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Abstract

Any production activity including recycling of waste materials and consumption emits waste. This paper presents an accounting framework describing the interdependence between the flow of goods and waste among different sectors of the economy, and derives a linear input-output model from it that can be used for analyzing the relationships among environmental loads, technology/institutions, and life-style. The accounting framework is used to analyze the MSW flow of a city in Hokkaido with an extensive waste management policy. The input-output model is used to evaluate the effectiveness of the policy with respect to the requirements for landfill capacity and energy.

1 Introduction

Any production activity including recycling of waste materials and consumption (household production) emits waste. Just as goods producing sectors are related to each other through input-output relationships, goods producing sectors and waste management sectors (recycling and disposal) are related to each other through extended input-output relationships involving both goods and waste. Recently, this aspect of inter-relatedness between goods and waste has greatly increased its importance in connection with sustainability issues because of the increasing awareness that excessive emission of wastes from the industrial process and final demand is the single most important impact of human activity on the environment.

The Input-Output (IO) table is an accounting framework that describes the flow of goods (and services) among different sectors of the economy. The purpose of this paper is to propose an accounting framework involving both goods and waste by extending the IO table to accommodate the flow of waste. Development of this sort of accounting framework is fundamental to analyzing relationships between the level of economic activity and the emission of waste.

This is so due to the importance of properly taking account of the condition of material balance. This importance cannot be overemphasized in the analysis of waste. A production activity emits waste because some portion of materials inevitably becomes waste residue. The waste treatment sector merely transforms a give type of waste into different types of wastes but can never extinguish it because of the first law of thermodynamics.

Based on the extended IO table, I derive a linear model that describes the relationships among the level of emission of waste, technical input and emission coefficients representing technology and institutions, and the level and composition of final demand representing life-style.

I estimated the proposed extended IO table for a city in Hokkaido that is known for its extensive waste management policy and the remarkably high recycling rate of municipal solid waste (MSW). The linear model was then used to evaluate the efficiency of the policy with respect to the saving of landfill capacity and energy requirements.

The paper is organized as follows. Section 2 shows the accounting framework. Section 3 derives the linear model from the accounting framework and discusses its properties. The results of empirical application are shown in Section 4. Section 5 closes the paper with remarks for future directions for research including its application to Inverse Manufacturing (IM).

2 The Flow of Goods and Waste

2.1 Waste and Effluents

Waste can be classified into two categories depending on whether it remains within the sphere of economic activity to undergo further waste management processes such as recycling and disposal, or leaves the sphere and is emitted into the environment. I call the former "waste" and denote it by w, and the latter "effluents" and denote it by e. MSW going into a public incinerator belongs to the former, while the emission of CO_2 from the incinerator belongs to e.

A waste treatment process transforms a particular waste into different types of waste and effluents. At the end of a series of treatment processes, wastes are emitted into the environment as effluents: e is the final form of w. Hidden material requirements [1] can also be considered as a component of e.

2.2 The Extended IO Table

Consider an economy that consists of N industry sectors, L recycling sectors, K waste treatment sectors, and final demand sectors, which I respectively denote by o, r, z, and f. The production activity of these sectors (including f) emits M wastes and M' effluents. Denote by X_o the N vector of industrial outputs, by X_r the L vector of recycled goods, by W_w the M vector of wastes, and by W_e the M' vector of effluents.

The emission of waste and effluents associated with X_o are denoted respectively by an $M \times N$ matrix W_{wo} and an $M' \times N$ matrix W_{eo}. The matrices W_{wi} and W_{ei}, $i = r, f$ are defined in the same manner. The conventional intersectoral flows of goods (and services) are represented by X_{ij}, $i \in (o, r)$, $j \in (o, r, z, f)$.

Waste disposal sectors transform a given set of wastes into different types of wastes and effluents. This transformation is represented by an $M \times K$ matrix W_{wz} and an $M' \times K$ matrix W_{ez}. Suppose that z_j is a public incinerator of MSW. It transforms MSW into ash, dust captured by dust filters, and waste gas. Suppose that ash and dust are disposed of in a controlled landfill site and that gas is emitted into the atmosphere. Then ash and dust occur as elements of the j-th column of W_{wz}, while waste gas occurs as an element of the j-th column of W_{ez}. The activity level of z_j, X_{zj}, is measured by the volume of waste it treated (incinerated), but not by the volume of waste it emitted.

Recycling sectors use waste as input but at the same time emit their own waste. The net emission of waste in recycling sectors is represented by an $M \times L$ matrix $W_{wr} - X_{wr}$, where the first term represents the emission of waste and the second term the input of waste as materials. Recycling is effective in reducing the volume of waste to be disposed of if some elements of the matrix are strictly negative.

The following balancing equation (in matrix form) then holds for the flow of waste:

$$W_w = W_{wo} + W_{wr} - X_{wr} + W_{wz} + W_{wf} \tag{1}$$

Using the same notational convention, Table 1 represents the flow of goods and wastes among different sectors of the economy in the form of an extended input-output table, where Σ refers to the row sum.

	o	r	z	f	Σ
o	X_{oo}	X_{or}	X_{oz}	X_{of}	X_o
r	X_{ro}	X_{rr}	X_{rz}	X_{rf}	X_r
w	W_{wo}	$W_{wr} - X_{wr}$	W_{wz}	W_{wf}	W_w
e	W_{eo}	W_{er}	W_{ez}	W_{ef}	W_e

Table 1. Flow of Goods and Waste

3 The Model

3.1 Input and Emission Coefficients

Dividing the column elements of o, r and z by the corresponding activity (output/disposal) levels gives the input or emission coefficients, as in Table 2. A_{oo} corresponds to the conventional input coefficients matrix in IO analysis. The i-th row and j-th column element of $G_{wr} - A_{wr}$ refers to the negative of the input of waste i into recycling sector j net of waste i emitted by the recycling sector itself. Following the practice of IO analysis, I assume that the input/emission coefficients obtained this way are approximately constant in the neighborhoods of realized activity and price levels.

	o	r	z
o	A_{oo}	A_{or}	A_{oz}
r	A_{ro}	A_{rr}	A_{rz}
w	G_{wo}	$G_{wr} - A_{wr}$	G_{wz}
e	G_{eo}	G_{er}	G_{ez}

Table 2. Matrix of input and emission coefficients

In general there will be no one-to-one correspondence between wastes and waste disposal; it is likely that the number of types of waste exceeds the number of waste disposal processes. The coefficients matrix of "endogenous sectors" in the middle panel of Table 2 excluding the bottom panel referring to e is not square, and the standard calculation of the input-output model is not applicable.

In order to make the matrix of endogenous sectors into a square one, the row elements referring to wastes (w) need to be transformed into the corresponding waste disposals. Let a $K \times M$ matrix $S = [s_{ij}]$ be the allocation matrix with s_{ij} being the proportion of waste j treated by disposal sector i in the absence of any recycling activity. For instance, consider the case where waste disposal consists of incineration ($j = 1$) and landfill ($j = 2$). We will then have $s_{i1} = 1$ and $s_{i2} = 0$ when waste i is combustible and $s_{i1} = 0$ and $s_{i2} = 1$ when it is noncombustible.

By definition, $\sum_{i=1}^{K} s_{ij} = 1$, $j = 1, \ldots, M$. At a given moment of time, S will be to a large extent determined by the prevailing waste disposal technology and institutional arrangements (regulations). In the following I assume that S is a constant matrix that does not depend on the volume of waste disposal.

Multiplication from the left of both sides of (1) by S transforms the M vector W_w into the K vector of waste disposals W_z, the i-th element of which refers to the volume of wastes processed by the i-th disposal sector:

$$\begin{aligned} W_z &= SW_w = SW_{wo} \\ &+ S(W_{wr} - X_{wr}) + SW_{wz} + SW_{wf} \end{aligned} \quad (2)$$

Note that in (2) recycling sectors reduce *not* the volume of *wastes* but the activity level of *waste disposals*.

3.2 Life-style, Technology, and Effluents

Transformation of the input coefficients matrix in Table 2 into a square one is now straightforward: multiply the row elements of w by S from the left. The balancing equations can then be represented in terms of input-and emission coefficients as follows:

$$\begin{pmatrix} A_{oo} & A_{or} & A_{oz} \\ A_{ro} & A_{rr} & A_{rz} \\ SG_o & S(G_r - A_{wr}) & SG_z \end{pmatrix} \begin{pmatrix} X_0 \\ X_r \\ X_z \end{pmatrix} + \begin{pmatrix} X_{0f} \\ X_{rf} \\ SW_{wf} \end{pmatrix} = \begin{pmatrix} X_0 \\ X_r \\ X_z \end{pmatrix}$$

Or using a simplifying notation:

$$AX + F = X \quad (3)$$

where $X = (X_0\, X_r\, X_z)^\top$ and other elements are defined in an analogous manner. Assuming that the characteristic values of A are not equal to unity (the matrix derived from real data satisfies this condition automatically), we can solve this system of equations for output/ activity levels:

$$X = (I - A)^{-1}F \quad (4)$$

If none of the elements of A is negative, it is known that (4) gives a non-negative X for *any* non-negative F [4]. Since A includes negative elements in our case (otherwise, the recycling activity does not reduce waste) this result does not hold. Still, (4) will give a non-negative (economically meaningful) solution in the neighborhood of realized F, and this will suffice for most practical purposes.

In (4) X represents the level of economic activity that is required to support the *life-style* represented by F for a given set of technology and institutions represented by A. If the complete recycling of waste (in any form including waste heat) is feasible, there would be no waste disposal activity since waste does not occur, and no effluents would be emitted into the environment.

Since any production activity emits waste, and this holds for recycling as well, complete recycling is not possible, and the economy emits effluents into the environment. Let G_e be the $M' \times (N + L + K)$ matrix of effluents emission coefficients in the bottom panel of Table 2. Like A this matrix also represents technology (in use) and institutions (such as emission standards of waste water and gas).

The level of *additional* environmental loads resulting from X and hence from a given set of life-style, technology and institutions will then be given by

$$W_e = G_eX = G_e(I - A)^{-1}F \quad (5)$$

(5) provides an analytical tool for quantitatively evaluating certain aspects of environmental loads of the economic activity represented by a given set of life-style, technology, and institutions.

Provided the stock of W_e is within the sink and regeneration capacity of the natural environment, this economy is sustainable, i.e., F can be realized over an extended period of time. If the stock level exceeded this critical level, however, there would emerge adverse environmental effects on the economy, and F would not be sustained under *given* A and G_e. Therefore, (5) can also be used for the analysis of sustainability issues. In the next section, I apply the accounting framework and the model to real data to show its potential applicability.

4 Empirical Application to the MSW Flow of a City

4.1 The MSW Flow Table

I applied the above accounting framework to the MSW flow of City F, a rural city in Hokkaido with a population of 23000. The major industries are agriculture and tourism. The city is remarkable in that it recycles some 56 percent of the collected MSW (the national average is about 8 percent).

A separated collection of combustible and noncombustible waste is nowadays a widespread practice in Japan. What makes the waste management policy of City F remarkable is the separated collection of food waste for composting, and waste plastics (except PVC), waste paper and waste textiles as materials for the production of refuse derived fuels (RDF). Of the total combustible waste in 1995, 45 percent was composted, 20 percent was used as materials for RDF, and the remaining 35 percent was incinerated.

Table 3 represents the MSW flow of City F in the form of Table 1 (the flow of goods is not shown) for 1995 in tons. Since the disposal of noncombustible waste and the recycling of metals and glass were taken care of outside the city, these wastes were excluded from the Table. Also excluded were medical and industrial wastes excluding agricultural waste plastics.

In the following, I limit the analysis to five types of waste (composting waste w_1, RDF waste w_2, other combustible waste w_3, agricultural waste plastics w_3, and incinerator ash w_5), two types of waste disposal (incineration z_1 and landfill z_2), and two types of recycled goods (compost r_C and RDF r_R). Note that Table 3 was made using published data sources of City F only, and required no extra inquiry. This demonstrates the relative ease of implementing the proposed accounting framework.

	o	z_1	z_2	r_C	r_R	f	Σ
r_C	2176						2176
r_R	989						989
w_1	1148			-3269		2121	0
w_2	272				-1490	1218	0
w_3	592			461	167	1888	3108
w_4	757						757
w_5		457					457

Table 3. Flow of Waste in City F

Table 3 reads as follows. The composting sector, r_C, makes out of 3269 tons of food waste generated by household, f, and industry, o. (mainly tourism related service sectors) 2.2 kilo tons of compost that is used by agriculture, and emits .46 kilo tons of residue as combustible waste. The RDF sector, r_R, makes out of 1.5 kilo tons of RDF waste .99 kilo tons of RDF that is used by the public sector (public schools, public buildings) as a substitute for coal, and emits 167 tons of residue as combustible waste. Agricultural waste plastics are not used as materials for RDF but landfilled because of their high PCV content.

Note that the mass balance does not hold here because of the evaporation of water content, the exclusion of incombustible items, and the use of additives in the composting process. The incinerating sector transforms 3.1 kilo tons of combustible waste into .46 kilo tons of incinerator ash that goes to landfill.

To complete the extended IO table, I also estimated an IO table with 46 endogenous sectors for City F based on the regional IO table for Hokkaido, and using other supplementary data sources (see [3] for details). Adding the two recycling sectors and two waste disposal sectors, the extended IO table has 50 endogenous sectors. The transformation of 5 types of waste into 2 types of waste disposal was done by the following S matrix. Once the square table has been estimated this way, the derivation of an analytical model is straightforward.

	w_1	w_2	w_3	w_4	w_5
z_1	1	1	1	0	0
z_2	0	0	0	1	1

Table 4. The Transformation Matrix S

4.2 Analysis

The estimated model is now used to evaluate the waste management policy of the city. The main motivation behind the waste management policy was a minimization of waste to be landfilled because of difficulty in expanding the landfill capacity. It is obvious that composting is an effective remedy for this purpose.

As for RDF, however, its effect on landfill is not obvious because its consumption emits ash that has to be landfilled. The production of RDF requires an input of energy but would be justifiable if it produced more energy than it used. The issue of energy is also of interest for compost because (provided it has a certain CN ratio) it can substitute for chemical fertilizers that require the extensive input of fossil fuels.

I evaluated the policy by comparing the solutions of (4) obtained under alternative policy scenarios with the realized values for 1995 that served as *Control*. The following scenarios were considered.

1. *No recycling*: all the combustible waste is incinerated.
2. *No composting*: the share of RDF production is as in *Control*, but the rest is incinerated.
3. *No RDF production*: the share of composting is as in *Control*, but the rest is incinerated.

Each of these scenarios was implemented by changing the input coefficients of compost in agriculture and RDF in the public sector. For instance, the case of *No recycling* corresponds to setting both the input coefficients equal to zero.

My treatment of energy sectors (oil/coal and electricity) in the computation will require some explanation. Since City F does not have any energy sectors and imports oil/coal and electricity from outside the city, a change in the demand for energy has no direct effect on its economic activity. Hence, if the analysis were strictly limited to activity inside the city, there would be no way to evaluate the implications of alternative scenarios on energy requirements. I therefore prodeeded as if the energy sectors existed in City F and set the rate of self-satisfaction of oil/coal and electricity to unity (note that the estimated IO table is of a non-competitive import type). Since these energy sectors emit wastes that do not occur in City F, however, I excluded from the analysis the wastes originating from them. To see the effects on energy requirements of a shift in agriculture from chemical fertilizers to composts, an analogous procedure was also applied to the chemical industry because one did not operate in the city.

Figure 1 shows the effect of the recycling scenarios on the demand for incineration and landfill with the *Control* values set to unity. The no-recycling scenario increased landfill by almost 40%, and indicates the effectiveness of the recycling policy for reducing the landfill requirement. As expected, this was to a large extent due to the composting. The contribution of RDF production to the reduction of landfilling is mostly limited to the reduction in its emission of ash resulting from a possible improvement of combustion efficiency.

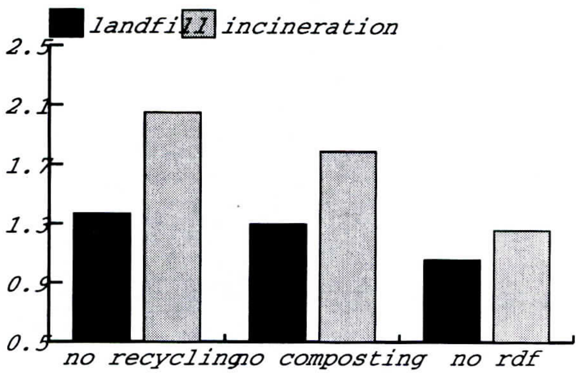

Figure 1. Incineration and Landfill under Alternative Recycling Scenarios

Figure 2 shows the effect of alternative recycling scenarios on the demand for fossil fuels (oil and coal products) and electricity with the *Control* values set to unity. Note that the demand for both fossil fuels and electricity declined under the no-recycling scenario! This is consistent with the often made claim that "recycling is energy intensive". Note that my calculation took into account the substitution of RDF for coal and compost for chemical fertilizers. Since composting in City F is rather petroleum intensive, it is no surprise that it was not effective in saving energy.[1]

What I find noteworthy is that RDF might not be a net producer of energy. While the zero production of RDF increased the demand for coal, it decreased the total demand for electricity. In particular, the increase in the expenditure for electricity outweighed the decrease in the expenditure for coal/oil.

Given that the contribution of RDF to the saving of landfill capacity was negligible, this finding may cast doubt on the effectiveness of RDF production (the emission of dioxins is another issue with RDF). This result, however, contradicts [2], who found the effectiveness of RDF production in city F in terms of calorific value, based on the adding-up method. Further investigation is required to reconcile these contradictory results.

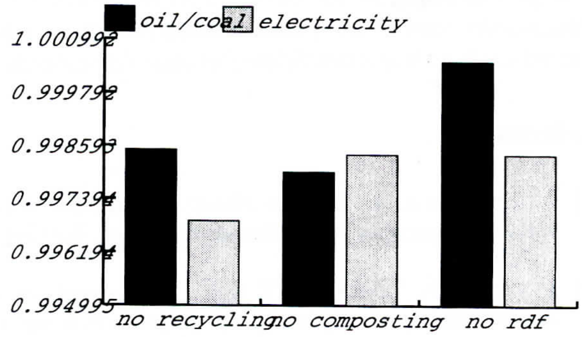

Figure 2. Consumption of Fossil Fuels and Electricity Under Alternative Recycling Scenarios

5 Concluding Remarks

This paper presented an accounting framework describing the interdependence between the flow of goods and wastes among different sectors of the economy, derived the associated static IO model, and applied it to the MSW flow of a city to analyze the efficiency of its waste management policy.

The model can also be used to analyze certain economic as well as environmental effects of the implementation of several aspects of IM. A change in the design of a product, for instance, changes the input and emission coefficients of the sector producing the product but also changes the level of activity and emission of the other sectors as well through input-output relationships. In terms of the above model, a change in product design in sector j can be represented as a change in the elements of the j-th column of A and G_e.

Some manufacturers of electrical appliances have recently started providing waste disposal sectors with detailed information on procedures for efficiently disassembling waste appliances to raise the productivity of disposal sectors. This aspect of IM can be represented in the model as a change in the column elements of A and G_e of disposal sectors.

The above model assumes a linear relationship between the level of production and the emission of waste. While this approximation may come close to the reality in many cases, it appears rather hard to imagine for the generation of bulky wastes such as car wrecks and waste appliances, except under special circumstances.

[1] Still, my computation did not take account of energy requirements for the construction of an additional landfill capacity, which could outweigh the energy requirements for composting.

A generalization of the model to accommodate for the process over time of the transformation of durable goods into wastes is an important future direction for research.

References

[1] A. Adriaanse et al. *Resource Flows: the material basis of industrial economies*. World Resource Institute, Washington, D.C., 1997.

[2] T. Matsuto, N. Tanaka, and Y. Kim. Energy, cost, and environmental impact nalysis of five RDF production facilities. *Journal of the Japan Society of Waste Management Experts*, 7(2):68–77 (In Japanese), March 1996.

[3] S. Nakamura. A linear economic model of waste cycles. *mimeo* (In Japanese), September 1998.

[4] F. Nikaido. *Introduction to Sets and Mappings in Modern Economics*. North-Holland, Amsterdam, 1970 (the Japanese original, Tokyo, 1960).

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