Waste Input-Output Linear Programming Model with Its Application to Eco-Efficiency Analysis

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Abstract: This paper is concerned with a decision analytic extension of the waste input-output (WIO) model (Nakamura and Kondo, 2002) based on the method of linear programming. The resulting model, which is named the waste input-output linear programming model, allows one to automatically obtain an "optimal" waste management and recycling strategy from among a given set of alternative feasible strategies. The model can thus explore the extent to which a given measure of eco-efficiency can be maximized by an appropriate combination of existing (technological and resource) potentials. An application to Japanese data is also presented.

Keywords: Waste input-output analysis, Linear programming, Life-cycle assessment, Eco-efficiency

1 Introduction

The purpose of this paper is to present a decision analytic extension of the waste input-output (WIO) model (Nakamura, 1999; Nakamura and Kondo, 2002) based on the method of linear programming (LP), and to propose a systematic method for eco-efficiency analysis. Usefulness of the proposed model and method is also illustrated through an empirical analysis of waste management and recycling strategies in Japan.

The WIO model is an extension of the conventional input-output model in regard to an explicit consideration of the interdependence between the flow of goods and the flow of waste in the whole economy. The WIO model is also a generalization of the Leontief-Duchin environmental input-output (EIO) model (Leontief, 1970, 1972; Duchin 1990) with respect to waste flows; the EIO assumes a strict one-to-one correspondence between waste types and treatment methods while the WIO model does not. The WIO model, therefore, provides a general framework for hybrid life cycle assessment (LCA) of waste management and recycling (see Lave et al. (1995), Hendrickson et al. (1998), Joshi (2000), and Suh (2004), among others, for details of hybrid LCA, and see also Nakamura and Kondo (2002) and Kondo and Nakamura (2004) for hybrid LCA by the WIO model). This paper presents a decision analytic extension of the WIO model, named the waste input-output linear programming (WIO-LP) model. It provides a systematic scheme for choosing an "optimal" waste management and recycling strategy from among alternative feasible ones.

It is known in the literature of eco-efficiency analysis that '*eco-efficiency* may be reserved for the ratio between economy and environment, with environment in the denominator (IEEC, 2004)'; see also WBCSD (2000) in which the term 'eco-efficiency ratio' is used. It accordingly is popular to define an eco-efficiency measure at the macro (nationwide) level as a ratio of the gross domestic product (GDP) to some measure of environmental load such as the direct material input (DMI). However, this type of efficiency, or productivity, measure suffers from several shortcomings. First, it cannot properly take into account issues concerned with the composition of final demand, in particular, household consumption that constitutes the largest part of GDP in most economies. Because a same level of household consumption can be accomplish with many different patterns of expenditure, it is important to pay proper attention not only to the total amount of GDP but also to its composition. Second, eco-efficiency measures such as GDP per DMI are mostly descriptive by nature, and do not provide analytical tool that can be used to assess effects of alternative policies or business strategies on eco-efficiency. These points can be taken care of by using the EIO model. However, EIO has a shortcoming that it cannot deal with the interdependence between the flow of goods (production and consumption) and the associated waste stream (waste management). Because of this, EIO thus is not applicable to evaluate effects of alternative waste management strategies including recycling of waste materials on whatever measure of eco-efficiency.

Our methods for eco-efficiency analysis by the WIO and WIO-LP models presented later can properly take care of all these points. These features enable the method to be used, among others, for evaluating effects of a prolonged product life of home appliances under a particular waste management system, which may not be possible with EIO models. A further distinguishing characteristic of our method is its incorporation of decision analysis based on the method of linear programming that allows one to identify the highest level of eco-efficiency that can be achieved by an "optimal" waste management and recycling strategy.

In Section 2, we briefly review the WIO model and then explain our method for eco-efficiency analysis based upon the WIO model. We develop the WIO-LP model by taking into account the possibility of selection of technologies in Section 3. Based on this theoretical development, we perform an empirical analysis using Japanese data in Section 4. Section 5 concludes the paper.

2 The WIO analysis

In this section, we briefly review the WIO model and then explain the method for eco-efficiency analysis based upon the WIO model. We ignore import and export in this and the next sections to keep notations simple although they are properly dealt with in our empirical analysis as mentioned later. See also Nakamura and Kondo (2002) for detail of the WIO model.

2.1 The WIO model

Let there be n^{I} goods- and service-producing sectors (hereafter "goods sector"), n^{II} waste treatment sectors, n^{W} waste types, and n^{E} types of environmental loads, and define $n = n^{I} + n^{II}$. Let us rewrite the well-known balance equation, $x = A\,x + X_{F}$, in the conventional IO analysis, by partitioning all the n sectors into the n^{I} goods sectors and n^{II} waste treatment sectors, as

$$\begin{bmatrix} x_{I} \\ x_{II} \end{bmatrix} = \begin{bmatrix} A_{I,I} & A_{I,II} \\ A_{II,I} & A_{II,II} \end{bmatrix} \begin{bmatrix} x_{I} \\ x_{II} \end{bmatrix} + \begin{bmatrix} X_{I,F} \\ X_{II,F} \end{bmatrix}, \qquad (1)$$

where the subscripts I, II, and F attached to a vector or matrix stand for goods sector, waste treatment sector, and final demand sector, respectively. x_{I} and x_{II} are output vectors of goods sectors and waste treatment sectors, respectively. For a waste treatment sector, its "output" level is measured by the weight of waste it treated; all the n^{II} components of x_{II} have a common measurement unit. A's are input coefficient matrices and X's with subscript F are final demand vectors.

The WIO counterpart of (1), introduced by Nakamura (1999) and Nakamura and Kondo (2002), is given by

$$\begin{bmatrix} x_{I} \\ x_{II} \end{bmatrix} = \begin{bmatrix} A_{I,I} & A_{I,II} \\ S\,G_{\cdot,I} & S\,G_{\cdot,II} \end{bmatrix} \begin{bmatrix} x_{I} \\ x_{II} \end{bmatrix} + \begin{bmatrix} X_{I,F} \\ S\,W_{\cdot,F} \end{bmatrix}, \tag{2}$$

where $G_{\cdot,I}$ is an $n^{w} \times n^{I}$ matrix of net waste generation coefficients, the (k, j)-component, g_{kj}, of which refers to the net generation (generation minus input) of the k-th waste per unit of output of the j-th goods sector, and $G_{\cdot,II}$ is similarly defined. Namely, the last n^{II} equations in the system (2) of n equations are constructed by premultiplying the allocation matrix S to the mass balance equation of waste stream,

$$w = G_{\cdot,I}\,x_{I} + G_{\cdot,II}\,x_{II} + W_{\cdot,F} \quad \text{with} \quad x_{II} = S\,w. \tag{3}$$

Note that, if $g_{kj} < 0$, sector j uses a larger amount of waste k than it generates and reduces the amount of waste k that has to be treated by waste treatment sectors. $W_{\cdot,F}$ is an $n^{w} \times 1$ vector of waste generations by the final demand sector. S is an $n^{II} \times n^{w}$ allocation matrix, the (i, k)-component, s_{ik}, of which refers to the share of waste k that is treated by waste treatment sector i; the equality $\sum_{i=1}^{n^{II}} s_{ik} = 1$ holds by definition for every k.

The allocation matrix S is peculiar to the WIO model and it plays an important role as follows. Premultiplying S to a matrix of net waste generation $(G_{\cdot,I}, G_{\cdot,II}, W_{\cdot,F})$ converts the net generation of waste into the demand for waste treatment. Note that the net waste generation coefficient matrices, $G_{\cdot,I}$ and $G_{\cdot,II}$, represent technologies of goods sectors and waste treatment sectors, respectively, while the input coefficient matrices, $A_{II,I}$ and $A_{II,II}$, may not. For instance, it is sometimes the case that a firm knows how much wastes it generates are taken charge of but it does not know how they are treated or recycled. The allocation pattern of wastes to various treatment sectors considerably depends upon institutional factors such as environmental regulations; a prohibition against landfilling of combustible wastes is an example. Namely, the input coefficient matrices, $A_{II,I}$ and $A_{II,II}$, represent a mongrel of technology and institutional factors. Therefore, they may change as a result of institutional factors even if technologies are kept unchanged.

The solution to the WIO model (2) and associated amount of environmental load emission are obtained as

$$\begin{bmatrix} x_{I} \\ x_{II} \end{bmatrix} = \left(I_n - \begin{bmatrix} A_{I,I} & A_{I,II} \\ S\,G_{\cdot,I} & S\,G_{\cdot,II} \end{bmatrix} \right)^{-1} \begin{bmatrix} X_{I,F} \\ S\,W_{\cdot,F} \end{bmatrix}, \tag{4}$$

$$e = R_{\cdot,I}\,x_{I} + R_{\cdot,II}\,x_{II} + E_{\cdot,F} = \begin{bmatrix} R_{\cdot,I} & R_{\cdot,II} \end{bmatrix} \left(I_n - \begin{bmatrix} A_{I,I} & A_{I,II} \\ S\,G_{\cdot,I} & S\,G_{\cdot,II} \end{bmatrix} \right)^{-1} \begin{bmatrix} X_{I,F} \\ S\,W_{\cdot,F} \end{bmatrix} + E_{\cdot,F}, \tag{5}$$

where I_n is an identity matrix of order n, $R_{\cdot,I}$ and $R_{\cdot,II}$ are $n^{E} \times n^{I}$ and $n^{E} \times n^{II}$ matrices, respectively, of direct emission coefficients of environmental loads, and $E_{\cdot,F}$ is an $n^{E} \times 1$ vector of direct emission of environmental loads from the final demand sector.

In order to keep presentation simple, we have so far assumed that coefficient matrices (A's, G's, and R's) are constant. In other words, the WIO model has been assumed to be linear in variables $x_{\rm I}$, $x_{\rm II}$, e, and w. However, the coefficient matrices ($A_{\rm I,II}$, $G_{\cdot,\rm II}$, and $R_{\cdot,\rm II}$) of waste treatment sectors, in particular, are significantly affected by the level and composition of wastes feedstock. The WIO model takes into account this nonlinearity by incorporating an engineering process model of waste treatment (Tanaka and Matsuto, 1998). We continue to assume the linearity of the model to avoid notational complexity although the nonlinearity is properly dealt with in our empirical analysis in Section 4.

2.2 Eco-efficiency Analysis by the WIO model

We consider a class of eco-efficiency measures at the macro level, which includes a well-known resource productivity, GDP per DMI. Define an eco-efficiency measure as a ratio of "economy" to "environment" (IEEC, 2004):

$$\varepsilon = \frac{p\,X_{\rm F}}{u\,e} = \frac{p_{\rm I}\,X_{\rm I,F} + p_{\rm II}\,X_{\rm II,F}}{u\,e} = \frac{p_{\rm I}\,X_{\rm I,F} + p_{\rm II}\,S\,W_{\cdot,\rm F}}{u\,e}. \tag{6}$$

The numerator $p\,X_{\rm F}$, which corresponds to GDP, is a monetary value of the final demand vector $X_{\rm F}$, given a $1 \times n$ price vector $p = [\,p_{\rm I},\, p_{\rm II}\,]$. The denominator $u\,e$ is a weighted sum of environmental loads e, given a $1 \times n^{\rm E}$ vector u of weights. Note that the first part $p_{\rm I}$ of the price vector p is usually equal to the vector of unities, because the final demand vector $X_{\rm I,F}$ is measured in a monetary unit. Note also that the vector u of weights may depend on policy objectives or scientific information such as characterization factors in the life cycle impact

assessment (LCIA) (Guinée, 2002). The weight vector u can, of course, be a unit vector, which has unity at a position and zeros at the other positions, when a single environmental load is of interest.

Environmental load emission associated with economic activities originates in consumers' lifestyle, technologies to meet it, and prevailing institutions. The WIO model provides a simple quantitative expression (5) among them. In the expression, the lifestyle is quantitatively represented by the vectors of the final demand sector ($X_{\rm I,F}$, $W_{\cdot,\rm F}$ and $E_{\cdot,\rm F}$), the technologies are by coefficient matrices ($A_{\rm I,\cdot}$, $G_{\cdot,\cdot}$, and $R_{\cdot,\cdot}$), and the prevailing institutions on waste management are by the allocation matrix (S). The final demand sector includes investment and government expenditure besides household consumption; they all can be said to originate in consumers' life style in the end if the purpose of the economic activities is to meet consumers' demand. In view of this, the WIO model (5) is a 'function' in the mathematics terminology which assigns an environmental load emission e to each combination $\langle X_{\rm I,F}, W_{\cdot,\rm F}, E_{\cdot,\rm F}, A_{\rm I,\cdot}, G_{\cdot,\cdot}, R_{\cdot,\cdot}, S\rangle$. Such a combination is called a scenario. An LCA study based on the WIO model (WIO-LCA) thus is carried out by comparing and/or interpreting calculated results (dependent variables of the 'function') among several scenarios.

The eco-efficiency measure in (6) in combination with the WIO model (5) is also a 'function' which assigns a level ε of eco-efficiency to each scenario $\langle X_{\rm I,F}, W_{\cdot,\rm F}, E_{\cdot,\rm F}, A_{\rm I,\cdot}, G_{\cdot,\cdot}, R_{\cdot,\cdot}, S\rangle$, given a price vector p and a vector of weights u. It follows that the eco-efficiency measure (6) can properly deal with the issues concerned with the composition of the final demand because the 'function' has a *vector*, $X_{\rm F}$, of the final demand as a part of its independent variable. Namely, the value of the denominator $u\,e$ of the eco-efficiency measure is calculated by (5) for a given expenditure pattern represented by X_F, and it may vary even when the value of the numerator $p\,X_F$ remains unchanged. Besides the price vector p and weights u, the level of eco-efficiency ratio ε is determined by a given scenario through the WIO model (5) that links the numerator and the denominator of the ratio together, and plays a role of an analytical model for explaining, forecasting, and controlling the level of the eco-efficiency.

We have so far discussed a similarity between LCA and eco-efficiency analysis by the WIO model; a scenario is an independent variable of the 'function' to give the result. There is another closely related point in LCA and eco-efficiency analysis, which is a reference basis. On the one hand, an *observed* final demand X_F is a vector satisfying a functional unit in the terminology of LCA, say "enjoying *the* standard of living for a year," which is defined with physical quantities of economic flows. Namely, a physically quantified functional unit is a reference basis in LCA. On the other hand, a monetary value $p\,X_F$ of the final demand vector is a reference basis in eco-efficiency analysis.

3 WIO-LP Model and Alternative Strategies

We develop the WIO-LP model that is a decision analytic extension of the WIO model based on the method of linear programming (LP) in this section. Application of LP to process LCA has been considered by Azapagic and Clift (1995, 1998) while the WIO-LP model is an application of LP to the WIO model for hybrid LCA and eco-efficiency analysis. The extension of the WIO model is basically performed by taking into account the possibility of selection of technologies.

We first consider the selection of goods-producing technologies. Recall that, in Section 2, there were n^{I} goods sectors, that is, there were n^{I} goods and a single technology for each of n^{I} goods. In other words, the number of goods was equal to the number of technologies for producing goods, and the possibility of selection of technologies were excluded. Considering the possibility, let there be n^{I} goods and m^{I} technologies for producing them such that $n^{\mathrm{I}} \leq m^{\mathrm{I}}$. Note that the input coefficient matrix $A_{\mathrm{I,I}}$ is of $n^{\mathrm{I}} \times m^{\mathrm{I}}$ and is not square in general. The balance equation of the flow of goods, which is the first n^{I} equations in the system (2) of n equations, is generalized and written as

$$J\,x_{\mathrm{I}} = A_{\mathrm{I,I}}\,x_{\mathrm{I}} + A_{\mathrm{I,II}}\,x_{\mathrm{II}} + X_{\mathrm{I},F}, \tag{7}$$

where J is an $n^{\mathrm{I}} \times m^{\mathrm{I}}$ matrix of zeros and unities, and its (i, j)-component J_{ij} is defined as

$$J_{ij} = \begin{cases} 1 & \text{technology } j \text{ produces goods } i, \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

As for the selection of waste treatment technologies, it should be noted that an allocation pattern of wastes to treatment methods itself represents a combination of selected waste treatment technologies. Hence it is not necessary to introduce another notation like m^{II} so as to consider the possibility of selection of waste treatment technologies because the WIO model can contain an arbitrary number of waste treatment sectors regardless of their activity levels; for instance, the i-th row of the allocation matrix S is an n^{w}-vector of zeros when the i-th waste treatment sector treats no wastes. Thus, the only thing to do is to replace a fixed allocation matrix S with a variable one.

The basic form of the WIO-LP model is defined as a minimization problem:

$$\text{minimize} \quad u\,(R_{\cdot,\text{I}}\, x_{\text{I}} + R_{\cdot,\text{II}}\, x_{\text{II}} + E_{\cdot,F}) \tag{9}$$

$$\text{subject to} \quad J\, x_{\text{I}} = A_{\text{I},\text{I}}\, x_{\text{I}} + A_{\text{I},\text{II}}\, x_{\text{II}} + X_{\text{I},F}, \tag{10}$$

$$w = G_{\cdot,\text{I}}\, x_{\text{I}} + G_{\cdot,\text{II}}\, x_{\text{II}} + W_{\cdot,F}, \quad x_{\text{II}} = S\, w, \tag{11}$$

$$\iota_{n^{\text{II}}}^{\mathsf{T}}\, S = \iota_{n^{\text{w}}}^{\mathsf{T}}, \tag{12}$$

$$x_{\text{I}} \geq \mathbf{0}_{n^{\text{I}}},\ x_{\text{II}} \geq \mathbf{0}_{n^{\text{II}}},\ S \geq O_{n^{\text{II}},n^{\text{w}}}, \tag{13}$$

$$\text{with respect to} \quad x_{\text{I}},\ x_{\text{II}},\ w,\ S, \tag{14}$$

where ι_n is an $n \times 1$ vector of unities, $\mathbf{0}_n$ is an $n \times 1$ vector of zeros, $O_{m,n}$ is an $m \times n$ matrix of zeros, the superscript T refers to the transpose of a matrix or vector, and an inequality between vectors holds when all the inequalities between the corresponding components hold. The objective function (9) of the WIO-LP model may be a specific environmental load or an integrated indicator of various environmental impacts, depending upon a given vector u of weights. The constraints (10) and (11) refer to the balance equations of the flow of goods and wastes, respectively. The constraint (12) is necessary for guaranteeing the matrix S to be a valid allocation matrix.

The minimization problem above is not a linear programming problem due to the presence of a nonlinear constraint, $x_{\text{II}} = S\,w$, in (11), so that the name 'WIO-LP' might seem inappropriate. In addition, it is well-known in the literature of mathematical programming and algorithms that an optimization problem with nonlinear constraints is generally much harder to solve than a problem with only linear constraints. To avoid this difficulty, let us introduce

an $n^{\text{II}} \times n^{\text{w}}$ matrix Z, the (i,k)-component of which refers to the amount of waste k that is treated by the i-th waste treatment sector; the equalities $x_{\text{II}} = Z\,\iota_{n^{\text{w}}}$ and $w = Z^{\mathsf{T}}\,\iota_{n^{\text{II}}}$ hold by definition. Thus, the constraints (11) and (12) can be replaced with

$$Z^{\mathsf{T}}\,\iota_{n^{\text{II}}} = G_{\cdot,\text{I}}\, x_{\text{I}} + G_{\cdot,\text{II}}\, x_{\text{II}} + W_{\cdot,F}, \quad x_{\text{II}} = Z\,\iota_{n^{\text{w}}}, \tag{15}$$

and the non-negativity condition $Z \geq O_{n^{\text{II}},n^{\text{w}}}$.

To summarize, the basic form of the WIO-LP model is defined as a linear programming problem:

$$\text{minimize} \quad u\,(R_{\cdot,\text{I}}\, x_{\text{I}} + R_{\cdot,\text{II}}\, x_{\text{II}} + E_{\cdot,F}) \tag{16}$$

$$\text{subject to} \quad J\, x_{\text{I}} = A_{\text{I},\text{I}}\, x_{\text{I}} + A_{\text{I},\text{II}}\, x_{\text{II}} + X_{\text{I},F}, \tag{17}$$

$$Z^{\mathsf{T}}\,\iota_{n^{\text{II}}} = G_{\cdot,\text{I}}\, x_{\text{I}} + G_{\cdot,\text{II}}\, x_{\text{II}} + W_{\cdot,F}, \quad x_{\text{II}} = Z\,\iota_{n^{\text{w}}}, \tag{18}$$

$$x_{\text{I}} \geq \mathbf{0}_{n^{\text{I}}},\ x_{\text{II}} \geq \mathbf{0}_{n^{\text{II}}},\ Z \geq O_{n^{\text{II}},n^{\text{w}}}, \tag{19}$$

$$\text{with respect to} \quad x_{\text{I}},\ x_{\text{II}},\ Z. \tag{20}$$

One may take into consideration additional constraints such as the capacity of a recycling sector, that of a treatment sector, and environmental regulations. For instance, an upper bound for a component of x_{I} works as a constraint on the capacity of the corresponding recycling sector, and an upper bound for the sum of a row of Z restricts the activity level of the corresponding waste treatment sector. An equality constraint $s_{ik} = 0$ should be appended if an environmental regulation which prohibits waste k from being treated by treatment sector i is in force.

4 Empirical Analyses

We applied the WIO-LP model to the Japanese WIO table of 1995 (Nakamura, 2003), which has 80 goods sectors, 4 waste treatment sectors (incineration, landfill, composting, and shredding), and 42 types of waste. We deal with import and export in a standard manner although we have so far ignored them for simplicity. To be concrete, we consider only the domestic products in the balance equation of the flow of goods as follows: the domestic demand for imported goods is taken away by multiplying the import coefficients to the input coefficient matrix and the domestic final demand vector; and export is included in the final demand vector. Therefore, we account for the environmental loads emitted inside Japan in our empirical analyses.

As for environmental emissions, we consider the two loads. One is the consumption of landfill site in volume. The other is the CO_2 emission originating from burning fossil fuel and limestone. It also includes the global warming potential over 100 years (GWP100) CO_2-equivalent value of methane (CH_4) originating from biomass fermenting at landfill sites and that of chlorofluorocarbons (CFC's) from end-of-life refrigerators and air conditioners. The main reason why we consider quite a small number of environmental loads only is the lack of appropriate data. However, the two environmental loads are appealing in their own rights. A landfill site is one of the scarce resources at least in Japan. It can, in addition, be regarded as an environmental impact if reclaiming of a closed landfill site is technologically excluded in the foreseeable future. The CO_2 emission can be regarded as a proxy, or a first approximation, of a greenhouse gas impact, where we assume an input-output structure same as the Japanese structure prevails in relevant foreign countries.

4.1 Setting of Possible Alternatives and Constraints

We take into account the following possible alternative technologies, besides ones given in the Japanese WIO table of 1995:

- Gasification of kitchen garbage with power generation (JAFIC, 2002);
- Intensive disassembling and shredding of end-of-life electric home appliances in compliance with the law coming into enforcement in April 2001, called "the Japan model" (AEHA, 1999, Kondo and Nakamura 2004);
- Regional concentration of incineration;
- Injection of waste plastics into blast furnaces (Sanou et al., 2000);
- Substitution of converter steel with electric furnace steel by 'hot rolled steel' sector to recycle more iron scraps (Kondo and Nakamura 2004); and
- Substitution of virgin materials (copper, aluminum, and silica stone) with recycled materials (copper scraps, aluminum scraps, and glass cullet, respectively) by 'rolled and drawn copper and copper alloys', 'rolled and drawn aluminum', and 'glass products' sectors (Kondo and Nakamura 2004);

Table 1 shows the distribution of incinerators by types. We consider the three types of incinerators though there are in reality many types of incinerators in Japan. We also identify a region with an incinerator when the regional concentration of incineration is not carried out; for instance, we call a region 'Region I' if wastes generated there are treated by a Type I incinerator. The regional concentration of incineration is assumed to be performed by replacing a large number of smaller types (Types II and III) of incinerators with a small number of the largest type (Type I) of incinerators which have the same capacity in total. The decrease in the number of incinerators leads to the longer transportation distance (given in the last row of Table 1) that is assumed to increase proportionally to the square root of the ratio of capacities. For instance, wastes generated in Region II are transported over the distance of 12 km and treated by a Type II incinerator without regional concentration while the wastes are transported over the distance of 24.5 km (= 12 km $\times \sqrt{(500 \times 3) \div (180 \times 2)}$) and treated by a Type I incinerator under the regional concentration. Wastes generated in Region I are always transported over the distance of 12 km and treated by a Type I incinerator. As for the settings not mentioned here in detail, we use the same ones as Nakamura and Kondo (2002), Sanou et al. (2000), and Yoshida et al. (2000).

In order for unrealistic solutions to be ruled out, we employ several sorts of additional constraints. First, it is assumed that some treatment sectors can treat only limited types of waste:

- The gasification sector treats only kitchen garbage;
- Each of the shredding sectors treats only a type of waste specific to the sector; and
- The incineration sector does *not* treat bulky wastes such as bicycles & ovens, small electric appliances, TV sets, refrigerators, washing machines, and air conditioners.

Second, it is assumed that some types of waste can be treated only by a limited part of treatment sectors:

- Incineration only: Sawdust & wood chips, Waste oil, Waste acid, Waste alkali, and

Carcass;

- Landfill only: Glass bottles, Organic sludge, Inorganic sludge, Construction debris, Incineration ash, Dust, and Shredder dust;
- Shredding only: Automobiles;

Third, an upper bound is given to the percentage of incineration of each incombustible waste, in order to rule out unrealistic cases where too much incombustible waste mingle with combustible waste. Finally, an upper bound is given to the percentage of gasification of kitchen garbage.

As for eco-efficiency analysis, we consider only the case that the final demand vector is kept constant. We also consider two eco-efficiency measures, CO_2-efficiency and the landfill-efficiency: The former is defined as the ratio of GDP to the CO_2 emission, and the latter is defined as the ratio of GDP to the landfill consumption.

4.2 Results

Table 2 shows main results. The symbols, A, C1, L1, C2, and L2, in the first row labeled 'Case' indicate the possibility of selection of alternative options and the objective to be optimized. Case A corresponds to the current status of Japan in 1995. In Cases C1 and L1, the allocation pattern of wastes to treatment sectors can be optimally selected while any additional recycling technologies cannot be chosen; this is the case with $m' = n'$. In Cases C2 and L2, both the allocation pattern and additional recycling technologies can be optimally selected. The objective function to be minimized is the CO_2 emission in Cases C1 and C2, and the consumption of landfill site in Cases L1 and L2.

4.2.1 Optimally Selected Technologies

The middle of Table 2 shows which technologies are selected as components of an optimal solution to the WIO-LP model. It is found that alternative technologies chosen at optimality depend upon the possibility of selection of alternative options and the objective to be optimized. In Cases L1 and L2 where the landfill consumption is minimized, reducing the bulk of wastes is of great importance, so that garbage is gasified or incinerated with the regional concentration and waste plastics are injected into blast furnace or incinerated with the regional concentration. In Cases C1 and C2 where the CO_2 emission is minimized, on the other hand, garbage is not gasified but incinerated with the regional concentration and waste plastics are not incinerated but injected into blast furnace or landfilled. In particular, waste plastics are injected into blast furnace at optimality in all the cases up to the capacity. The optimal treatment method for the remaining waste plastics varies across cases: on the one hand, the incineration with regional concentration is chosen when the landfill consumption is minimized, on the other hand, the landfill is chosen when the CO_2 emission is minimized.

For the four items of electric home appliances (TV sets, refrigerators, washing machines, and air conditioners), not the shredding with iron recovery but the intensive disassembling and shredding are selected at optimality in Cases L1 and L2, where the landfill consumption is minimized. The treatment technology that generates the smallest amount of shredder dust seems to be selected in these cases because only the landfill sector can treat the shredder dust in our setting. In Cases C1 and C2, on the other hand, the treatment methods chosen at optimality diverges between the items of electric home appliances. The intensive disassembling and shredding are selected for refrigerator and air conditioner in both cases

because CFC's, which is included in the two items, have an enormous contribution to CO_2 emission.

TV set is landfilled at optimality in Case C1 where the objective is to minimize CO_2 emission and additional recycling technologies are not available. The shredding and/or disassembling are not selected because these treatment technologies require electricity but merely reduce the bulk of waste. In Case C2 where additional recycling technologies are available, on the other hand, the shredding with iron recovery that does not recover glass cullet is selected at optimality. The reason for this result seems that the recycler of iron scraps reserves strength enough to accept more iron scraps while no more glass cullet is recycled due to the capacity of the recycler. Washing machine is landfilled in Case C1 and it is treated by the intensive disassembling and shredding in Case C2 because more iron scraps can be recovered from washing machine than from TV set.

4.2.2 Trade-off relationship between CO_2 emission and landfill consumption

In minimizing CO_2 emission, it decreases by 5.3% in Case C2 where both the allocation pattern and additional recycling technologies can be optimally selected while CO_2 emission decreases by 5.0% in Case C1 where only the allocation pattern of waste to treatment can be optimized. Namely, more than $5.0 \div 5.3 \approx 93\%$ of CO_2 emission reduced in Case C2 can be reduced in Case C1. In other words, optimizing allocation pattern of wastes to treatment sectors is quite effective in the reduction of CO_2 emission. However, in minimizing CO_2 emission, the landfill consumption increases by 9.2% in Case C1 and by 5.2% in Case C2. It is found that there is a trade-off relationship between our two objective functions, CO_2 emission and landfill consumption. That is, the one of the two objective functions increases when the other is minimized and reduced.

In minimizing the landfill consumption, it decreases by 28% in Case L2 where both the allocation pattern and additional recycling technologies can be optimally selected while the landfill consumption decreases by 26% in Case L1 where only the allocation pattern of waste to treatment can be optimized. In the same way as in minimizing CO_2 emission, more than 93% of landfill consumption reduced in Case L2 can be reduced in Case L1. It is noteworthy that, in minimizing the landfill consumption, the CO_2 emission also decreases by 4.1% in Case L1 and by 4.5% in Case L2. A trade-off relationship between CO_2 emission and landfill consumption is observed again although both emissions decrease in this case.

Turning to eco-efficiency, we can easily obtain the best available eco-efficiency of the Japanese economy as a ratio of GDP to the optimal value of the WIO-LP model. The results are shown at the bottom of Table 2. The obtained best available eco-efficiency is measured as "factor" in the sense that each value of the eco-efficiency measure is divided by the corresponding value of the current status of Japan in 1995 (Case A). The trade-off relationship discussed above can be observed also as, for instance, the CO_2-efficiency (1.056) is greater than unity while the landfill-efficiency (0.950) is smaller than unity in Case C2.

4.2.3 Environmental Efficiency Frontier and Eco-Efficiency Frontier

The trade-off relationship found above motivates us to derive an environmental impact minimizing "efficiency" frontier (Miettinen and Hamalainen, 1997), or an eco-efficiency maximizing frontier. The four scenarios that are optimal solutions to the WIO-LP model can be viewed as extreme cases while an environmental impact minimizing frontier corresponds to a set of all intermediate scenarios.

Figure 1 shows eco-efficiency maximizing frontiers which is obtained by the method explained below. Five points, A, C1, L1, C2, and L2, corresponds to the five cases in Table 2. The pair of the coordinates of Point A is $(1, 1)$ because it is a basis of comparison. The curve passing through Points C2 and L2 is located to the northeast of the curve passing through Points C1 and L1 because more options, including additional recycling technologies, are available in Cases C2 and L2 than in Cases C1 and L1. On the one hand, any point inside the frontier which lies in the southwest of the frontier is feasible but not optimal. On the other hand, any point outside the frontier which lies in the northeast of the frontier is infeasible under the possibility of selection of alternative options taken into consideration. Any point on the frontier is "optimal" with regard to the criterion represented by the objective function. In other words, every point on the frontier represents "the best available eco-efficiency" of Japanese economy. Priority of objectives needs to be explicitly stated for answering to the question 'which point on the frontier should be adopted?'

An eco-efficiency maximizing frontier (or environmental impact minimizing frontier) can be obtained quantitatively by the WIO-LP model. Recall that we deal with the two environmental emissions, the CO_2 emission and the landfill consumption. A point on the frontier is given as an optimal solution to the WIO-LP model in which the objective function is one of the two environmental emissions and an upper bound is provided to the other environmental emission. Therefore, an eco-efficiency maximizing frontier can be obtained by repeatedly solving the WIO-LP model. The frontier drawn in Figure 1 was actually calculated by the following linear programming problem:

$$\text{minimize} \qquad \text{the consumption of landfill site} \tag{21}$$

subject to (17), (18), (19), and (22)

$$(CO_2 \text{ emission}) \leq r \times (CO_2 \text{ emission in Case A}) \quad (23)$$

with respect to $x_{\mathrm{I}}, x_{\mathrm{II}}, Z,$ (24)

where r is one of the grid points over the interval $[0.9467, 0.9594]$ and its extreme points are set based on the results in Table 2.

A single point on the frontier will be selected by explicitly stating the priority of policy objectives. The selected point is a pair of the CO_2-efficiency and the landfill-efficiency, and it is also a scenario; a combination of alternative options to actualize the scenario is quantitatively understood. The WIO-LP model, namely, enables one not only to identify a goal of reducing environmental emissions or improving eco-efficiency but also to understand a quantitatively concrete waste management strategy to accomplish the goal.

5 Concluding Remarks

This paper has studied a decision analytic extension of the WIO model (Nakamura and Kondo, 2002) based on the method of linear programming. The resulting model, the WIO-LP model, allows one to search waste management and recycling strategies, which are "optimal" under the possibility of selection of alternative options taken into consideration. It is also possible to assess waste management strategies which may be a policy device or plan, once an eco-efficiency maximizing frontier is quantitatively obtained. For instance, there are not-yet-exploited latent possibility of reducing environmental impacts if a waste management policy lies inside the frontier. We believe that assessing existing strategies from this point of view

significantly contributes to the effective use of resources and the improvement of waste management policies.

It is desirable to move the eco-efficiency maximizing frontier to the northeast direction, i.e., to expand the possibility for attaining a less amount of environmental emission, in order for a sustainable society to materialize. Important points to investigate are which constraint should be relaxed, and what kind of expansion of the possibility is the most effective in the sense of cost effectiveness. The optimal solution to the dual problem of the WIO-LP model is expected to provide information which constraint can effectively be relaxed. Important future research topics are to develop further the WIO-LP model in this respect and to expand availability of the model as an LCA and eco-efficiency methodology, as well as to perform sensitivity analyses, to deal with the final demand vector as a variable in eco-efficiency analysis, and to carry out empirical analyses with more options including additional recycling technologies.

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Table 1: Distribution of incinerators by types

Incinerator types, regions	I	II	III
Incinerator size [tonne/day]	500	180	30
Incinerators per plant	3	2	1
Operation	F.C.[a]	F.C.[a]	Batch
Power from waste heat	Yes	No	No
Capacity share	.343	.144	.513
One-way transportation distance [km]			
Not regionally concentrated	12.0	12.0	12.0
Regionally concentrated	–	24.5	84.9

[a] "F.C." stands for "Full continuous."

Table 2: Main results of the WIO-LP model

Case	A	C1	L1	C2	L2
1. Alternative waste treatment technologies[a]					
(L) landfilling	yes	yes	yes	yes	yes
(S) old shredding	yes	yes	yes	yes	yes
(H) new shredding	no	yes	yes	yes	yes
(I) regional concentration	no	yes	yes	yes	yes
(G) gasification	no	yes	yes	yes	yes
2. Alternative recycling technologies[a]					
(B) blast furnace	no	no	no	yes	yes
(R) recovered materials	no	no	no	yes	yes
Objective to minimize		CO_2	LC	CO_2	LC
Alternative technologies chosen at optimality[b]					
garbage		I	G/I	I	G/I
waste plastics		L	I	B/L	B/I
TV sets		L	H	S	H
washing machine		L	H	H	H
refrigerator, AC[c]		H	H	H	H
metal scraps		L	L	R	R
glass cullet		L	L	R/L	R/L
Environmental load emission[d]					
CO_2	0.00	−4.97	−4.06	−5.33	−4.45
landfill consumption	0.00	9.22	−26.02	5.22	−27.95
Best available eco-efficiency[e]					
CO_2-efficiency	1.00	1.052	1.042	1.056	1.046
landfill-efficiency	1.00	0.916	1.352	0.950	1.388

[a] The alternative technologies are: (L) landfilling, (S) shredding with iron recovery, (H) shredding with high yield rate, (I) regionally concentrated incineration, (G) gasification of garbage and power generation, (B) injection of waste plastics into blast furnace, and (R) recycling of recovered materials.
[b] Chosen technologies are indicated with symbols in the upper part of the table. However, two symbols connected by a slash, say "G/I", indicate that a type of waste is gasified up to the capacity of the gasification, and the remaining part of that waste is treated by regionally concentrated incineration.
[c] "AC" stands for "air conditioner".
[d] Rate of change relative to the current status (A) in percentage.
[e] Measured as "factor" in the sense that each value of the eco-efficiency measure is divided by the corresponding value of the current status (A).