MANAGERIAL AND DECISION ECONOMICS, VOL. 18, 195–208 (1997)

Environmental Management in Japan: Applications of Input–Output Analysis to the Emission of Global Warming Gases

Hitoshi Hayami[1], Masao Nakamura,[2]* Mikio Suga[3] and Kanji Yoshioka[4]

[1]*Keio University, Tokyo, Japan*
[2]*University of British Columbia, Vancouver, Canada*
[3]*Tokai University, Tokyo, Japan*
[4]*Keio University, Tokyo, Japan*

Environmental management requires, among other things, the incorporation of environmentally friendly technologies into production processes at the producer level and the adoption of energy consumption patterns which save energy use at the household level. The systemwide approach involving both technology choice and consumer preference seems particularly essential for controlling the total emission of global warming gases. CO_2 and other global warming gases, as well as certain pollution causing gases, are produced when fossil fuels are burnt; and the consumption of fossil fuels occurs in both the production and consumption of goods and services. In this paper we discuss how input–output analysis can be used to estimate the entire production and consumption of global warming gases conditional on production technology and consumer preferences. We also present estimation results and their application to some environmental management issues in Japan.

Manage. Decis. Econ. 18: 195–208 (1997)

No. of Figures: 4 No. of Tables: 21 No. of References: 9

INTRODUCTION

Despite the Rio Summit's international agreement to reduce the per capita emission of CO_2 to the 1990 level by the year 2000, Japan's per capital CO_2 emission in 1994 exceeded the 1990 level by 6%. Japan's total CO_2 emission in 1994 was 343 million tons, a 5.9% increase over the previous year's level. The emission from transportation as well as from the household and service sectors has been increasing, and constitutes almost half of the total. The emission from the industrial sector has been stagnant, remaining near the 1990 level during the post-bubble recession. Yet any program to control fossil-fuel based emission of CO_2 must take into account the possible interactions among various sectors of the economy.

Leontief (1970, 1986) suggested that input–output (I–O) analysis is a potentially useful tool for analyzing the environmental implications of economic activities. I–O analysis is particularly appropriate for analyzing the environmental effects of the use of fossil fuels because they are consumed in almost every stage of economic activity. (See Smith, 1993), for estimates for the emission of global warming gases for Canada which were obtained by I–O analysis of Canadian data.)

In this paper we present some of the empirical results we have obtained in our on-going research effort to model the production processes of global warming gases and other pollutants using the I–O technique. We are particularly interested in the

* Correspondence to: Masao Nakamura, Faculty of Commerce, University of British Columbia, 2053 Main Mall, Vancouver, British Columbia, Canada V6T 1Z2.

CCC 0143–6570/97/020195–14 $17.50

impact of the use of alternative technologies on the generation of global warming gases (measured in CO_2 equivalent) and other pollutants such as SO_x.

The data requirement for our modeling approach is substantial. In addition to the standard I–O table with detailed industrial sector classifications, we need information regarding energy-consumption patterns for individual sectors. We have undertaken this data-collection task for the Japanese economy and have been able to collect the required data from both published as well as unpublished documents, and also from interviews with firms and industry associations.

We apply our estimation results to various technology management issues which face the Japanese economy and society as a whole: the choice between slag and Portland cement, the degree of use of recycled paper, and the choice of house-insulation materials. Other applications of this type of analysis, which are not discussed in this paper, include the environmental impacts of coal, liquefied natural gas and nuclear power generation, the environmental life cycle assessment of automobiles, and consumer preferences.

The organization of this paper is as follows. In the next section we describe our I–O approach to environmental analysis and its data requirement. The third section discusses how the I–O approach can be applied to various environmental issues, and gives some of our empirical findings for Japan. The paper ends with some conclusions.

INPUT–OUTPUT APPROACH TO ENVIRONMENTAL ANALYSIS

We divide an economy into n broad industrial and other relevant sectors where the production of goods and services takes place. a_{ij} amount is consumed by sector j from a unit amount of sector i's output, where a_{ij} lies between 0 and 1 $(i, j = 1, 2, \ldots, n)$. We denote by x an $n \times 1$ vector with its component x_j representing domestic production of sector j $(j = 1, 2, \ldots, n)$. We denote final domestic demand, exports and imports for sector j, respectively, by d_j, e_j and m_j, and their corresponding $n \times 1$ vectors by d, e and m. Then we have the I–O equation

$$Ax + d + e - m = x \tag{1}$$

Assuming a competitive imports structure, m is rewritten by

$$m = M(Ax + d) \tag{2}$$

where M is an $n \times n$ diagonal matrix with its diagonal M_{jj} representing the imports coefficient for sector j. Substituting Eqn (2) into Eqn (1), we get

$$x = (I - (I - M)A)^{-1}((I - M)d + e) \tag{3}$$

Suppose we have estimates $E1_j$ $(j = 1, 2, \ldots, n)$ for the amounts of CO_2 produced in n sectors. We denote by $E1$ the corresponding $n \times n$ diagonal matrix. Then the amount of CO_2 produced by a unit demand for output of sector j is given by

$$E1(I - (I - M)A)^{-1}u_j \tag{4}$$

where u_j is a unit $n \times 1$ vector with one in the jth position. If output from the jth sector is energy, then the above production process is also associated with the consumption of the unit final demand which generates $E2_j$ amount of CO_2. We denote by $E2$ the corresponding $n \times 1$ vector. Let i be a $1 \times n$ vector of ones. Then the total CO_2 produced as a result of a unit production in sector j is given by

$$E_j = iE1(I - (I - M)A)^{-1}u_j + E2_j \quad j = 1, 2, \ldots, n$$

Using 1985 estimates for the Japanese I–O matrices (A, M) and energy consumption–CO_2 emission matrices ($E1$ and $E2$) for 440 $(= n)$ sectors, we have calculated E_j $(j = 1, 2, \ldots, 440)$. The unit of production activity (output) is one 1985 million yen. Table 1 shows CO_2 emissions per one 1985 million Japanese yen worth of output for various sectors in the Japanese and Canadian economies. The amounts of CO_2 emissions for 1985 and 1990 are also presented in per capita terms in Table 2. The largest sources of CO_2 emission are Housing, Heating, Lighting and Water Supply, followed by Transportation and Communication and Food, Beverage and Tobacco. Table 2 also shows expenditure patterns for Japanese households. In policy analysis CO_2 emissions from the actual consumption of the proposed final products must be taken into account, to evaluate the tradeoff between investing in energy saving devices in production processes and devising energy-saving final products.

APPLICATION OF ENVIRONMENTAL I–O ANALYSIS TO TECHNOLOGY MANAGEMENT ISSUES

In this section we discuss applications of our I–O analysis to the Japanese environment. We analyze the

Table 1. CO_2 Emission per One 1985 Million Yen Worth of Output by Sector, Japan and Canada (kg)

Sector	Emission from production process—Japan	Emission from consumption process—Japan	Total emission —Japan	Emission from production process —Canada
Cement	76 423	0	76 423	15 817[a]
Electric power	19 380	0	19 380	27 334
Pulp	12 045	0	12 045	7167
Aluminum	9980	0	9980	10 740
Coal	6080	195 972	202 052	6200
Agr. machinery	3768	0	3768	2452
Soft drinks	3056	0	3056	3581
Sugar	3028	0	3028	4050
Motor vehicles	2973[b]	0	2973	1892
Dairy products	1282	0	1282	4048
Tobacco	685	0	685	2293

Notes: Canadian figures are based on Smith (1993) who derived the Canadian emission figures per $1000 Canadian for 1985. The 1985 exchange rate of 175 Japanese yen per Canadian dollar was used. Japanese figures are from Yoshioka (1996).
[a] Cement and concrete products.
[b] Trucks, buses and other cars.

types of technology policy issues that our analysis can address.

CO_2 Emission Effects of Using Blast Furnace Cement in Japan

Portland cement, which is the most widely used type of cement in the world, is produced by grinding and mixing limestone and other raw materials and then heating them to a maximum temperature of 1450°C in a rotary kiln. During this process, CO_2 is produced in two ways: (1) calcium carbonate ($CaCO_3$), the main component of limestone, decomposes into calcium oxide (CaO) and CO_2 at about 825°C; and (2) fossil fuels are burned to heat the kiln. On the other hand, blast furnace slag, a component of blast furnace cement, is a byproduct in the blast furnace production process for pig iron. About 300 kg of slag in liquefied form at 1500°C is produced per each ton of pig iron produced. Rapid water cooling of liquefied slag produces granulated blast furnace slag.

The chemical composition of blast furnace slag is very similar to that of Portland cement (see Table 3). The strength of blast furnace cement is less than that of Portland cement at first, but it gradually increases over time: 3 months after it is produced the strength of blast furnace cement exceeds that of Portland cement. The main type of blast furnace cement (Japanese standard B type) sold in Japan consists of 55% Portland cement and 45% slag (Fig. 1). Table 4 compares the raw material and fuel inputs for Portland and slag cement.

Table 2. Per Capita CO_2 Emission: Japan 1990, 1985

Consumption item group	CO_2 emission (per capita) kg (%)				Expenditure (per capita) 10 000 yen (%)			
	1990		1985		1990		1985	
Food, beverage, tobacco	739 kg	(15%)	654	(17)	38	(19)	34	(22)
Clothing, footwear	239	(5)	216	(6)	14	(7)	11	(7)
Housing, water, power	1186	(25)	1062	(27)	37	(19)	28	(18)
Furniture, appliances	218	(5)	230	(6)	8	(4)	8	(5)
Medical/health care	363	(8)	325	(8)	20	(10)	18	(12)
Transportation, communication	1111	(23)	758	(19)	23	(12)	16	(11)
Recreation, leisure, education	454	(10)	316	(8)	28	(14)	17	(11)
Other	425	(9)	350	(9)	29	(15)	22	(14)
Total	4735	(100)	3911	(100)	197	(100)	155	(100)

Table 3. Chemical Composition: Portland Cement and Granulated Blast Furnace Slag (%)

	CaO	SiO_2	Al_2O_3	Fe_2O_3
Portland cement	63.8	27.5	5.2	2.0
Blast furnace slag	42.2	33.1	13.4	0.0

Blast furnace cement has been used for many years in Japan. It was first produced in Japan by the government-owned Yawata Iron and Steel Works in 1910. In 1933 42% of the total cement used (4 million tons) in Japan was blast furnace cement. However, by 1975 blast furnace cement constituted only 4% of the total cement production (66 million tons). This proportion increased to 17% (out of the total cement production of 87 million tons) in 1990. As our simulation results suggest below, more extensive use of blast furnace cement will further reduce CO_2 emission from the Japanese cement sector.

In order to evaluate the CO_2 emission effects of the two methods of cement production, we divide the cement sector into Portland (P) and blast furnace slag (S) cement subsectors and derive two input coefficient matrices A_P and A_S for the subsectors. (The components of these matrices are identical except those portions related to the cement sector.) A_P and A_S are estimated using the information on inputs into the cement sector given in Table 4. The I–O matrix used in our simulation is $A_* = rA_P + (1-r)A_S$ where $r=1$ ($r=0$) corresponds to using only Portland cement (using only blast furnace cement). The corresponding CO_2 emission vector e_* is given by $e_* = re_P + (1-r)e_S$ where e_P and e_S are, respectively, the emission vectors when only Portland and blast furnace cement were used. The CO_2 emission vector for all sectors is given by $e_*(I-(I-M)A_*)^{-1}I$.

The simulation results when both Portland and blast furnace cement are used in various proportions in the Japanese economy are shown in Tables 5 and 6. In practice, how much blast furnace cement can be produced depends on the amount of blast furnace slag produced. In 1985 24.65 million tons of blast furnace slag was produced in Japan, of which 8.57 million tons was sold for cement production. If all the slag were used for cement production, the cement sector's CO_2 emission would decrease by 14 million tons, which would amount to about 1% of the total Japanese production of CO_2 in 1985. (Note that the largest CO_2 emission occurs in the household sector

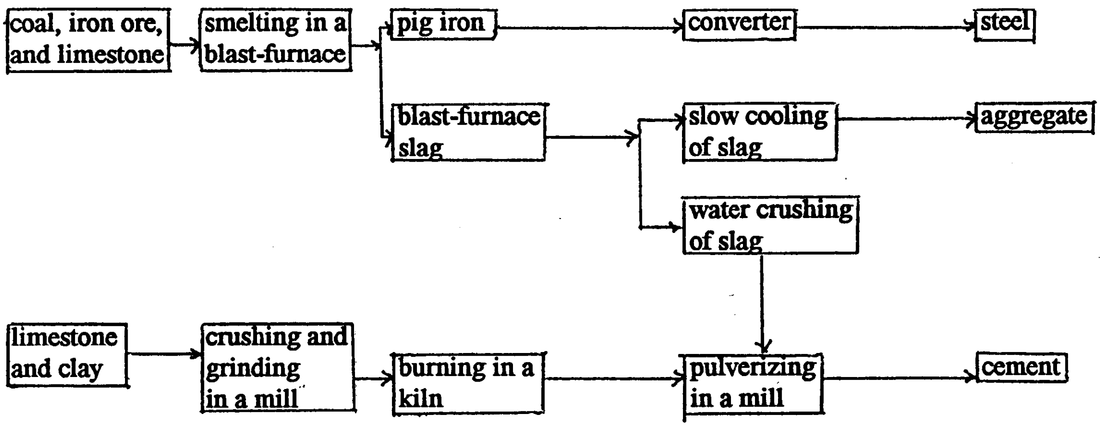

Figure 1. Cement production process.

Table 4. Raw Material and Fuel Inputs for Cement Production

Material inputs (kg)	Portland cement per ton	Slag cement per ton	Fuel inputs per ton of cement	Portland cement per ton	Slag cement per ton
Limestone	1149	0	Coal (kg)	110	14
Silicon	56	0	Heavy oil (1)	1.1	0
Iron oxide	29	0	Electricity (kW/h)	110	70
Gypsum	38	0	Water (ton)	0	7

Table 5. Reductions in Induced CO_2 Emission per 1 Million 1985 Yen Worth of Final Demand: Largest 20 Sectors

Sector	CO_2 emission: Portland (tons)	CO_2 emission: slag (tons)	Reduction in emission
Cement	85 277.4	10 704.6	74 572.8
Mixed concrete	20 888.6	4884.0	16 044.6
Cement products	16 272.9	8111.6	8161.3
Construction: agricultural public utilities	5354.8	3206.1	2148.7
Construction: railway	5619.3	4044.7	1574.6
Road construction: public utilities	4377.4	2921.8	1455.6
River construction: public utilities	4445.2	2989.9	1455.3
Construction: other	4672.8	3367.2	1305.6
Construction: repair work	4195.1	3077.4	1117.7
Construction: electric utilities	3740.6	2891.2	849.4
New residential construction: non-wood	3634.4	2897.0	737.4
New non-residential construction: non-wood	3510.8	2782.8	728.0
New residential construction: wood	2689.3	2161.3	528.0
New non-residential construction: wood	2541.4	2127.6	413.8
Utilities: telecommunication	3069.3	2775.4	293.9
Cast iron pipes and tubes	13 200.4	12 917.7	282.7
Service: public water transport	1991.6	1727.1	224.5
Ceramic, stone and clay	27 940.4	27 808.4	132.0
Clay refectories	7560.8	7453.8	107.0
Unclassified activities	4764.9	4673.3	91.6

(91 million tons) followed by iron and steel production (73 million tons) and cement production (55 million tons).

The use of blast furnace cement is very limited outside Japan even though it effectively reduces the CO_2 emission in the cement sector. The fractions of blast furnace cement use are: 0% (Taiwan), 1% (USA, Canada, Portugal) and 1.7% (South Korea). This suggests that use of blast furnace cement is consistent with firms' profit-maximization objectives to a larger extent in Japan than in other countries.

Production of CO_2 and Use of Recycled Paper

Our input–output approach is also well suited to analyze the complex environmental implications of the increased use of recycled paper in Japan and elsewhere. The pulp and paper sector has many I–O relationships and byproducts. Figures 2 and 3 show the production flow and the associated energy flow of the pulp and paper sector. The impact of the use of recycled paper must be evaluated in the framework of these interrelationships. One of the byproducts in processing virgin pulp is pulp black liquor, which can be used as a fuel at the paper-manufacturing plant. Discarded woodchips may also be burned to generate energy. The use of recycled paper as an input to the paper sector reduces the amount of virgin pulp input used but increases the demand for fossil fuels, which are required for the paper-recycling process. In addition, fuel is required to collect recycled paper. (The activity flow of collecting recycled paper is given in Fig. 4.) The consumption of fossil fuels required for using recycled paper in paper production

Table 6. Combined Use of Portland and Slag Cement: Reductions in CO_2 Emission

Fraction of slag cement (%)	Induced annual CO_2 emission (tons)	Reduction in emission from the 0 slag cement level
0	1 019 398 857	0
10	1 013 557 274	6 841 583
30	1 001 874 273	17 524 584
50	990 191 478	29 207 380
70	978 508 919	40 889 939
90	966 826 571	52 572 286
100	960 985 482	58 413 375

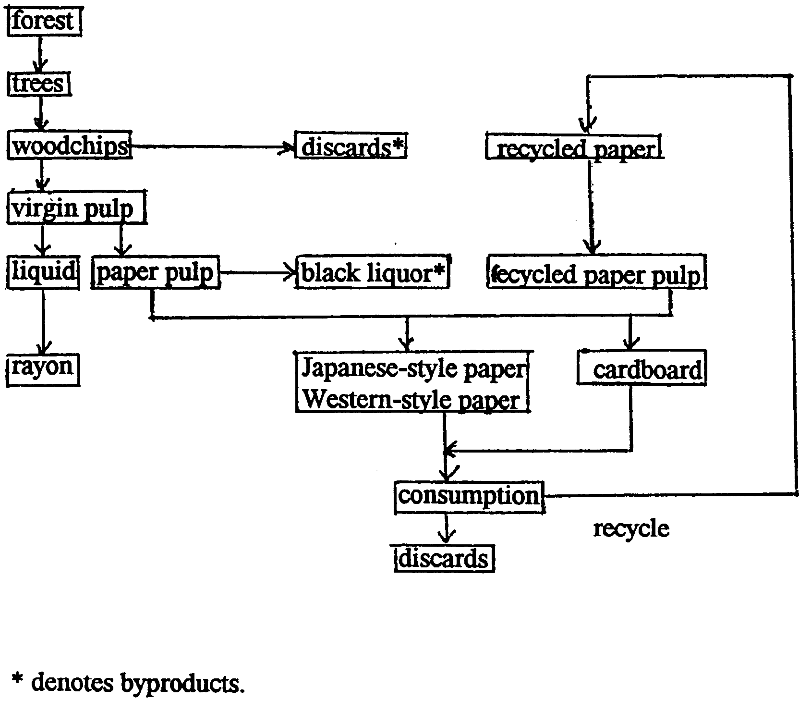

Figure 2. Production of paper and pulp (* byproducts).

must be compared with the benefits from the reduction in the quantity of virgin pulp used. Another implication of the use of recycled paper is the possible economic effects such as declines in the paper price which arise because of the poorer quality of the paper produced.

We make the following assumptions for the production processes used in the pulp and paper sector:

(1) It is efficient to burn pulp black liquor and other pulp waste on-site for generating electricity and steam. (Note in particular that pulp black liquor is hard to transport.) Thus the proportions of these byproducts produced in the production processes are constant.

(2) Firms' self-power generation at production sites produces electricity which is cheaper than the electricity purchased from the power compa-

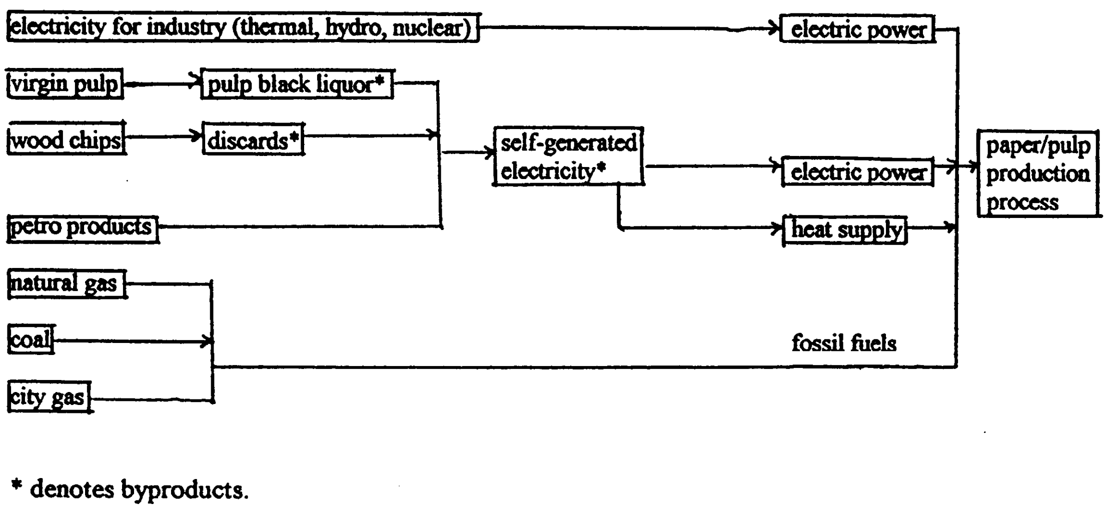

Figure 3. Energy flow in the paper/pulp sector.

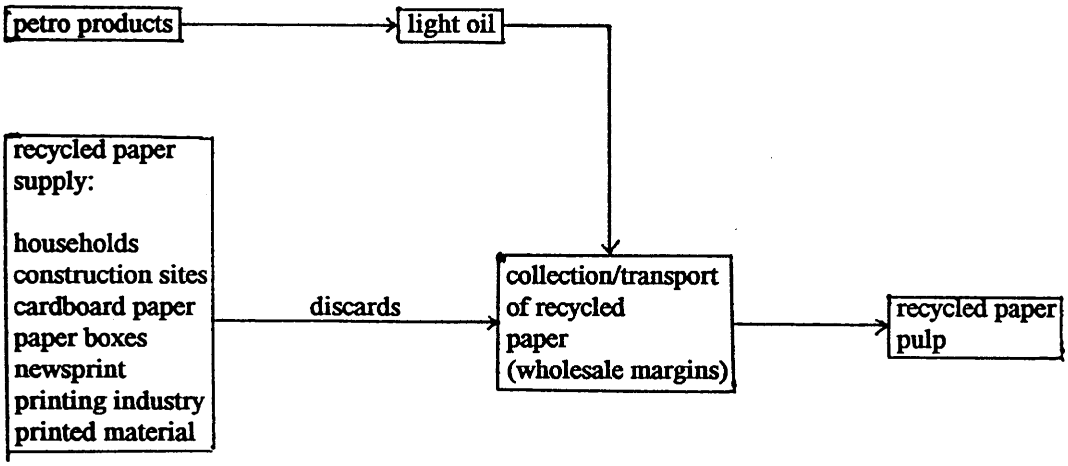

Figure 4. Flow of paper recycling.

nies. Thus self-power generation facilities are utilized fully and their output is constant.

(3) Self-power generation in the pulp and paper sector provides a constant proportion of Japan's total electricity in the benchmark case of our simulation experiments below.

(4) The increased use of recycled paper pulp leads to a reduction in the demand for new paper pulp and also an excess supply of self-generated electricity and steam. The excess supply of electricity generated by the pulp mill is sold to the power companies and excess steam is discarded.

Table 7. Recycled Paper and CO_2 Emission: Simulation Experiments

	New pulp : recycled paper pulp	Transportation energy consumed per transporting recycled paper (Mcal per 1 ton)
Benchmark case	52 : 48	121
A1	48 : 52	242
A2	42 : 58	242
A3	37 : 63	242
A4	33 : 67	242
A5	28 : 72	242
A6	24 : 76	242
B1	28 : 72	242
B2	28 : 72	483
B3	28 : 72	725
B4	28 : 72	966
B5	28 : 72	1208
B6	28 : 72	1449

CO_2 Emission Effects of Recycled Paper and Transportation Energy Consumption

The amount of energy required for collecting recycled paper depends on the quantity, type and geographical location of paper, among other things. We have simulated CO_2 emission for various values of the paper pulp/recycled pulp ratio, and various values for the amount of transportation energy required per ton of recycled paper (Table 7). Our simulation results are given in Tables 8 and 9. Table 8 shows that the increased use of recycled paper reduces CO_2 emission due to the burning of the byproducts of virgin pulp production (pulp black liquor and pulp waste). However, Table 8 also shows that the reduction in the use of these byproducts leads to an increased use of fossil fuels, causing more CO_2 to be emitted. In Table 10 we assume that 72% of paper pulp input to paper production is recycled. The CO_2 emission exceeds the standard case once the transportation energy required for transporting one ton of recycled paper exceeds 725 Mcal. A freight truck can travel up to approximately 360 km using 725 Mcal.

Price Effects of Recycled Paper and Transportation Energy Consumption

We suppose that the raw materials for recycled paper cost 1.5 yen per kg. Using the 28 : 72 ratio for new and recycled paper pulp inputs we can make high-quality paper at a cost of 71 yen/kg, and newsprint at a cost of 51 yen/kg. Since we are interested in relative cost, we can simulate this effect by setting the production cost of low-quality paper equal to 1.5 yen/kg and high quality paper equal to

Table 8. CO_2 Emission When Recycled Paper Pulp is Used (million tons)

Ratio (new pulp/recycled paper pulp)	CO_2 Emission due to fossil fuels	CO_2 Emission due to pulp black liquor and discards
Benchmark 52 : 48	991	14
A1 48 : 52	992	13
A2 42 : 58	992	12
A3 37 : 63	993	10
A4 33 : 67	994	9
A5 28 : 72	995	8
A6 24 : 76	996	7

Table 9. CO_2 Emission When Energy Consumption for Transporting Recycled Paper Is Varied (million tons)

Transport energy required for one ton of recycled paper (Mcal/ton)	CO_2 Emission due to fossil fuels	CO_2 Emission due to pulp black liquor and discards
Benchmark 121	991	14
B1 242	995	8
B2 483	996	8
B3 725	997	8
B4 966	998	8
B5 1208	1000	8
B6 1449	1001	8

Table 10. Simulation Experiments of Price Effects

	New pulp : recycled paper pulp	Transportation energy consume for transporting recycled paper (Mcal per 1 ton)	Price of recycled paper (yen per kg)
Benchmark case	52 : 48	121	1.5
C1	28 : 72	242	1.5
C2	28 : 72	483	1.5
C3	28 : 72	725	1.5
C4	28 : 72	966	1.5
C5	28 : 72	1208	1.5
C6	28 : 72	1449	1.5
D1	28 : 72	242	22
D2	28 : 72	483	22
D3	28 : 72	725	22
D4	28 : 72	966	22
D5	28 : 72	1208	22
D6	28 : 72	1449	22

21.5 yen/kg $(=1.5+(71-51))$. (See the last column in Table 10.) Table 10 defines several cases involving different transportation energy requirements and paper production costs. Our price simulation results are presented in Table 11. (See Appendix A for the derivation of the expression for the price.)

The paper price for the benchmark case is set equal to one. The price of newsprint quality paper increases from below one (Cases C1, C2), to one (C3), and then to close to 1.05 (C6), depending on the amount of energy requirement per ton of recycled paper collected. Prices of higher-quality paper also increase as the amount of energy requirement increases.

The Effects of House Insulation on CO_2 Emission

The Japanese household sector produced 27% of the total amount of CO_2 emitted in Japan in 1985. In this subsection we will show that it would be possible to reduce the total CO_2 emission by 4% if certain insulation materials were used in all commercial and residential buildings in Japan.

We simulate the effects on CO_2 emission of using two alternative sets of material for house wall, windows and doors. (See Table 12.) The total and annualized costs of materials needed for the alternatives are given in Table 13. Cases 1 and 2 require, respectively, 9610 yen and 22 727 yen more per year to operate than the conventional housing. Assuming that the house life is 20 years, the annualized emission of CO_2 by the adoption of these alternative materials is given in Table 14. Cases 1 and 2 produce, respectively, 52 kg and 102 kg per year more of CO_2 than the conventional housing. The annualized expenditures for fossil fuels and CO_2 emission from using these materials per housing unit are given, respectively, in Tables 15 and 16. Cases 1 and 2 reduce the total annualized emission of CO_2 by 523 kg $(=575-52)$ and 587 kg $(=689-102)$, respectively, from the conventional level (Tables 14 and 16). These reductions in CO_2 are achieved with a reduction (an increase) of the operating cost by 9273 yen (136 yen) per year for Case 1 (case 2). (From Tables 13 and 15 we have $9273=18\,883-9610$ for Case 1 and $22\,591-22\,727=-136$ for Case 2.) If we decided to adopt Case 1 for all 37 million houses in Japan, there would be a reduction of 347.9 billion yen in the housing expenditure per year as well as a reduction in CO_2 emission of 19.57 million tons.

Comparison of the SO_2 Emission in Japan and China

According to one estimate (*Chinese Statistical Annual*) the total emission of SO_x in China (excluding the emission from small establishments)

Table 11. The Shadow Prices When Recycled Paper Produced is Newsprint Versus High-quality Paper (Benchmark Shadow Price = 1)

	Newsprint quality paper replaces new pulp paper					
Recycled paper transport energy	C1	C2	C3	C4	C5	C6
(Mcal/t)	242	483	725	966	1208	1449
Paper shadow price	0.98	0.99	1.00	1.02	1.025	1.045
	Recycled paper with whiter than newsprint color replaces new pulp paper					
Recycled paper transport energy	D1	D2	D3	D4	D5	D6
(Mcal/t)	242	483	725	9	1208	1449
Paper shadow price	1.08	1.09	1.105	1.12	1.13	1.145

Table 12. Alternative Insulation Methods

	Case 1	Case 2
Outside wall/ceiling/floor Insulation	Glass wool (100 mm)	Glass wool (100 mm) and Styrofoam (150 mm)
Window	Resin frame, normal paired glass	Wood frame, coated paired glass
Door	Wood	Wood
Heat loss coefficient (kcal/m^2/h, C)	1.2	0.8

was 14.12 million tons in 1987 and increased to 16.85 tons in 1992. Our own estimate for China for 1987 is 20 million tons. This compares with 21 million tons for the USA and 1.15 million tons for Japan. Judging from these estimate, it is likely that China produces the largest amount of SO_x in the world. One of the serious environmental implications of the Chinese SO_x emission is acid rain in Japan.

In this example, we attempt to identify the factors which contribute to such a large SO_x emission in China. We first prepare an I–O input coefficient matrix for Japan whose sectors correspond to the 45 sectors for which Chinese I–O matrix exists. Then we simulate the amount of SO_x China would produce if certain characteristics of the Chinese economy were replaced by the Japanese counterparts.

Suppose that the SO_x emission is given by

$$S_k = F(A_{1k}, A_{2k}, A_{3k}, A_{4k}, A_{5k}, A_{6k}, A_{7k}, A_{8k})$$
$$k = \text{J (Japan), C (China)} \qquad (5)$$

where

A_1 = final consumption pattern
A_2 = goods–service ratio in final consumption
A_3 = imports coefficients
A_4 = patterns of non-energy inputs
A_5 = patterns of energy inputs
A_6 = sulfur content in energy
A_7 = energy efficiency
A_8 = removal ratios for SO_x and sulfur

We assume for simplicity that the Japan–China SO_x emission difference is characterized by the following:

$$\begin{aligned} &F(A_{1J}, A_{2J}, A_{3J}, A_{4J}, A_{5J}, A_{6J}, A_{7J}, A_{8J}) \\ &\quad - F(A_{1C}, A_{2C}, A_{3C}, A_{4C}, A_{5C}, A_{6C}, A_{7C}, A_{8C}) \\ &\quad = \sum_{k=1}^{8} [F(A_{1C}, \ldots, Ai_J, \ldots, A_{8C}) \\ &\quad - F(A_{1C}, A_{2C}, A_{3C}, A_{4C}, A_{5C}, A_{6C}, A_{7C}, A_{8C})] \\ &\quad + \text{cross-factor effects} \qquad (6) \end{aligned}$$

where the first term in the brackets denotes the emission level when the ith Chinese factor level Ai_C is replaced by the Japanese level Ai_J ($i = 1, 2, \ldots, 8$).

Our simulation results are given in Table 17. Replacing A_1 and A_2 by the corresponding Japanese levels would result in increases in China's SO_x production. On the other hand, replacing A_5–A_8 by the corresponding Japanese levels would result in a substantial reduction in the SO_x emission. Replacing A_3 and A_4 seem to have little impact. The cross-factor effects would lead to a large increase in the emission. We discuss these replacement effects below.

Final Consumption Patterns (A_1) and Goods–Service Ratio (A_2)

The final consumption patterns for the two countries are given in Table 18. During the mid-1980s the Japanese economy was heavily investing in its production facilities. Such fixed capital formation absorbed 23.4% of the Japanese final consumption while the figure is 21.3% for China. This, among other factors, explains our simulation results. If China adopted Japan's goods–service ratio in the final consumption, there will be less production of SO_x in the agriculture and forestry sectors but much more SO_x will be emitted from the expanded production of

Table 13. Construction Costs of Alternative Insulation Methods

House parts	Insulation material	Conventional house	Case 1	Case 2	Savings: case 1	Savings: case 2
Ceiling	Glass wool	9672	61 963	92 976	+52 291	+83 304
Outside wall	Wood	346 202	373 235	373 235	+27 032	+27 032
	Glass wool	22 620	722 602	72 602	+49 982	+49 982
	Styrofoam	0	0	158 474	0	+158 474
Floor	Wood	165 987	180 689	210 567	+14 702	+44 579
	Glass wool	9672	28 579	67 080	+18 907	+57 408
Window	Aluminum	28 392	0	0	− 28 392	− 28 392
	Plastic	0	52 320	0	+52 320	0
	Wood	0	0	51 230	0	+51 230
	Glass	5565	11 130	16 695	+5565	+11 130
Door	Aluminum	710	0	0	−710	− 710
	Wood	0	474	474	+474	+474
	Glass wool	0	19	19	+19	+19
Total cost		588 821	781 012	1 043 352	192 191	454 532
Annualized Cost		29 441	39 051	51 168	9610	22 727

Note: these figures (in 1985 producer price in yen) are for a house with 125 m^2 living space.

Table 14. Annualized CO_2 Emission for Materials Used in Alternative Insulation Methods

House parts	Insulation material	Conventional house	Case 1	Case 2	Change: case 1	Change: case 2
Ceiling	Glass wool	3.64	23.32	35.00	+19.68	+31.36
Outside wall	Wood	18.71	20.17	20.17	+1.46	+1.46
	Glass wool	8.51	27.33	27.33	+18.81	+18.81
	Styrofoam	0	0	26.94	0	+26.94
Floor	Wood	8.97	9.76	11.38	+0.79	+2.41
	Glass wool	3.64	10.76	25.25	+7.12	+21.61
Window	Aluminium	6.32	0	0	− 6.32	− 6.32
	Plastic	0	8.9	0	+8.90	0
	Wood	0	0	2.77	+0.00	+2.77
	Glass	1.71	3.43	5.14	+1.71	+3.43
Door	Aluminium	0.16	0	0	− 0.16	− 0.16
	Wood	0	0.03	0.03	+0.03	+0.03
	Glass wool	0	0.01	0.01	+0.01	+0.01
Total		51.67	103.7	154.01	+52.03	+102.34

Notes: these figures (in kg) are for a house with 125 m^2 living space. The house life of 20 years is assumed.

Table 15. Annual Energy Consumption Savings for Alternative Insulation Methods (in Yen, Per Unit House)

Energy type	National average	Case 1	Case 2	Change: Case 1	Change: Case 2
Electricity	89 089	81 055	79 532	8034	9557
Gas	36 856	34 084	33 526	2772	3330
LPG	7785	7393	7314	392	471
Kerosene	16 486	8805	7258	7681	9227
Coal	9	5	4	5	6
Total	150 224	131 341	127 634	18 883	22 591

power, steel and transportation equipment, among other products. (See Table 19.)

Import Coefficients (A_3)

Table 20 presents import coefficients for Japan and China. On average, Japan's dependence on imports is 11.5% and is greater than China's (7.5%). While Japan's import ratios for coal, oil, minerals and other mining products are higher than China's, the import ratios for chemicals, steel, machinery and transportation equipment are higher for China than for Japan. This implies that China imports relatively more

Table 16. Annual CO_2 Emission Savings for Alternative Insulation Methods (in kg, Per Unit House)

Energy type	National average	Case 1	Case 2	Change: Case 1	Change: Case 2
Electricity	1726.50	1570.80	1541.29	155.70	185.20
Gas	672.29	621.72	611.54	50.57	60.75
LPG	386.71	367.25	363.33	19.46	23.38
Kerosene	747.72	399.36	329.21	348.36	418.51
Coal	1.89	0.95	0.76	0.94	1.13
Total	3535.11	2960.08	2846.13	575.03	688.98

products produced by energy-consuming and SO_x-generating industries than Japan. The effects of imports on SO_x emission are negligible, however (Table 17).

Production Sector Effects (A_4–A_8)

Table 21 suggests that the only effective way to reduce the SO_x emission in China is through certain production effects and presents our simulation results of these production effects in detail. The most substantial reduction effect (736 tons per $100 million) would arise if the Chinese energy input levels were changed to the Japanese level (A_5). The second effective way consists of reducing the current energy sulfur content (A_6) to the Japanese level (706 tons); and increasing the removal rate (A_8) of SO_x and sulfur from energy sources (585 tons) and increasing energy efficiency (A_7, 457 tons). Changing non-energy input level (A_4) to the Japanese level seems to have little effect on the total emission.

Cross-factor Effects

We have discussed the effects of replacing the level for each of the eight factors (A_1–A_8) by the Japanese level one at a time. The sum of these individual effects does not equal the total effect because of

Table 18. Composition of Final Consumption: Japan and China

	Japan, 1985	China, 1987
Final consumption		
Other consumption	12.7%	8.1%
Household consumption	50.5	47.4
Fixed capital formation	23.4	21.3
Inventory	0.5	4.8
Exports	12.9	18.3
Total	$1542 billion	$1612.3 billion

Notes: the figures for China are adjusted by an p.p.p. index which is set equal to one for 1985 Japanese prices. In nominal terms the percent consumption proportions for 1987 China are 10.1%, 45%, 28.8%, 4.3% and 11.9%, with the total consumption given by $355.1 billion.

cross-factor effects. These effects are positive, implying the presence of certain canceling effects in emission reductions among the factors. (See Appendix B for the method for calculating the cross-factor effects.) For example, suppose China adopted the Japanese level of SO_x and sulfur removal equipment (A_8). This would significantly reduce SO_x emission because of China's heavy dependence on coal. Suppose also that China adopted the Japanese energy input patterns with much more weight on oil than coal (A_5). While switching its energy dependence from coal to oil would significantly reduce its SO_x emission, China would not be able to take as much advantage of SO_x- and sulfur-removal equipment with the use of oil as it could with the use of coal. Thus the simultaneous adoption of Japanese levels for A_8 and A_5 would not result in the reduction in SO_x emission which equals the simple sum of the individual effects (i.e. $585 + 736$).

We would expect China to continue relying on coal with much sulfur content. This suggests that the most effective ways to reduce its SO_x emission in China would be: (1) to introduce SO_x- and sulfur-removal equipment, particularly in the electric power industry, which, if implemented at the Japanese level, would result in the reduction of 249 tons of SO_x emission per $100 million; and (2) to increase energy

Table 17. Reductions in Chinese SO_x Emission when A_1–A_8 Are Set to the Japanese Levels (tons per $100 million)

Factor	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	Cross-factor effects
Reduction	− 69	− 640	− 5	6	736	706	457	585	− 625

Note: negative (positive) values correspond to increased (reduced) emissions of SO_x. These factors are: A_1 (final consumption pattern), A_2 (goods-service ration in final consumption), A_3 (imports coefficients), A_4 (non-energy inputs pattern), A_6 (energy inputs pattern), A_6 (sulfur content in energy), A_7 (energy efficiency) and A_8 (removal ratio for SO_x and sulfur.

Table 19. Reductions in the Chinese Emission of SO_x When China Adopted the Japanese Consumption Patterns (tons per \$100 million)

Agriculture/forestry	18.7
Paper/pulp	−16.6
Power/electricity	−319.2
Pottery	−75.7
Iron and steel	−170.5
Transportation machinery	−63.5
Railway	−23.0
Commerce	−25.0
Household	240.7
Total	−640.2

Note: negative (positive) values correspond to increased (reduced) emissions of SO_x.

Table 20. Import Coefficients for Some Industries for Japan and China

Sector	China	Japan
Agriculture/forestry	0.02924	0.18136
Fishery	0.00187	0.19411
Coal	0.01163	0.82286
Oil	0.00000	0.98608
Minerals	0.15719	0.77608
Non-ferrous metal ore	0.05786	0.11878
Food	0.04899	0.06083
Apparels, leather	0.24573	0.08010
Paper, pulp	0.08613	0.04822
Chemicals	0.15989	0.08110
Iron and steel	0.17057	0.02183
Non-ferrous products	0.10072	0.28712
Machinery	0.23976	0.03441
Transportation equipment	0.22316	0.04150
Electrical machinery	0.10418	0.02988
Electronics, communication	0.28989	0.04619
Precision	0.35501	0.05627
Other manufacturing	0.38843	0.02532
Air transportation	0.05120	0.24765
Other transportation	0.00000	0.31069

efficiency, particularly in electric power and pottery industries, which if implemented at the Japanese level, would result in the reduction of 189 tons of SO_x emission per \$100 million. (See Table 21.) Technology transfer in these areas combined with official development aid from developed countries may turn out to be effective from the global environmental point of view.

CONCLUSIONS

In this paper we have discussed how I–O analysis can be applied to analyzing certain public policy issues involving the choice of technology in dealing with global warming. In particular, we have discussed Japanese environment management applications in cement production, the use of recycled paper, house insulation and an international comparison of CO_2 emission. Each of these examples involves the choice of technology as related to the emission of CO_2 and other environment-sensitive gases.

Because I–O data describe the cross-sectional relationships among various sectors in an economy for a particular year, there are limitations on the extent we can extrapolate the results derived from a sample year to other years. We can overcome these considerably by repeating our analysis over time. We are currently repeating our entire analysis using the 1990 data. Another limitation of the environmental I–O analysis is its data requirement. It requires gas emission and other data at a desegregate level for alternative technologies. The accumulation of more data over time on the I–O activities, energy consumption and gas emissions in different countries will certainly alleviate the problems associated with the data requirement.

Table 21. Reduction in Chinese SO_x Emission When Japanese Production Activities Were Used in China (tons per \$100 million)

Sector	A_4: non-energy inputs	A_5: energy inputs	A_6: sulfur content in energy	A_7: energy efficiency	A_8: removal of SO_x and sulfur
Agric./forestry	4.4	17.6	18.2	11.3	17.7
Coal mining	2.0	33.7	35.4	30.0	12.1
Paper/pulp	−37.7	−0.1	13.2	12.4	19.0
Power supply	7.2	190.0	190.2	100.0	248.7
Chemicals	11.8	17.1	18.6	0	25.2
Pottery	19.7	53.5	55.2	88.6	53.9
Iron/steel	4.7	−28.1	48.4	45.9	72.3
Total incld. Household sec.	5.6	735.8	705.8	457.0	585.0

APPENDIX A: CALCULATION OF THE PRICE VECTOR WHEN RECYCLED PAPER IS USED

Let p_j be the unit price of the jth sector output, x_j ($j = 1, 2, \ldots, n$). Then

$$[1 - \{t_j/(1 + t_j)\}]p_j = \sum_{i=1}^{n} p_i a_{ij} + p_{Zj}S_{Zj} + p_{Lj}S_{Lj} + p_{Kj}S_{Kj} \qquad (*)$$

In (*) the a_{ij} ($i, j = 1, 2, \ldots, n$) denote the I–O coefficients for intermediate goods. S_b denotes cost share for input b for sector j ($b = Zj$ for recycled paper input, with corresponding unit price p_{Zj}; $b = Lj$ for labor input, with p_{Lj}; and $b = Kj$ for capital input, with price p_{Kj}). t_j is the net indirect tax rate for sector j and is equal to $t_j = \{\mathrm{tax}_j/(p_j x_j - \mathrm{tax}_j)\}$ where tax_j is the net indirect tax payable by sector j. Let $p' = (p_1, p_2, \ldots, p_n)$ and $v' = (v_1, v_2, \ldots, v_n)$, where $v_j = p_{Zj}S_{Zj} + p_{Lj}S_{Lj} + p_{Kj}S_{Kj}$. (*) can be rewritten as

$$Tp = A'p_v + v$$

or

$$p = (T - A')^{-1}v$$

where T is an $n \times n$ diagonal matrix with its jth diagonal elements given by $[1 - \{t_j/(1 + t_j)\}]$ and A is the I–O matrix. For each case in our simulation experiments A is estimated. Then it is substituted into the above expression to obtain price vector p.

APPENDIX B: FACTOR DECOMPOSITION IN ENVIRONMENTAL INPUT–OUTPUT ANALYSIS

Suppose we have calculated the SO_x emission per unit of final consumption. Let S_{jk} denote the induced SO_x emission from the jth sector of country k, where $k = J$, C and $j = 1, 2, \ldots, n$ ($= 42$). Let S_{Crk} denote the emission from the rth element of country k's final consumption vector, where $r = 1$ (other consumption) and $r = 2$ (household consumption). Then we have:

$$S_{jk} = R_{jk}(U_{jk}/X_{jk}) \sum_{m=1}^{m^*} [(U_{mjk}/U_{jk})(e_{mjk}/u_{mjk})]x_{jk} \qquad \text{(A1)}$$

$$S_{Crk} = R_{Crk}(U_{Crk}/F_{Crk}) \sum_{m=1}^{m^*} \times [(u_{Cmrk}/U_{Crk})(e_{Cmrk}/u_{Cmrk})]\, f_{Crk} \qquad \text{(A2)}$$

where R_{jk} and R_{Crk} denote, respectively, $\{1 - SO_x$ removal rate$\}$ for sector j and final consumption type r for country k (index k will be omitted below); U_j and U_{Cr} denote energy consumption measured in T cal; X_j and F_{Cr} denote real production and consumption, respectively, measured in 1985 million yen; u_{mj} and u_{Cmr} denote consumption of fuel type m ($m = 1, 2, \ldots, m^*(= 19)$); e_{mj} and e_{Cmr} denote the amount of SO_x content in energy type m measured in SO_2 equivalent; and f_{Cr} denotes the proportion of final consumption of type r. The x_{jk} is the jth component of the column vector calculated for country k by (subscript k is omitted below)

$$x = (I - (I - M)A)^{-1}f \qquad \text{(A3)}$$

where the unit final consumption vector f is given by:

$$f = \begin{matrix} (1 - m_1)fx_{11}(1 - m_1)fx_{12} \ldots (1 - m_1)fx_{1,r^*-1}fx_{1,r^*} & fc_1 \\ (1 - m_2)fx_{21}(1 - m_2)fx_{22} \ldots (1 - m_2)fx_{2,r^*-1}fx_{2,r^*} & fc_2 \\ \ldots\ldots\ldots\ldots\ldots\ldots & \ldots \\ \ldots\ldots\ldots\ldots\ldots\ldots & fc_{r^*} \\ \ldots\ldots\ldots\ldots\ldots\ldots & \\ (1 - m_n)fx_{n1}(1 - m_n)fx_{n2} \ldots (1 - m_n)fx_{n,r^*-1}\, fx_{n,r^*} & \end{matrix} \qquad \text{(A4)}$$

In Eqn (A4) m_j ($J = 1, \ldots, n$) is the imports coefficient for sector j, fx_{jr} is the fraction of the jth output used in the rth final demand ($r = 1, 2, \ldots, r^* = 5$) and the r^*th final demand ($r = 5$) is exports. Other elements of the final demand vector are: other consumption ($r = 1$), household consumption ($r = 2$), fixed capital formation ($r = 3$) and net increase in inventories ($r = 4$).

By definition, we have:

$$\sum_{j=1}^{n} fx_{jr} = 1 \qquad r = 1, \ldots, r^*(= 5)$$

$$\sum_{r=1}^{r^*} fc_r = 1$$

The total SO_x emission per unit of final consumption for country k is given by the sum of the total induced emission and the total emission from the final consumption

$$S_k = \sum_{j=1}^{n} S_{jk} + \sum_{r=1}^{r^*} S_{Crk}$$

Using the eight factors ($A_{1k} - A_{8k}$) introduced in the text, S_k is given by Eqn (A1). Using the quantities introduced in this appendix, these factors are defined as follows:

A_1: final consumption pattern. fc_r ($r = 1, 2, 3, \ldots r^*$), where $r^* = 5$ here.

A_2: goods–service ratios in final consumption. fx_{jr} ($j = 1, 2, \ldots, n$; $r = 1, 2, \ldots, r^*$)

A_3: import coefficient matrix M.

A_4: non-energy inputs x_{ij} ($j = 1, 2, \ldots, n$; $i =$ non-energy inputs)

A_5: patterns of energy inputs. a_{ij} ($j = 1, 2, \ldots, n$; $i =$ energy inputs); (u_{mj}/U_j) for $m = 1, 2, \ldots, m^*$ and $j = 1, 2, \ldots, n$; (u_{Cmr}/U_{Cr}) for $m = 1, 2, \ldots, m^*$ and $r = 1, 2, \ldots, r^*$.

A_6: sulfur (SO_x) content in energy. (e_{mj}/u_{mj}) for $m = 1, 2, \ldots, m^*$ and $j = 1, 2, \ldots, n$; (e_{Cmr}/u_{Cmr}) for $m = 1, 2, \ldots, m^*$ and $r = 1, 2, \ldots, r^*$.

A_7: energy efficiency. (U_j/X_j) for $j = 1, 2, \ldots, n$; (U_{Cr}/F_{Cr}) for $r = 1, 2$.

A_8: removal ratios for SO_x and sulfur. R_j ($j = 1, 2, \ldots, n$); R_{Cr} ($r = 1, 2$).

The cross-factor effects in Eqn (A2) is calculated by the following (Yoshioka and Arai, 1980):

$$\sum_{i1=1}^{7} \sum_{i2=i1+1}^{8} [F(A_{1\mathrm{C}}, \ldots, A_{i1,\mathrm{J}}, \ldots, A_{i2,\mathrm{J}}, \ldots, A_{8\mathrm{C}})$$
$$- F(A_{1\mathrm{C}}, \ldots, A_{i1,\mathrm{J}}, \ldots, A_{8\mathrm{C}}$$
$$- F(A_{1\mathrm{C}}, \ldots, A_{i2,\mathrm{J}}, \ldots, A_{8\mathrm{C}})$$
$$+ F(A_{1\mathrm{C}}, A_{2\mathrm{C}}, A_{3\mathrm{C}}, A_{4\mathrm{C}}, A_{5\mathrm{C}}, A_{6\mathrm{C}}, A_{7\mathrm{C}}, A_{8\mathrm{C}})]$$
$$+ \ldots$$
$$+ \sum_{i1=1}^{1} \sum_{i2=i1+1}^{2} \ldots$$
$$\times \sum_{in=8}^{8} [F(A_{1\mathrm{J}}, A_{2\mathrm{J}}, A_{3\mathrm{J}}, A_{4\mathrm{J}}, A_{5\mathrm{J}}, A_{6\mathrm{J}}, A_{7\mathrm{J}}, A_{8\mathrm{J}}) - \ldots$$
$$+ (-1)^{n+1} F(A_{1\mathrm{C}}, A_{2\mathrm{C}}, A_{3\mathrm{C}}, A_{4\mathrm{C}}, A_{5\mathrm{C}}, A_{6\mathrm{C}}, A_{7\mathrm{C}}, A_{8\mathrm{C}})]$$

Acknowledgements

The research reported in this paper is based on an on-going research project on environmental management at the Keio Economic Observatory of Keio University. M. Nakamura's research is in part supported by the Social Sciences and Humanities Research Council of Canada. We thank R. Smith for helpful comments.

REFERENCES

Chinese National Statistical Agency (various years). *Chinese Statistical Annual*, Beijing.

H. Hayami, A. Ikeda, M. Suga, Y.C. Wong and K. Yoshioka (1995). A simulation analysis of the environmental effects of energy saving housing (in Japanese), Keio Economic Observatory Occasional Paper E. No. 20, June.

H. Hayami and K. Yoshioka (1996). Interdependency of economic activity and CO_2 emission: some applications of environmental input–output analysis. In *Global Environment and Human Activity* (edited by K. Watanuki and K. Yoshioka), Tokyo: Maruzen, 97–143.

W.W. Leontief (1970). Environmental repercussions and the economic structure: an input–output approach. *Review of Economics and Statistics*, **52**, 262–71.

W.W. Leontief (1986). Air pollution and the economic structure: empirical results of input–output computations. In *Input–Output Economics*, 2nd edition, New York: Oxford University Press, 273–93.

R. Smith (1993). *Canadian Greenhouse Gas Emissions: An Input–Output Study*, *Statistics Canada*, Cat. No. 11-528E.

K. Yoshioka and M. Arai (1980). The structural change of the Japanese energy demand (in Japanese). *Mita Shogaku Kenkyu*, **23**, No. 3, August, 55–80.

K. Yoshioka and H. Hayami (1995). I–O analysis of the Japan–China environmental problems (in Japanese). *Innovation & I–O Technique*, **5**, No. 4, January, 19–28.

K. Yoshioka, H. Hayami, A. Ikeda and M. Suga (1995). Recommending the use of blast furnace cement to reduce CO_2 emission (in Japanese). *Innovation & I–O Technique*, **4**, October, 21–28; also Keio Economic Observatory Occasional Paper E. No. 21, June 1995.

