). We analyzed the ratio of emissions within the sector itself, for other in-company sectors, and for companies outside the group.

Figure 4 shows the ratio results for the sectors. In the device sectors, the CO_2 emissions generated within the sectors made up a relatively large share (more than 30% in semiconductor device sector). In contrast, for hardware sectors, around 90% of the sales-based CO_2 were attributed to outside the group. Similarly, around 80% of the sales-based CO_2 emissions from the software sectors were attributed to the production of the externally procured products.

The results have implications for corporate environmental management. To abate CO_2 impacts from sector products in semiconductor device sector, for example, efforts to further improve the energy efficiency within the sector are important ("CO_2 in the sector" was large). For electronic device sector, energy efficiency improvement in upstream sector (semiconductor device sector) is important ("CO_2 in other in-company sectors" was large). In hardware and software sectors, CO_2 abatement in upstream companies outside the group or procurement of less-CO_2 intensive products (green procurements) would be more effective in reducing CO_2 impacts ("CO_2 outside the group" was large).

6 Conclusions and future work

In the present study, we formulated micro EIO and macro EIO models. We proposed the calculation of sales-based CO_2 emissions for in-company sectors (products) using the models. The emissions contributions can be used as metrics for evaluating in-company sectors' environmental management even if organizational restructuring occurs within the company. In addition, the breakdown of the CO_2 impacts of the in-company sectors --- the ratios of CO_2 caused by production within the sector, by production in other upstream in-company sectors, and by production outside the company --- are analyzed using the methods. EIO models could improve the accuracies of product life cycle assessments (LCAs). In previous LCAs, national IO tables have been used when process CO_2 analysis data for a company is not available. Using EIO tables instead of national IO tables enables analyses that are more accurate because EIO tables contain company-specific data.

In the current study, we applied the EIO models to a group of electronics companies in Japan. EIO models have not previously been applied to electronics companies, not to Japanese companies. We described the outline of the EIO table and presented the results of the sales-based CO_2 emissions calculation. The analysis revealed CO_2 flows within the group and interdependencies among the in-company sectors in terms of CO_2 emissions. However, the EIO table could only be generated for one fiscal year in the current study. In the future, we will apply our model to generate tables for different years. Changes in the prices of electronics products could affect the input coefficient values. A comparison of years would insure the stability of input coefficients.

We also analyzed the (macro) sales-based CO_2 emissions of the in-company sectors (Figure 4) by source. The group procured materials and parts from other companies, while the main processes of the group were device processing and product assembly. Therefore, a large amount of CO_2 emissions was generated by upstream production. To abate the group's CO_2 impacts, cooperation with such companies is necessary.

Environmentally sustainable manufacturing industries require various levels of pollution control measures, associated with product design, manufacturing, corporate management, governmental policy, and international policy. To plan for and evaluate control measures, a framework for consistently modeling the various levels is needed; the EIO model provides a framework for modeling monetary/material/CO_2 flow at both the in-company sector and national levels. In the current study, we applied the model to CO_2 flow analyses. However, the model could also be applied to material flow analyses. In electronics industries, for example, material flow analyses are gaining more attentions as legislative efforts restrict chemical and hazardous substances. Our goal is to extend the applicability of the EIO model and to develop a more integrated framework for supporting corporate environmental management.

References

Huber, P, Mills, PM. (1999), "Dig more coal-the PCs are coming". *Forbes*.

Kawamoto, K, Koomey, J, Nordman, B, Brown, R, Piette, M, Ting, M, Meier, A. (2002), "Electricity used by office equipment and network equipment in the U.S.". *Energy – The International Journal*, Vol. 27, No. 3: pp. 255–69.

METI (The Ministry of Economy, Trade and Industry, Japan), (2008), *Green IT initiatives* Available from: <http://www.meti.go.jp/press//20071207005/03_G_IT_ini.pdf> (in Japanese); [accessed 08.05.01]

Plepys, A. (2000), "The grey side of ICT", *Environmental Impact Assessment Review*, Vol. 22, pp. 509–523.

Leontief, W. (1936), "Quantitative input-output relations in the economic system of the United States", *Review of Economics and Statistics*; Vol. 18, pp. 105–25.

Isard, W, Kuenne RE. (1953), "The impact of steel upon the greater New York-Philadelphia industrial region", *Review of Economics and Statistics*, Vol. 35, pp. 289–301.

Miller, RE. (1957), "The impact of the aluminum industry on the pacific northwest: a regional input-output analysis", *Review of Economics and Statistics*, Vol. 39, pp. 200–209.

Leontief, W, Ford, D. (1970), "Environmental repercussions and the economic structure: An input-output approach", *Review of Economics and Statistics*, Vol. 52, pp. 262–71.

Wyckoff, AW, Roop, JM. (1994), "The embodiment of carbon in imports of manufactured products - implications for international agreements on greenhouse gas emissions", *Energy Policy*, Vol. 22, pp. 187–94.

Albino, V, Dietzenbacher, E, Kuhtz, S. (2003), "Analyzing material and energy flows in an industrial district using an enterprise input-output model", *Economic Systems Research*, Vol. 15, pp. 457–80.

Albino, V, Kuhtz, S, Petruzzelli, A. (2008), "Analysing logistics flows in industrial clusters using an enterprise input-output model", *Interdisciplinary Information Sciences*, Vol. 15: pp. 457–80.

Grubbstrom, R, Tang, O. (2000), "An overview of input-output analysis applied to production -inventory systems", *Economic Systems Research*, Vol. 12, No. 1, pp. 3–25.

Lin, X, Polenske, KR. (1998), "Input-output modelling of production processes for business management", *Structural Change and Economic Dynamics*, Vol. 9, No. 205–26.

Marangoni, G., Colombo, G., Fezzi, G. (2004), "Modelling intra-group relationships", *Economic Systems Research*, Vol. 16, pp. 85–106.

Polenske, K. R., (1997), "Linked System of Enterprise, Regional, National Input-Output Accounts for Policy Analysis", in: Chatterji, M., *Regional Science: perspectives for the future, Macmillan*, London.

Polenske, KR, McMichael, FC. (2002), "A Chinese cokemaking process-flow model for energy and environmental analyses", *Energy Policy*, Vol. 30, pp. 865–883.

Bullard, CW, Penner, PS, Pilati, DA. (1978), "Net energy analysis. Handbook for combining process and input-output analysis", *Resources and Energy*, Vol. 1, pp. 267-313.

Joshi, S. (2001), "Product environmental life cycle assessment using input-output techniques", *Journal of Industrial Ecology*, Vol. 3, pp. 95–120.

Tekawa M, Miyamoto S, Inaba A. (1997), "Life cycle assessment: an approach to environmentally friendly PCs", *Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment*, pp. 124–30.

Williams E. (2003), "Environmental impacts in the production of personal computers", In: Kuehr R, Williams E, eds. *Computers and the Environment: Understanding and Managing their impacts*. Kluwer Academic Publishers.