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NAKAMURA Shinichiro and KONDO Yasushi

No. 0204

July 2002

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NAKAMURA Shinichiro and KONDO Yasushi
School of Political Science and Economics, Waseda University,
1-6-1 Nishi-waseda, Shinjuku-ku, Tokyo, 169-8050 Japan

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Abstract

Any economic activity generates waste of some kind. The conventional input-output analysis (IOA), however, does not take into account the interdependence between the flow of goods and the flow of waste. We elsewhere introduced the concept of Waste Input-Output (WIO) that properly takes into account this interdependence (Nakamura (1999), Nakamura and Kondo (2002)). The WIO generalizes the Leontief-Duchin type environmental IO model to make it applicable to waste management issues. Effects of a waste management policy that is environmentally sound cannot be materialized unless its introduction is also economically affordable. An analytical tool is required that can evaluate Life-Cycle-Costs of a waste management policy within the framework of WIO. We develop a model of cost and price that is dual to the WIO quantity model. In the conventional IOA, a cost and price model that is dual to the quantity model can easily be obtained in an obvious fashion. For WIO, however, this is not the case because of the presence of joint products that refer to the sale and purchase of recovered waste materials. Explicit consideration of the sale and purchase of recovered waste materials is a distinguishing feature of the WIO price model. The model is empirically implemented using Japanese data, and applied to evaluate the effects of regionally concentrating incineration facilities. It is found that while regional concentration can be effective in reducing the emission of CO_2 and the consumption of landfill capacity, the associated economic cost is substantial unless the efficiency of waste transport is significantly improved.

keywords: waste input-output model, waste treatment cost, regional disposal, duality
e-mail: S. Nakamura: `nakashin@waseda.jp`, Y. Kondo: `ykondo@waseda.jp`

1 Introduction

Any economic activity generates waste of some kind, which needs to be subjected to treatment before it is finally discharged into the environment. Corresponding to any flow of goods among different sectors of the economy, there thus exists the associated flow of waste involving waste treatment sectors. The input-output analysis (IOA) was originally developed to represent the intersectoral flow of goods, but not the flow of waste associated with it. Consequently, in its conventional form, the IOA is not able to take account of the interaction between the flow of goods and waste.

Leontief (1970, 1972) extended the conventional IOA to take into account the emission of pollutants, their abatement activity, and the interdependence between conventional goods-producing sectors and pollution abatement sectors. With regard to its relevance to issues of waste management, the Leontief environmental IO (EIO) model can be characterized by the existence of a strict one-to-one correspondence between a pollutant (waste) and its abatement (waste treatment) method (Nakamura and Kondo (2002)). The same applies to Duchin (1990), who extended the EIO to take account of the generation of treatment residue that is subjected to final disposal into water. Three implications follow from this. First, the number of waste types must equal the number of treatment methods. Secondly, a joint treatment of multiple pollutants in a single abatement process is excluded. Thirdly, a joint application of multiple treatment methods to a single pollutant (waste) is also excluded.

In waste management, the joint treatment of a wide range of different types of waste in a single treatment method is commonly observed. For instance, any solid waste can be landfilled and any flammable waste can be incinerated. On the other hand, a wide range of different treatment methods can be applied to a given type of waste. For instance, kitchen waste could be subjected, among others, to composting, biogasification, incineration, and/or landfilling. In short, the one-to-one correspondence between waste types and treatment methods does not hold in the empirically relevant case of waste management that involves a large number of waste types and treatment methods. The one-to-one correspondence assumed in the Leontief EIO model is not consistent with the reality of waste management.

With the aim of making the EIO model applicable to waste management issues, we elsewhere developed a new model called Waste Input-Output (WIO for short) (Nakamura (1999), Nakamura and Kondo (2002)). It can deal with an arbitrary combination of treatment methods applied to an arbitrary combination of waste types, provided that the combinations are technically feasible. The number of waste types and treatment methods can be set arbitrarily, and are not required to be equal. Furthermore, it can take account of waste generated from virtually any waste source in the economy including municipal solid waste (MSW) from final demand sectors, industrial and commercial waste from the goods- and service-producing sectors, and treatment residues from waste treatment sectors.

The WIO model in its original form deals with the quantitative aspect of the interdependence between goods and waste, but it does not consider the aspect of cost and price associated with it. However sound a waste management program or policy is from the point of view of environmental considerations, it cannot be widely introduced into the economy unless it is also economically affordable. Without a wide ranging introduction, its environmental effectiveness cannot be realized.

With this in mind, we develop a model of cost and price that is dual to the WIO quantity model. In the conventional IOA, a cost and price model that is dual to the quantity model can be obtained in an obvious fashion. In the case of WIO, however, this is not the case because of the presence of wastes as joint products and the sale and purchase of waste materials. Explicit consideration of the sale and purchase of recovered waste materials is a distinguishing feature of the WIO model. As illustration, we apply the WIO quantity and price model to evaluate the regional concentration of incineration facilities in Japan.

The structure of the paper is as follows. The first part of Section 2 gives a breif summary of the WIO model to readers who are unfamiliar with it. We then proceed in the second part of Section 2 to the derivation of the cost and price counterpart of the WIO model, which is the main topic of this paper. Section 3 then shows the empirical results obtained by applying the Japanese WIO model to an evaluation of the regional concentration of waste incinerators. Concluding remarks close the paper.

2 The Waste Input-Output Model

2.1 The Quantity Model

Let there be n^{I} goods- and service-producing sectors (henceforth "goods sector"), n^{II} waste treatment sectors, n^{w} waste types, and $n := n^{\text{I}} + n^{\text{II}}$. For ease of exposition, we define the sets of natural numbers referring to each of these sectors and waste types by $N^{\text{I}} := \{1, \ldots, n^{\text{I}}\}$, $N^{\text{II}} := \{n^{\text{I}}+1, \ldots, n^{\text{I}}+n^{\text{II}}\}$, $N := N^{\text{I}} \cup N^{\text{II}}$, and $N^{\text{w}} := \{1, \ldots, n^{\text{w}}\}$. We then denote, for sector j ($j \in N$), its output by x_j, the input from sector i ($i \in N$) by X_{ij}, the generation of waste k ($k \in N^{\text{w}}$) by $W^{\oplus}_{kj}$ and the input of waste k by $W^{\ominus}_{kj}$. For a waste treatment sector, its "output" is measured by the amount of waste it treated. Similarly, we denote the final demand for i ($i \in N$) by X_{iF}, the generation of waste k ($k \in N^{\text{w}}$) from the final demand sector by $W^{\oplus}_{kF}$, and the input of waste k into the final demand sector by $W^{\ominus}_{kF}$. We denote by $W_{kj} := W^{\oplus}_{kj} - W^{\ominus}_{kj}$ the net generation of waste k from sector j. When $W_{kj} > 0$, sector j generates a greater amount of waste k than it uses as input, and creates a positive demand for waste treatment. On the other hand, when $W_{kj} < 0$, sector j reduces the amount of waste k that has to be treated as waste. The sum of W_{kj}'s for all j, w_k, then gives the total amount of waste k that undergoes waste treatment.

We then have the following equations for the output of goods, the amount of waste treatment, and net generation of waste:

$$x_i = \sum_{j \in N^{\text{I}}} X_{ij} + \sum_{j \in N^{\text{II}}} X_{ij} + X_{i\text{F}} \quad (i \in N^{\text{I}}), \tag{1}$$

$$x_l = \sum_{j \in N^{\text{I}}} X_{lj} + \sum_{j \in N^{\text{II}}} X_{lj} + X_{l\text{F}} \quad (l \in N^{\text{II}}), \tag{2}$$

$$w_k = \sum_{j \in N^{\text{I}}} W_{kj} + \sum_{j \in N^{\text{II}}} W_{kj} + W_{k\text{F}} \quad (k \in N^{\text{W}}). \tag{3}$$

The output x_i ($i \in N^{\text{I}}$) of goods sectors can be measured in terms of their specific units. In terms of waste, however, we assume that each type is measured by a common unit, that is, in weight. Accordingly, the output x_i ($i \in N^{\text{II}}$) of a waste treatment sector is also measured in weight. Because waste needs to be treated, the total amount of waste for treatment must equal the total output of the waste treatment sectors:

$$\sum_{k \in N^{\text{W}}} w_k = \sum_{j \in N^{\text{II}}} x_j. \tag{4}$$

Let a_{ij} be the conventional input coefficient, $g^{\oplus}_{kj} := W^{\oplus}_{k}/x_j$ be the waste generation coefficient, $g^{\ominus}_{kj} := W^{\ominus}_{kj}/x_j$ be the waste input coefficient, and $g_{kj} := g^{\oplus}_{kj} - g^{\ominus}_{kj}$ be the net waste generation coefficient where $k \in N^{\text{W}}$, $j \in N$. Using these coefficients, (1), (2) and (3) can be written as

$$x_i = \sum_{j \in N^{\text{I}}} a_{ij}x_j + \sum_{j \in N^{\text{II}}} a_{ij}x_j + X_{i\text{F}} \quad (i \in N^{\text{I}}),$$

$$x_l = \sum_{j \in N^{\text{I}}} a_{lj}x_j + \sum_{j \in N^{\text{II}}} a_{lj}x_j + X_{l\text{F}} \quad (l \in N^{\text{II}}),$$

$$w_k = \sum_{j \in N^{\text{I}}} g_{kj}x_j + \sum_{j \in N^{\text{II}}} g_{kj}x_j + W_{k\text{F}} \quad (k \in N^{\text{W}}),$$

or in an obvious matrix notations as

$$x_{\text{I}} = A_{\text{I,I}}x_{\text{I}} + A_{\text{I,II}}x_{\text{II}} + X_{\text{I,F}}, \tag{5}$$

$$x_{\text{II}} = A_{\text{II,I}}x_{\text{I}} + A_{\text{II,II}}x_{\text{II}} + X_{\text{II,F}}, \tag{6}$$

$$w = G_{\cdot,\text{I}}x_{\text{I}} + G_{\cdot,\text{II}}x_{\text{II}} + W_{\cdot,\text{F}}. \tag{7}$$

With the aim of obtaining an IO model that is capable of analyzing issues of waste management and recycling, Nakamura (1999) and Nakamura and Kondo (2002) developed the Waste IO (WIO) model. In terms of WIO, the solution of the above system of equations is given by

$$\begin{pmatrix} x_{\text{I}} \\ x_{\text{II}} \end{pmatrix} = \left(I - \begin{pmatrix} A_{\text{I,I}} & A_{\text{I,II}} \\ SG_{\cdot,\text{I}} & SG_{\cdot,\text{II}} \end{pmatrix} \right)^{-1} \begin{pmatrix} X_{\text{I,F}} \\ SW_{\cdot,\text{F}} \end{pmatrix}, \tag{8}$$

where S is an $n^{\text{II}} \times n^{\text{W}}$ non-negative allocation matrix whose (i, j)-component s_{ij} represents the share of waste j that is treated by treatment method i. The environmental IO (EIO) model of Leontief (1970, 1972) and Duchin (1990) corresponds to a special case of (8) where S is an identity matrix of order n^{II}. Implicit in the EIO model is the assumption that there exists for each pollutant one and only one abatement method that treats no other pollutant but that pollutant. This condition is hardly applicable to the reality of waste management because, in general, there is no one-to-one correspondence between a waste and its treatment method. It is usually the case that a multiplicity of treatment methods can be applied to a given solid waste, either separately or jointly. For instance, garbage can be composted, gasified, incinerated, and/or landfilled. Any of these methods can be applied separately or in combination. On the other hand, any solid waste can be landfilled (MacDonald 1996).

The WIO represents a significant generalization over the EIO as for its implications for waste management. First, because the allocation matrix S is not required to be square, the condition $n^{\text{II}} = n^{\text{w}}$ is no longer necessary. The number of waste types and that of treatment methods can be arbitrary. Secondly, it can handle the case where a single treatment method is applied to multiple types of waste, because each row of S can contain more than one non-zero element. Third, it can handle the case where several treatment methods are jointly applied to a single type of waste, because each column can contain more than one non-zero element. These cases were excluded in the EIO model (see Nakamura and Kondo (2002) for further details of the WIO quantity model).

Let there be n^{E} types of emissions under consideration. Write $\Gamma_{\cdot,\text{I}}$ for an $n^{\text{E}} \times n^{\text{I}}$ matrix of the emissions from a unit of output in goods sectors and $\Gamma_{\cdot,\text{II}}$ for an $n^{\text{E}} \times n^{\text{II}}$ matrix of the emissions from a unit of output in waste treatment sectors. The vector of total emissions e is then given by

$$e = \Gamma \left(I - \begin{pmatrix} A_{\text{I},\text{I}} & A_{\text{I},\text{II}} \\ SG_{\cdot,\text{I}} & SG_{\cdot,\text{II}} \end{pmatrix} \right)^{-1} \begin{pmatrix} X_{\text{I},\text{F}} \\ SW_{\cdot,\text{F}} \end{pmatrix} + E_{\cdot,\text{F}}, \tag{9}$$

where $\Gamma = (\Gamma_{\cdot,\text{I}}, \Gamma_{\cdot,\text{II}})$, and $E_{\cdot,\text{F}}$ refers to the direct emission from the final demand sector. This gives a WIO based generalization of the conventional EIO, a recent example of which is Joshi (2000).

2.2 The WIO Price Model

2.2.1 The Definition of Cost

We now turn to the aspect of cost and price of the WIO model. Let p_j be the price of output of sector j ($j \in N$), p_k^{w} be the price of waste $k \in N^{\text{w}}$, V_j be the cost for primary factors of production that includes depreciations as well as taxes less subsidies, and $R_{kj} > 0$ be the quantity of waste $k \in N^{\text{w}}$ that was used as an input in sector $j \in N \cup \{\text{F}\}$. This explicit consideration of the sale and purchase of recovered waste materials distinguishes the definition of costs in the WIO from that of the conventional IOA. The sale of recovered waste materials is an important source of revenue for waste recyclers. A typical example is the disassembly of discarded automobiles, the major revenue source of which has been the sale of scrap metal to steel makers operating electric arc furnaces.

There are, however, cases where the price of waste materials is negative, that is, waste materials are "accepted" with a charge by the user. For instance, some Japanese steel makers operating blast furnaces accept waste plastics with a charge and use them as reduction agents together with pulverized coal. Another example is the acceptance with charge of scrap tires and waste plastics in some Japanese cement makers who use them as supplementary heat sources in the kiln. The price of waste can thus become negative. Based on its sign condition, three cases can be distinguished: the waste is valuable when $p_k^{\text{w}} > 0$; it has no value but can be accepted by other sectors as input with no charge when $p_k^{\text{w}} = 0$; and it has no value and its acceptance needs a positive charge when $p_k^{\text{w}} < 0$. Henceforth, R_{kj} is called "sale of waste" regardless of whether the price of waste k is positive, zero, or negative.

In the input-output account system we have the identity that equates the value of output to the total cost. Considering the trade of waste, this identity can be given for sector j ($j \in N$) by:

$$p_j x_j = \underbrace{\sum_{i \in N^{\text{I}}} p_i a_{ij} x_j}_{\text{(a)}} + \underbrace{\sum_{l \in N^{\text{II}}} p_l \sum_{k \in N^{\text{w}}} s_{lk}(g_{kj}^{\oplus} x_j - R_{kj})}_{\text{(b)}} + \underbrace{\sum_{k \in N^{\text{w}}} p_k^{\text{w}} g_{kj}^{\ominus} x_j}_{\text{(c)}} - \underbrace{\sum_{k \in N^{\text{w}}} p_k^{\text{w}} R_{kj}}_{\text{(d)}} + \underbrace{V_j}_{\text{(e)}}. \tag{10}$$

The cost can be decomposed into five parts: (a) the cost for the input of goods, (b) the cost for waste treatment, (c) the cost for the input of waste materials, (d) the revenue from the sale of waste materials, and (e) the cost for the input of primary factors. The terms (b), (c), and (d) are unique to the WIO-price model. When there is no recycling, $R_{kj} = 0$ holds for all k and j, and the terms (c) and (d) vanish, while the term (b) reduces to the treatment cost of wastes generated in the sector. The term (b) indicates that the amount of waste for treatment is reduced by the amount of R_{kj}.

The sale of waste materials at positive prices can reduce the cost of production or treatment in two ways. First, it can reduce the cost directly by creating a new source of revenue other than the sale of "main" output. The term (d) refers to this component. Secondly, it can reduce the waste treatment cost that would have been necessary if the waste materials were not sold but had to be treated at a positive charge. The term (b) refers to this component. On the other hand, the sale of waste at negative prices reduces the production cost of the sectors that use the waste as input.

Rearranging the terms yields the following expression, which shows the contribution of the sale of waste materials to the cost in a more explicit way

$$p_j x_j = \underbrace{\sum_{i \in N^{\text{I}}} p_i a_{ij} x_j}_{\text{(a)}} + \underbrace{\sum_{l \in N^{\text{II}}} p_l \sum_{k \in N^{\text{w}}} s_{lk} g^{\oplus}_{kj} x_j}_{\text{(f)}} + \underbrace{\sum_{k \in N^{\text{w}}} p^{\text{w}}_k g^{\ominus}_{kj} x_j}_{\text{(c)}} - \underbrace{\sum_{k \in N^{\text{w}}} \left(p^{\text{w}}_k + \sum_{l \in N^{\text{II}}} p_l s_{lk} \right) R_{kj}}_{\text{(g)}} + V_j, \tag{11}$$

Here, the term (f) refers to the waste treatment cost that would have been necessary if no waste materials were sold. When waste is sold to other sectors, it can affect the cost via the term (g). The extent to which the cost can be reduced by the sale of waste depends on the sign condition of the expression inside the parentheses of (g). When $p^{\text{w}}_k > 0$, the sale of waste certainly reduces the cost of production. It is important to note that even if $p^{\text{w}}_k \leq 0$, the sale of waste could reduce the cost as long as the following condition is satisfied:

$$p^{\text{w}}_k + \sum_{l \in N^{\text{II}}} p_l s_{lk} > 0 \iff | p^{\text{w}}_k | = -p^{\text{w}}_k < \sum_{l \in N^{\text{II}}} p_l s_{lk}. \tag{12}$$

This refers to the case where the sale of wastes to other sectors at negative prices costs less than submitting it to waste treatment.

2.2.2 System of Price Equations

While the term R_{kj} plays a vital role in the cost equation (11), it does not occur in the system of equations for the quantity model (8). Our task now is to establish the relationship between R_{kj} and the elements occuring in (8). Let R_{kji} be the amount of waste k generated by j ($j \in N \cup \{\text{F}\}$) that was used as input in sector i ($i \in N$). It then follows by definition

$$R_{kj} = \sum_{i \in N} R_{kji}. \tag{13}$$

Here, we assumed $W^{\ominus}_{k\text{F}} = 0$; the household does not "directly" engage in recycling in the sense that it does not directly use waste, while they would indirectly engage in recycling by purchasing goods made of recovered waste or produced by using waste heat. The input of waste k into sector i can then be represented as:

$$W^{\ominus}_{ki} = g^{\ominus}_{ki} x_i = \sum_{j \in N \cup \{\text{F}\}} R_{kji}. \tag{14}$$

Suppose that the classification of waste is detailed enough such that the user (recycler) of a given type of waste is indifferent to its origin. Of waste k used in sector i, the portion that originates from sector j would then be proportional to the share of sector j in the total generation of that waste, $W^{\oplus}_{kj} \,/\, W^{\oplus}_k$. Accordingly, we obtain the following expression for the amount of waste k that is generated in sector j and is used in sector i:

$$R_{kji} = W^{\ominus}_{ki} (W^{\oplus}_{kj} \,/\, W^{\oplus}_k). \tag{15}$$

It then follows from (13) and (15)

$$R_{kj} = \sum_{i \in N} R_{kji} = \sum_{i \in N} W^{\ominus}_{ki} (W^{\oplus}_{kj} \,/\, W^{\oplus}_k) = W^{\oplus}_{kj} (W^{\ominus}_k \,/\, W^{\oplus}_k) =: W^{\oplus}_{kj} r_k,$$

where r_k refers to the rate of recycling of waste k with $r_k := W_k^{\ominus}/W_k^{\oplus}$, and the third equality follows from $\sum_{i \in N} W_{ki}^{\ominus} = W_k^{\ominus}$. Recalling the definition of $W_{kj}^{\oplus}$, we obtain

$$R_{kj} = W_{kj}^{\oplus} r_k = g_{kj}^{\oplus} x_j r_k. \tag{16}$$

Insertion of (16) into (11) yields the following expression of the cost equation:

$$\begin{aligned} p_j x_j = & \sum_{i \in N^{\mathrm{I}}} p_i a_{ij} x_j + \sum_{l \in N^{\mathrm{II}}} p_l \sum_{k \in N^{\mathrm{w}}} s_{lk} g_{kj}^{\oplus} x_j \\ & + \sum_{k \in N^{\mathrm{w}}} p_k^{\mathrm{w}} g_{kj}^{\ominus} x_j - \sum_{k \in N^{\mathrm{w}}} \Big(p_k^{\mathrm{w}} + \sum_{l \in N^{\mathrm{II}}} p_l s_{lk} \Big) r_k g_{kj}^{\oplus} x_j + V_j. \end{aligned}$$

Division of both the sides by x_j yields the following price equation:

$$p_j = \sum_{i \in N^{\mathrm{I}}} p_i a_{ij} + \sum_{l \in N^{\mathrm{II}}} p_l \sum_{k \in N^{\mathrm{w}}} s_{lk} g_{kj}^{\oplus} + \sum_{k \in N^{\mathrm{w}}} p_k^{\mathrm{w}} g_{kj}^{\ominus} - \sum_{k \in N^{\mathrm{w}}} \Big(p_k^{\mathrm{w}} + \sum_{l \in N^{\mathrm{II}}} p_l s_{lk} \Big) r_k g_{kj}^{\oplus} + v_j, \tag{17}$$

where v_j refers to the mean price of primary inputs used in sector j.

Using obvious matrix notations, (17) can be rewritten as

$$\begin{aligned} \begin{pmatrix} p_{\mathrm{I}} & p_{\mathrm{II}} \end{pmatrix} = & \begin{pmatrix} p_{\mathrm{I}} & p_{\mathrm{II}} \end{pmatrix} \begin{pmatrix} A_{\mathrm{I,I}} & A_{\mathrm{I,II}} \\ S(I-D)G_{\mathrm{I}}^{\oplus} & S(I-D)G_{\mathrm{II}}^{\oplus} \end{pmatrix} \\ & + p^{\mathrm{w}} \begin{pmatrix} G_{\mathrm{I}}^{\ominus} - DG_{\mathrm{I}}^{\oplus} & G_{\mathrm{II}}^{\ominus} - DG_{\mathrm{II}}^{\oplus} \end{pmatrix} + \begin{pmatrix} v_{\mathrm{I}} & v_{\mathrm{II}} \end{pmatrix}, \end{aligned} \tag{18}$$

where $p = (p_{\mathrm{I}}, p_{\mathrm{II}}) = (p_1, \ldots, p_n)$, $v = (v_{\mathrm{I}}, v_{\mathrm{II}}) = (v_1, \ldots, v_n)$, $p^{\mathrm{w}} = (p_1^{\mathrm{w}}, \ldots, p_{n^{\mathrm{w}}}^{\mathrm{w}})$, D is a diagonal matrix whose k-th diagonal component is r_k, i.e., $D = \mathrm{diag}(r_1, \ldots, r_{n^{\mathrm{w}}})$, and I is an identity matrix of an appropriate order. This can be further rewritten in a more compact way as

$$p = p \begin{pmatrix} A_{\mathrm{I},\cdot} \\ S(I-D)G^{\oplus} \end{pmatrix} + p^{\mathrm{w}}(G^{\ominus} - DG^{\oplus}) + v \tag{19}$$

Provided it is possible to solve (19) for p, this solution can be given by

$$p = \left\{ p^{\mathrm{w}}(G^{\ominus} - DG^{\oplus}) + v \right\} \left(I - \begin{pmatrix} A_{\mathrm{I},\cdot} \\ S(I-D)G^{\oplus} \end{pmatrix} \right)^{-1}. \tag{20}$$

Recall from (8) that the solution of the WIO quantity model is given by

$$x = \begin{pmatrix} x_{\mathrm{I}} \\ x_{\mathrm{II}} \end{pmatrix} = \left(I - \begin{pmatrix} A_{\mathrm{I},\cdot} \\ S(G^{\oplus} - G^{\ominus}) \end{pmatrix} \right)^{-1} \begin{pmatrix} X_{\mathrm{I},F} \\ S(W_F^{\oplus} - W_F^{\ominus}) \end{pmatrix}. \tag{21}$$

Comparing the inverse matrices occurring in (20) and (21), we find that the latter reduces to the former for arbitrary S and D only if $DG^{\oplus} = G^{\ominus}$ holds, that is the following holds:

$$r_k g_{kj}^{\oplus} = g_{kj}^{\ominus} \quad (k \in N^{\mathrm{W}},\ j \in N). \tag{22}$$

Under this condition, each sector is self-sufficient with respect to waste materials it requires, and hence the sale of waste to other sectors does not occur. The solution (20) then reduces to

$$p = v \left(I - \begin{pmatrix} A \\ S(G^{\oplus} - G^{\ominus}) \end{pmatrix} \right)^{-1}, \tag{23}$$

which corresponds to a dual price model in the conventional IOA. Note that (22) includes the case where there is no recycling of waste at all, that is $r_k = 0$ for all k.

3 Application: the Effects of Concentrated Treatment

3.1 Scenarios and setups

We developed a WIO model for Japan using Japanese IO tables for 1995, data on waste generation and recycling, and engineering information on waste treatment methods. The compiled WIO table comprises seventy-eight industry sectors (see Table 2 below), five basic treatment methods (composting, gasification, shredding, incineration, and landfilling), thirty-four waste types, and nine types of bulky waste (see Table 4 below). Incineration was further distinguished into several types depending on the size of incinerators, methods of energy recovery, and the treatment of incineration residues (see Nakamura and Kondo (2002) for details).

The WIO model is now applied to evaluate the economic and environmental effects of regional concentration of treatment where a large number of small incinerators is replaced by a smaller number of large incinerators. Table 1 shows the capacity share distribution of incinerators in terms of three representative incinerator types which are distinguished by size, continuity of operation, and the utilization of waste heat. The largest one, with a daily capacity of around 500 tons, Type I, is operated 24 hours a day, generates power from waste heat, and is equipped with a melting and solidification facility of incineration residues. The incinerator of middle size (around 180 tons per day), Type II, is also operated 24 hours a day, but does not generate power, and is not equipped with the facility for melting and solidification of incineration residues. The smallest one, Type III, is of a batch type that is operated only for a limited period of day.

Table 1 shows three distribution patterns. First, panel A shows the estimated pattern as of 1995 in Japan, where 34% of waste for incineration is allocated to Type I, 15% to Type II, and the remaining 51% to Type III. Panel B shows a hypothetical case of regional concentration where the MSW treated by Type II and Type III under A are entirely shifted to treatment by Type I incinerators. This corresponds to 31% of waste that was treated by Type III incinerators and 100% of that treated by Type II incinerators. The total number of incinerators is then reduced to about 70% of the 1995 level given by pattern A.

Panel C shows another hypothetical case where regional concentration is extended to all solid waste including both MSW and industrial waste. All the waste is then treated by Type I incinerators, and the total number of incinerators is reduced to 13% of the 1995 level. Note that in the WIO these "scenarios" can be represented by the allocation matrix. For instance, under scenario B, 65% of waste for incineration is allocated to Type I and the rest is allocated to Type III, whereas under scenario C 100% of waste is allocated to Type I.

Note that each of these scenarios can be represented by the allocation matrix. For instance, let S_B be the allocation matrix that corresponds to scenario B where 65% of waste for incineration is allocated to Type I and the rest is allocated to Type III. The level of sectoral output, emission, and the price of output that corresponds to scenario B can then be obtained by substituting S_B for S in (8), (9) and (19).

Because the number of incinerators is reduced under concentrated treatment, the portion of waste that is shifted to Type I incinerators has to be transported over longer distances than under A. Three simplifying assumptions are introduced with regard to waste transport. First, we assume that the mean distance of waste transportation under A is 12 km regardless of the type of incinerators (this is the default value used in Tanaka and Matsuto (1998)); large incinerators were used in areas of high population density, while smaller ones were used in areas of low density. Secondly, the size of the area covered by an incinerator is assumed to increase in proportion to the size of the incinerator. Thirdly, it is assumed that the transport distance of waste within the area is proportional to the square root of the area. It then follows that the shift from Type II to Type I increases the area covered by an incinerator by $500 \div 180 \approx 2.78$ times, and that the transport distance within the area becomes $12\,\text{km} \times \sqrt{500/180} = 20\,\text{km}$. Similarly, the shift of waste from Type III to Type I results in a transport distance of $12\,\text{km} \times \sqrt{500/26} \approx 52.6\,\text{km}$. Once the transport distance is determined in this way, we obtained the estimates of the required number of vehicles, their repair and maintenance, fuel, and personnel from an engineering model (Tanaka and Matsuto (1998)).

3.2 Results

We use the solution under A as the reference value, and report the results as rate of change relative to the reference solution in percentages. First, Table 2 shows the effects of regional concentration on sectoral output. We find that regional concentration reduces output in the majority of sectors; of eighty sectors, this applies to sixty-six sectors under B and to seventy-two sectors under C. The largest rate of reduction occurs in electric power generation (−1.5% under B and −3.2% under C), followed by coal products and other mining, which provide fuel for power generation. This reduction in electric power generation results from the increase in power generation from waste heat as a consequence of concentrated treatment. Recall that the Type I incinerator generates electric power from waste heat. While the level of output decreases in the majority of sectors, there are also sectors where the opposite is the case. This is the case for the sectors that are closely related to waste transport such as repair of vehicles (.1% under B and .3% under C) and rubber products.

It is interesting to note that in spite of the increase in waste transport, the overall demand for petroleum refinery products decreases (−.04% under B and −.07% under C). This implies that the increase in the demand for petroleum products that results from the increase in waste transport is more than offset by the decrease in the demand for petroleum products induced by the decrease in conventional electric power generation.

In fact, Table 3 shows that concentrated treatment reduces the overall emission of CO_2 by 0.4% under B and by 0.8% under C. From Table 3 we also find that concentrated treatment reduces landfill consumption by 0.4% in weight and 0.6% in volume under B and by 0.9% in weight and 1.3% in volume under C. Looking for factors behind the reduction in landfill consumption requires information on the net emission of individual waste items. This is given in Table 4. We find that concentrated treatment significantly reduces the generation of incineration ash and dust, while it increases the generation of molten slag. In particular, under C, incineration ash is reduced by more than 60% relative to the 1995 level, while molten slag is increased by more than 60%. Recall that in incinerators of Type I, incineration ash is transformed into molten slag. This transformation reduces the amount of final residue by 10% in weight and by 50% in volume. Also responsible for the reduction in landfill consumption, while to a lesser extent, is the generation of dust (flyash) from electric power generation due to the above-mentioned reduction in power generation.

Concentrated treatment thus appears effective in reducing both CO_2 emission and landfill consumption. Table 3 shows, however, that this *benefit* has its cost: the mean cost of incineration per ton of waste increases by 7% under B and by 35% under C. Largely responsible for this increase in cost is the increase in labor cost associated with waste transport. Table 3 indicates that the overall level of labor requirement in the Japanese economy increases by 0.02% under B and by 0.06% under C.

3.3 Discussion

Because of its high population density and the scarcity of flat areas, landfill capacity is a scarce resource in Japan. The saving of its consumption is hence of great importance, and needs to be pursued with diligence, while keeping consistent with the efforts to reduce CO_2 emission from fossil fuel origins. Our results indicate that concentration of incineration to a small number of large facilities with efficient energy recovery is effective in meeting this objective. The economic cost associated with this policy, however, could be quite substantial, largely owing to the increase in the cost of waste transport. Improving the efficiency of waste transport seems important to make this environmentally sound policy also economically affordable.

4 Concluding Remarks

With the increased awareness of environmental issues all over the world, waste management is expected to play an ever-increasing role in our society. For a waste management program to be sustainable, it needs, among other things, to be environmentally sound and economically affordable (McDougall et al. (2001)).

Given that waste is matter and is subject to the law of mass conservation, in designing a waste management program it is vital to consider the mutual interdependence between the flow of goods and waste from the perspective of a whole system. In this regard, input-output analysis is expected to play a central role in providing a basic analytical framework. The Waste Input-Output model was developed to meet this expectation.

We presented a dual counterpart of the WIO quantity model that could be used for evaluating life-cycle costings of a particular waste management program or policy. Its application to issues of regional concentration of incineration facilities in Japan indicated that while it can be environmentally sound the associated economic cost could be substantial unless measures are taken to increase the efficiency of waste transport.

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Table 1: Distribution of incinerators by types

Incinerator types	I	II	III
Properties of incinerators			
Size [ton/day]	500	180	30
Operation	Full continuous	Full continuous	Batch
Melting of residue	Yes	No	No
Power from waste heat	Yes	No	No
Scenarios			
A. Reference: as of 1995			
Capacity share	0.343	0.144	0.513
Plants	145	169	4177
B. Concentrated treatment of MSW			
Capacity share	0.650	0	0.350
Plants	274	0	2876
C. Concentrated treatment of MSW and industrial waste			
Capacity share	1.0	0	0
Plants	423	0	0

Includes both MSW and industrial waste. Source: Nakamura and Kondo (2002).

Table 2: Effects of Concentrated Treatment on Sectoral Output (continued)

Objects of Concentrated Treatment					
	Miunicipal solid waste only			Miunicipal & industrial waste	
62	Electric power	−1.451	62	Electric power	−3.123
21	Coal products	−0.511	21	Coal products	−1.090
7	Other mining	−0.303	7	Other mining	−0.639
76	Machine repair	−0.180	76	Machine repair	−0.382
73	Education, Research institutes	−0.046	65	Water supply	−0.125
20	Petroleum refinery products	−0.043	73	Education, Research institutes	−0.092
65	Water supply	−0.043	20	Petroleum refinery products	−0.070
48	Other non-ferrous metal products	−0.029	48	Other non-ferrous metal products	−0.056
80	Activities not elsewhere classified	−0.027	80	Activities not elsewhere classified	−0.054
60	Construction	−0.025	60	Construction	−0.053
50	Metal products for architecture	−0.022	50	Metal products for architecture	−0.047
79	Office supplies	−0.020	12	Timber and wooden products	−0.041
12	Timber and wooden products	−0.019	79	Office supplies	−0.039
17	Publishing and printing	−0.019	17	Publishing and printing	−0.039
71	Other transport and communication	−0.017	71	Other transport and communication	−0.035
13	Wooden furniture and accessories	−0.016	13	Wooden furniture and accessories	−0.034
70	Road transport	−0.015	70	Road transport	−0.030
78	Other services	−0.014	78	Other services	−0.030
15	Paper and paper board	−0.014	15	Paper and paper board	−0.027
14	Pulp	−0.013	14	Pulp	−0.026
64	Steam and hot water supply	−0.013	49	Metal products for construction	−0.026
49	Metal products for construction	−0.012	64	Steam and hot water supply	−0.025
3	Silviculture	−0.012	3	Silviculture	−0.025
45	Rolled and drawn aluminum	−0.010	45	Rolled and drawn aluminum	−0.018
28	Pottery and other earthenware	−0.009	28	Pottery and other earthenware	−0.017
51	Other metal products	−0.009	27	Cement and cement products	−0.017
27	Cement and cement products	−0.008	16	Converted paper products	−0.016
16	Converted paper products	−0.008	69	Railway transport	−0.014
5	Materials for ceramics	−0.008	67	Wholesale trade	−0.013
67	Wholesale trade	−0.008	5	Materials for ceramics	−0.013

The three-digit numbers refer to the rate of change relative to the reference solution in percentage.
The sectors are arranged according to ascending order with regard to the rate of change.

Table 2: Effects of Concentrated Treatment on Sectoral Output (concluded)

Objects of Concentrated Treatment					
	Miuniciapl solid waste only			Miuniciapl & industrial waste	
69	Railway transport	−0.007	6	Gravel and quarry	−0.011
39	Lead and Zinc (inc. regenerated lead)	−0.006	51	Other metal products	−0.011
6	Gravel and quarry	−0.005	57	Other transportation equipment	−0.010
37	Cast and forge materials (iron)	−0.005	53	Household electric appliances	−0.009
34	Steel pipes	−0.005	59	Other manufacturing	−0.008
40	Aluminum (inc. regenerated aluminum)	−0.005	43	Optical fiber cables	−0.007
57	Other transportation equipment	−0.005	63	Gas	−0.006
41	Other non-ferrous metals	−0.004	11	Wearing apparel and textile products	−0.005
33	Hot rolled steel	−0.004	10	Fabric	−0.005
31	Crude steel (converter)	−0.004	22	Paving materials	−0.005
59	Other manufacturing	−0.004	39	Lead and Zinc (inc. regenerated lead)	−0.005
53	Household electric appliances	−0.004	23	Plastic products	−0.004
35	Steel pipes and tubes	−0.004	54	Other electrical equipment	−0.004
23	Plastic products	−0.004	41	Other non-ferrous metals	−0.004
32	Crude steel (electric arc)	−0.004	66	Sewage treatment	−0.004
29	Pig iron	−0.004	61	Civil engineering	−0.004
30	Ferroalloys	−0.004	25	Leather and fur products	−0.004
63	Gas	−0.003	19	Chemical industry	−0.003
43	Optical fiber cables	−0.003	68	Retail trade	−0.003
54	Other electrical equipment	−0.003	26	Glass and glass products	−0.002
26	Glass and glass products	−0.003	2	Livestock	−0.002
10	Fabric	−0.003	4	Fisheries	−0.002
44	Rolled & drawn copper and copper alloys	−0.003	40	Aluminum (inc. regenerated aluminum)	−0.001
11	Wearing apparel and textile products	−0.003	58	Precision instruments	−0.001
19	Chemical industry	−0.003	1	Agriculture for crops	−0.001
66	Sewage treatment	−0.002	72	Public administration	−0.001
22	Paving materials	−0.002	9	Drinks, feeds, and tobacco fertilizers	−0.001
38	Copper	−0.002	8	Food	−0.001
42	Electric wires and cables	−0.002	74	Medical services and health	0.000
61	Civil engineering	−0.002	47	Nuclear fuels	0.000
25	Leather and fur products	−0.002	55	Passenger cars	0.000
68	Retail trade	−0.001	77	Eating and drinking places	0.000
58	Precision instruments	−0.001	42	Electric wires and cables	0.000
2	Livestock	−0.001	38	Copper	0.001
4	Fisheries	−0.001	34	Steel pipes	0.001
1	Agriculture for crops	−0.001	35	Steel pipes and tubes	0.001
72	Public administration	0.000	18	Chemical fertilizer	0.001
9	Drinks, feeds, and tobacco fertilizers	0.000	37	Cast and forge materials (iron)	0.002
8	Food	0.000	33	Hot rolled steel	0.002
74	Medical services and health	0.000	31	Crude steel (converter)	0.002
18	Chemical fertilizer	0.000	44	Rolled & drawn copper and copper alloys	0.004
47	Nuclear fuels	0.000	30	Ferroalloys	0.004
55	Passenger cars	0.000	32	Crude steel (electric arc)	0.004
77	Eating and drinking places	0.000	29	Pig iron	0.004
46	Non-ferrous metal castings and forgings	0.005	56	Other cars	0.033
36	Cold-finished steel and coated steel	0.006	46	Non-ferrous metal castings and forgings	0.034
52	General machinery	0.010	36	Cold-finished steel and coated steel	0.042
56	Other cars	0.011	24	Rubber products	0.043
24	Rubber products	0.011	52	General machinery	0.080
75	Repair of motor vehicles	0.106	75	Repair of motor vehicles	0.313

The three-digit numbers refer to the rate of change relative to the reference solution in percentage.
The sectors are arranged according to ascending order with regard to the rate of change.

Table 3: Effects of concentrated treatment on emission, employment and waste treatment

	Objects of Concentrated Treatment	
	Municipal solid waste only	Municipal & industrial waste
CO_2 emission	−0.391	−0.829
Employment	0.016	0.057
Incineration:		
Amount	−0.005	−0.010
Cost per ton	6.928	35.386
Landfill consumption:		
Weight	−0.428	−0.923
Area	−0.579	−1.251
Volume	−0.593	−1.281

The three-digit numbers refer to the rate of change relative to the reference solution in percentage.

Table 4: Effects of Concentrated Treatment on Net Waste Generation

Objects of Concentrated Treatment			
Municipal solid waste		Municipal & industrial waste	
15 Incineration ash	−20.27	15 Incineration ash	−43.82
14 Dust	−1.61	14 Dust	−3.46
23 Construction debris	−0.05	5 Iron scraps	−0.17
19 Inorganic sludge	−0.04	23 Construction debris	−0.11
10 Glass cullet	−0.03	19 Inorganic sludge	−0.09
24 Animal waste	−0.03	24 Animal waste	−0.07
16 Slag	−0.03	10 Glass cullet	−0.06
9 Glass bottles	−0.03	9 Glass bottles	−0.06
5 Iron scraps	−0.02	17 Sawdust & wood chips	−0.04
17 Sawdust & wood chips	−0.02	18 Organic sludge	−0.02
18 Organic sludge	−0.01	2 Waste paper	−0.01
22 Waste alkali	−0.01	22 Waste alkali	−0.01
2 Waste paper	−0.01	4 Waste plastics	−0.01
4 Waste plastics	−0.01	16 Slag	−0.01
21 Waste acid	0.00	21 Waste acid	0.00
13 Animal & vegetable residue	0.00	13 Animal & vegetable residue	0.00
7 Copper scraps	0.00	7 Copper scraps	0.00
25 Carcass	0.00	25 Carcass	0.00
1 Food waste	0.00	1 Food waste	0.00
8 Aluminum scraps	0.00	8 Aluminum scraps	0.00
11 Waste ceramics	0.00	11 Waste ceramics	0.00
26 Bulky waste: textile products	0.00	26 Bulky waste: textile products	0.00
27 Bulky waste: wooden furniture	0.00	27 Bulky waste: wooden furniture	0.00
28 Bicycles & ovens	0.00	28 Bicycles & ovens	0.00
29 Small electric appliances	0.00	29 Small electric appliances	0.00
30 TV sets	0.00	30 TV sets	0.00
31 Refrigerators	0.00	31 Refrigerators	0.00
32 Washing machines	0.00	32 Washing machines	0.00
33 Air conditioners	0.00	33 Air conditioners	0.00
34 Automobiles	0.00	34 Automobiles	0.00
12 Waste rubber	0.00	3 Waste textiles	0.00
3 Waste textiles	0.00	12 Waste rubber	0.00
20 Waste oil	0.01	20 Waste oil	0.02
6 Non-ferrous scraps	0.10	6 Non-ferrous scraps	0.08
35 Molten slag	29.01	35 Molten slag	62.74

The two-digit numbers refer to the rate of change relative to the reference solution in percentage. The wastes are arranged according to ascending order with regard to the rate of change.