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Shinichiro Nakamura

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1. P.6, the equation at the bottom.

$$\lim_{n\to\infty}\sum_{i=0}^{n} X^{(n)} = \begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow}(I+D)^{-1}X_w^{(1)}.$$

should read

$$\lim_{n\to\infty}\sum_{i=2}^{n} X^{(i)} = \begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow}(I+D)^{-1}X_w^{(1)}.$$

2. P.7, the second line.

$$\lim_{n\to\infty}\sum_{i=2}^{n} X^{(n)}$$

should read

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An Interindustry Approach to Analyzing Economic and Environmental Effects of the Recycling of Waste *

Shin'ichiro Nakamura
School of Political Science & Economics
Waseda Univeristy
169-50 Tokyo, Japan
nakashin@mn.waseda.ac.jp

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Abstract

Waste can be classified into two major categories depending on the way it is generated. The first category is concerned with those types of waste that are generated as by-products in the production process, and as such are 'waste from the very beginning'. On the other hand, any economic good is potentially doomed to become waste after it has lost its economic value. This paper presents an interindustry model for analyzing economic and environmental effects of the recycling of the latter types (the second category) of waste. As an illustration, I construct a numerical example for the case of the recycling of old paper using the Dutch NAMEA data set, and analyse the economic as well as the environmental (the emission of CO_2) impact of alternative recycling scenarios.

1 Introduction

Waste accumulates over time unless decomposed in the ecosystem or recycled. Today, the accumulation of waste has achieved such a magnitude that it can become a real threat to the existence of the whole ecosystem.

Waste can be classified into two major categories depending on the way it is generated. The first category is concerned with those types of waste that are generated as by-products in the production process, and as such are 'waste from the very beginning'. Examples include waste gas, waste water, toxic materials, and sludge.

On the other hand, any economic good is potentially doomed to become waste after it has lost its economic value. Old paper, discarded consumer- and producer durables, and construction debris are examples of this type of waste, which we classify as belonging to the second category. Waste of this category is fundamentally different from that of the first category in that when it was originally produced it posessed a positive economic value. Furthermore, its generation does not occur simultaneous with the current level of economic activity because it is not a by-product.

In his pioneering work, Wassily Leontief (1970) demonstrated the usefulness of applying interindustry analysis to environmental issues such as the emission of pollutants into the atmosphere. Faye Duchin (1993) extended the work of Leontief by taking into account the recycling and treatment of waste as

*I would like to thank Dr. Steven Keuning, Central Bureau of Statistics, Voorburg, for kindly providing me with the Dutch NAMEA data, and Ayu Ikeda and Anthony Newell (Waseda University) for helpful comments.

well as the generation of residuals which cannot be further treated and as such are exposed to the environment.

As indicated by the title 'Conversion of biological materials and waste to useful products', Duchin's model is mainly concerned with waste of the first category. While her model can deal with the recycling of waste generated as by-product as a negative input, it treats the process of generation, collection, and treatment of waste as a black box and does not identify individual processes. This is understandable, because waste of the first category is mostly treated in the same location where it is generated. A typical example is the treatment of waste water in a chemical plant.

In the case of waste of the second category, however, the location of its original production will be quite different from where it is generated. While the production of goods tends to be spatially concentrated, the generation of waste (or the conversion of goods into waste) tends to be distributed over a wide area because it occurs in the place of final use and/or consumption. Accordingly, the collection of waste is an important element of recycling programs, and deserves an explicit treatment rather than being putting into a black box.

The purpose of this paper is to present an interindustry model for analyzing economic and environmental effects of the recycling of waste of the second category. In particular, Duchin's model is extended with respect to the following points:

- The generation of waste does not occur simultaneous with the current economic activity.
- The collection of waste (for recycling purposes) and the recycling of waste are treated as different activities.
- The input of recycled goods into the production process is explicitly shown, and does not occur as a negative input.
- The effects of a reduction of waste through recycling on the activity of waste management sector are explicitly taken into account.

As an illustration of the proposed model, I will show a numerical example for the case of the recycling of old paper. While being a numerical prototype, it is based on the Dutch NAMEA data and information on recycling of old paper and waste management for Japan. As such, it is not a product of purely artificial numbers with no real economic/environmental content.

The Dutch NAMEA data provide an optimal platform for my purpose, because they provide detailed information on the emission of substances fully embedded within interindustry accounts. I chose the recycling of old paper because of the significance of discarded paper in total waste and of the possible contribution of the recycling of old paper to the preservation of woods, a vital factor of the ecosystem.

2 The Model

2.1 The setting

Any good produced in the industry sector has a possibility of turning into waste when it loses economic value with the passing of time. Except for when otherwise stated, 'waste' in the following refers to this second category of waste.

Let n be the number of well-defined good/service producing sectors. Since only goods can become waste, there are at most $k < n$ types of waste. Suppose that the recycling of waste requires a complete selective collection. The number of waste collecting sectors for recycling purposes, say m ($m \leq k$), is then equal to the number of recycled goods producing sectors ($k - m$ refers to the number of types of waste which are not collected for recycling). Let there be k waste management sectors (incineration, landfill etc.) each corresponding to a particular type of waste.

2.1.1 Accounts of industry sector

Denote the industry sector by o, the waste collection sector by z, the sector producing recycled goods by r, the waste management sector by w, and the final demand sector by f. Henceforth, the waste management sector refers to the sector where waste is treated in non-recycling manner (incineration, landfill etc). Each of these sectors consists of branches. Let $x_{o:i}$ be the amount of output of the i th branch of the industry sector ($i \in o$). This can be used as an input in the industry sector, waste collecting sector, recycled goods producing sector, and waste management sector. Denote by $x_{00:ij}$ the amount used in the j th branch of the industry sector, by $x_{0z:ih}$ that used in the h th branch of the waste collecting sector, by $x_{0r:iu}$ that used in the u th branch of the recycled goods producing sector, by $f_{0:i}$ that used in the i th branch of the final demand sector. Then the following balancing equation holds:

$$\sum_{j=1}^{n} x_{oo:ij} + \sum_{h=1}^{m} x_{or:ih} + \sum_{u=1}^{m} x_{or:iu} + \sum_{v=1}^{k} x_{ow:iv} + f_{o:i} = x_{o:i}, \; i = 1, \cdots, n. \tag{1}$$

2.1.2 Accounts of waste

Denote by $z_{t,j}$ the level of stock of the j, $j = 1, \cdots, k$ th waste at the beginning of t. The level of stock of waste depends on, among others, the amount of goods produced before t, the physical durability of goods, and the preferences of the consumers. We regard as given the level of stock of waste, and do not consider factors determining its level. Waste is either collected for recycling or treated as final waste in the waste management sector. Denote by $x_{z:j}$ the amount collected for recycling and by $x_{w:j}$ the amount treated as final waste. [1] The following identity holds:

$$\begin{aligned} \text{stock of waste} &= \text{collected for recycling} + \text{waste management}, \quad \text{or} \\ z_j &= x_{z:j} + x_{w:j}. \end{aligned} \tag{2}$$

Since z_j is given, once $x_{z:j}$ is determined, (2) determines $x_{w:j}$ as the residual.

2.1.3 Collection of waste

$x_{z:j}$ is primarily used in the recycled goods producing sector ($x_{zr:ju}, u = 1, \cdots, m$), but may also enter into the final demand sector ($f_{z:j}$) when it is exported and/or kept as inventory.

$$\sum_{u=1}^{n} x_{zr:ju} + f_{z:j} = x_{z:j} \tag{3}$$

We exclude the case where waste enters the industry sector directly as an input (when the industry sector engages in recycling activities, we move these activities from the industry sector to the recycling sector). Otherwise, it will be necessary to treat the input of recycled goods to the industry sector as by-products and denote them by negative entries.

[1] Henceforth, the suffix referring to time t is omitted except for when otherwise confusion may arise. Waste management includes the non-selective collection of waste.

The waste collecting sector uses as inputs goods and services provided by the industry sector, labor, and capital services.

Some notations are due. We denote a matrix or vector by a capital letter, and its elements by lowercase letters. For instance, the $n \times m$ matrix consisting of $x_{ow:ij}$, $i = 1, \cdots, n; j = 1, \cdots, m$ is denoted by X_{ow} .

2.1.4 Recycled goods

The recycled goods producing sector converts a particular amount of waste X_z into a particular amount of recycled goods X_r by using goods and services produced in the industry sector X_{or}, labor and capital services. The i th recycled good $x_{r:i}$ may be used as an intermediate input for the industry sector ($x_{ro:ij}, j = 1, \cdots, n$), and/or used as a final good ($f_{ro:i}$). The following identity holds:

$$\sum_{j=1}^{n} x_{ro:ij} + f_{r:i} = X_{r:i} \tag{4}$$

Like $f_{z:i}$, $f_{r:i}$ also includes inventory changes.

2.1.5 Waste management and emission of substances

The amount of waste to be treated by the waste management sector is derived from (2) once the amount of recycled goods is known. For its activity (combustion, land/sea disposal etc.) the waste management sector uses goods and services produced in the industry sector, and capital- and labor services.

Each of the five sectors (industry, waste collection, waste recycling, waste management, and final demand (household)) emits q types of unpriced pollutants, which we denote as X_{eo}, X_{ez}, X_{er}, andX_{ew}.

2.2 The extended interindustry table

The flow of goods and services, waste, and pollutants among the five sectors can now be expressed in the form of an extended interindustry table as in Table 1. X_{ro} is an $m \times n$ matrix the i row j column

	industry	recycling	collection of waste	waste management	final demand	production/ sum
industry	X_{oo}	X_{or}	X_{oz}	X_{ow}	F_o	X_o
recycling	X_{ro}	0	0	0	F_r	X_r
waste collection	0	X_{zr}	0	0	F_z	X_z
capital services	K_o	K_r	K_z	K_w		
labor services	L_o	L_r	L_z	L_w		
emission of pollutants	X_{eo}	X_{er}	X_{ez}	X_{ew}	X_{ef}	X_e

Table 1: Extended interindustry table with recycling

element of which is given by $x_{ro:ij}$. Other matrices also defined in an analogous manner.

Note that the above table does not have a row referring to the waste management sector because the stock of waste is exogenously given. Still, it is possible to incorporate waste of the first category into the above table. One simply needs to add new rows referring to the generation of waste and the equal number of new columns referring to the waste management.

2.2.1 Price and physical units of measurement

In many cases, waste has no market value, and has to be expressed in physical units. On the other hand, the usual input-output tables express the flow of goods and services in monetary units. It follows that both physical and monetary units of measurement coexist in the extended input-output table.

In particular, Table 1 is characterized by the presence of X_{zr}, X_{oz}, and X_{ow} which are located at the intersection of columns (rows) in physical units with rows (columns) in monetary units. Each element of X_{zr} refers to the amount in physical unit, say 1000Kg, of a particular waste that is required to produce one monetary unit of a particular recycled good. Furthermore, each element of X_{oz} (X_{ow}) refers to the amount of an input from the industry sector in monetary units that is required to collect (treat) one physical unit of a particular waste. Since the usual input-output tables do not report these variables, its estimation becomes an important issue in the empirical implementation of our approach.

2.3 The linear model and its solution

Define the input (emission) coefficients per unit of activity as $a_{kl:ij} \equiv x_{kl:ij}/x_{l:j}$, $k \in (o, r, z, K, L, e), l \in (o, r, z, w)$. Using the input (emission) coefficients thus defined, we can obtain from Table 1 the matrix of input coefficients as in Table 2. Here, A_{ro} is an $m \times n$ matrix with $a_{ro:ij}$ being its element in the i th

input/output	industry	recycled goods	collection	waste management
industry	A_{oo}	A_{or}	A_{oz}	A_{ow}
recycled goods	A_{ro}	0	0	0
collection	0	A_{zr}	0	0
capital services	A_{Ko}	A_{Kr}	A_{Kz}	A_{Kw}
labor services	A_{Lo}	A_{Lr}	A_{Lz}	A_{Lw}
emission	A_{eo}	A_{er}	A_{ez}	A_{ew}

Table 2: The matrix of input coefficients of goods·services·waste

row and j th column. Other matrices are defined in a similar manner.

In the following, we assume that the input coefficients thus defined are indeed fixed parameters of technical input-output relationships. The assumption of linear technology has a long tradition in economics in both theoretical and empirical analysis. One should be careful, however, in using the same linear approximation to the emission of pollutants. While it is legitimate to assume linearity between economic activity and the emission of CO_2 because the latter depends on fuel consumption (except for some special cases in chemical and steel industries), the same does not apply to the emission of NO_x and SO_2. Of the substances of emission, we henceforth consider CO_2 only [2].

Since the input coefficients are non-negative by assumption, if the Hawkins-Simon condition (Nikaido 1960, 1970) is satisfied, we can compute the output vector that is needed both directly and indirectly to

[2] Recent examples of empirical analysis of the emission of CO_2 by the use of fixed emission coefficients are Ikeda et al (1996) and Proops, Faber and Wagenhals (1993).

meet a given vector of final demand. Neglecting the waste management sector for a while, this vector of output, say $X^{(1)}$, can be given by

$$X^{(1)} = \begin{pmatrix} X_o^{(1)} \\ X_r^{(1)} \\ X_z^{(1)} \end{pmatrix} = \begin{pmatrix} (I_n - A_{oo}) & -A_{or} & -A_{oz} \\ -A_{ro} & I_m & O \\ O & -A_{zr} & I_m \end{pmatrix}^{-1} \begin{pmatrix} F_o \\ F_r \\ F_z \end{pmatrix}$$
$$= \begin{pmatrix} B_{oo} & B_{or} & B_{oz} \\ B_{ro} & B_{rr} & B_{rz} \\ B_{zo} & B_{zr} & B_{zz} \end{pmatrix} \begin{pmatrix} F_o \\ F_r \\ F_z \end{pmatrix} \tag{5}$$

Here, I_a refers to the unit matrix of order a and B_{ij} to each of the partitioned matrices.

When $X_z^{(1)}$ is determined this way, (2) then determines the amount of waste to be treated $X_w^{(1)}$:

$$X_w^{(1)} = Z - X_z^{(1)} = Z - (B_{zo}F_o + B_{zr}F_r + B_{zz}F_z) \tag{6}$$

The vector of output of the four sectors thus determined $X^{(1)^{\top}} = (X_o^{(1)^{\top}}, X_r^{(1)^{\top}}, X_z^{(1)^{\top}}, X_w^{(1)^{\top}})$ ($^{\top}$ refers to the transpose of a matrix), however, still does not give the final level of output. This is because $X_w^{(1)}$ still remains to be treated.

Let $X^{(2)}$ be the vector of output of the first three sectors except the waste management that is additionally needed to treat $X_w^{(1)}$:

$$X^{(2)} = \begin{pmatrix} X_o^{(2)} \\ X_r^{(2)} \\ X_z^{(2)} \end{pmatrix} = \begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow} X_w^{(1)}.$$

The sequence of derived demand does not finish here. This is because the additional collection of waste for recycling $X_z^{(2)} > 0$ reduces the amount of waste to be treated in the waste management sector by that amount, and results in a decrease in the derived demand that originates in the waste management sector (recall that the amount of stock is given as a stock).

The amount of decreased demand $X^{(3)}$ is given by

$$X^{(3)} = -\begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow} X_w^{(2)} = -\begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow} B_{zo} A_{ow} X_w^{(1)}$$

In general, therefore, for $n > 2$, $X^{(n)}$ can be given as follows:

$$X^{(n)} = (-1)^{n-2} \begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow} (B_{zo} A_{ow})^{n-2} X_w^{(1)}.$$

Define $D \equiv B_{zo} A_{ow}$, and let the characteristic roots of D be smaller than unity in absolute value. It then follows that

$$\lim_{n \to \infty} \sum_{i=0}^{n} (-D)^i = (I + D)^{-1},$$

and hence that

$$\lim_{n \to \infty} \sum_{i=0}^{n} X^{(n)} = \begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow} (I + D)^{-1} X_w^{(1)}.$$

The overall level of output that includes all repercussions, X, is then given by adding the initial output, $X^{(1)}$, representing the first order effect to the sum of derived demand, $\lim_{n\to\infty}\sum_{i=2}^{n} X^{(n)}$, representing the second-order effect:

$$
\begin{aligned}
X &= \begin{pmatrix} X_o \\ X_r \\ X_z \end{pmatrix} = \begin{pmatrix} B_{oo} & B_{or} & B_{oz} \\ B_{ro} & B_{rr} & B_{rz} \\ B_{zo} & B_{zr} & B_{zz} \end{pmatrix} \begin{pmatrix} F_o \\ F_r \\ F_z \end{pmatrix} \\
&+ \begin{pmatrix} B_{oo} \\ B_{ro} \\ B_{zo} \end{pmatrix} A_{ow}(I+D)^{-1} \left\{ Z - (B_{zo} B_{zr} B_{zz}) \begin{pmatrix} F_o \\ F_r \\ F_z \end{pmatrix} \right\}
\end{aligned} \tag{7}
$$

The increased awareness that landfills and incineration can have a significant impact on groundwater and air pollution has significantly contributed to increasing the significance of waste recycling (McClain 1995). As we saw above, our model takes explicit account of the effects of a reduction of waste through recycling on economic activities and on the emission of pollutants as well. In particular, we can use the emission matrix $A_e = (A_{eo}, A_{er}, A_{ez}, A_{ew})$ in Table 2 for this purpose. Given a vector of output X^o that corresponds to a particular set of final demand, technology (represented by the input coefficients matrix), and the stock of waste, the emission of CO_2, for example, will be given by $A_e X^o$. Use of this measure will make it possible to compare the economic as well as the environmental impact of alternative combinations of final demand, technology, and the stock of waste.

3 A numerical example of the recycling of old paper

As a first attempt to evaluate the empirical performance of the theoretical model of the previous section, we willconstruct a numerical prototype taking the recycling of old paper as an example. The Dutch NAMEA (National Accounting Matrix including Environmental Accounts) data set provides the basic input-output data for this exercise.

3.1 The Dutch NAMEA

The Dutch NAMEA contains detailed information on the emission of pollutants (for details, see Haan and Keuning 1996 and Centraal Bureau voor de Statistiek 1996). It represents interindustry flows of goods and services by the so-called *make* and *use* matrices, and identifies twenty industry sectors and thirty-seven goods and services. Emission is registered for each of the twenty industry sectors, and is classified into eleven substances. Since the data on emission are available only at the level of industry, I converted the *make* and *use* matrices to the usual input-output table with twenty industry sectors. Table 3 shows the classification of industries and pollutants.

3.2 The recycling of discarded paper

Paper is made of pulp. Pulp for paper production can be divided into two groups by its origin: the virgin pulp made of log chips and logs (chemical and mechanical pulp) and the secondary pulp made of old paper (Morisawa et al 1993 p.20). The two groups of pulp can be fairly substitutable for each other depending on the technology in use, and the quality of the paper to be produced and of the old paper.[3]

[3] In Japan, for example, their proportion is almost 1 to 1.

	Industry	Emissions
1	Agriculture, hunting, forestry, fishing	CO_2
2	Crude petroleum and natural gas	N_2O
3	Other mining and quarrying	CH_4
4	Food, beverage and tobacco industry	CFC_s and halons
5	Textile, wearing apparel and leather industry	NO_x
6	Wood and furniture industry	SO_2
7	Paper, paper products, printing and publishing industry	NH_3
8	Petroleum industry	P
9	Chemical industry	N
10	Rubber and synthetic materials processing industry	Waste
11	Manufacturer of building materials, earthenware and glass products	Waste water
12	Manufacturer of basic metals	
13	Manufacturer of metal products and machinery	
14	Industrial manufacturing n.e.c.	
15	Electricity	
16	Other public utilities	
17	Construction	
18	Transport and storage	
19	Environmental cleansing and sanitary services	
20	Other services	

Table 3: Classification of industries and emissions in the Dutch NAMEA

Table 4 shows a simplified input-output relationship among old paper, pulp, log chips, and paper in the form of Table 2.

		(1) paper	(2) virgin pulp	(r) secondary pulp
(2)	virgin pulp	a_{21}	0	0
(3)	log chips	0	a_{32}	0
(r)	secondary pulp	a_{r1}	0	0
(z)	old paper	0	0	a_{zr}

Table 4: Recycling of old paper in the paper manufacturing industry

We next need to incorporate Table 4 into the framework of the Dutch input-output table. The Dutch table is not detailed enough to identify paper, log chips, virgin pulp, and secondary pulp as separate branches of industry. We therefore had no choice but to assume that both 'paper' and 'virgin pulp' belong to the 'Paper, paper products, printing and publishing industry' (sector 7, henceforth called the 'paper industry' for simplicity), and 'log chips' to 'Wood and furniture industry' (sector 6, henceforth called the 'wood industry' for simplicity).

Since there is only one paper-producing sector, we implicitly assume that the demand for its output does not depend on the proportion of virgin and secondary pulp, a rather strong assumption.

Information on the degree of substitution between virgin and secondary pulp, on the recycling technology, on the collection and selection of old paper, on incineration and or landfill of discarded paper, was not available in a form that can be directly applied to the Dutch input-output table. We therefore made our own estimation based on available sources, the details of which are shown in the Appendix.

3.3 Computation results based on scenarios

3.3.1 Scenarios

We will now consider the economic and environmental impact of the following six scenarios each referring to different sets of the three basic parameters: the proportion of recycled goods (second pulp) in the total input (of pulp), θ, the efficiency of recycling technology, a_{zr}, and the efficiency of collection, β. At the time of writing, information on the state of the recycling of old paper in the Dutch paper industry was not available. I have therefore assumed that the realized data correspond to the state of no recycling.

Control θ=.20, β =1.0, $a_{zr} = 1.2$

A: **Increase in the proportion of second pulp** θ =0.40, the other parameters as in *Control*.

B: **Decline in the efficiency of collection** $\beta = 1.5$, the other parameters as in *Control*.

C: **Increase in the efficiency of collection** $\beta = 0.5$, the other parameters as in *Control*.

D: **Decline in the efficiency of recyling technology** $a_{zr} = 1.8$, the other parameters as in *Control*.

E: *A* **and** *B* θ =0.40, $\beta = 1.5$, the other parameters as in *Control*.

The efficiency of recycling technology a_{zr} refers to the amount of waste (old paper) needed to produce 1000 tonnes of recycled goods (second pulp). We say the efficiency of recycling technology increased (decreased) when a smaller (larger) amount of waste is needed to produce the same amount of recycled goods.

The efficiency of collection refers to the cost for intermediate goods and services needed to collect 1000 tonnes of old paper for recycling purposes. θ =1.5 refers to the situation where the cost increases to 1.5 times the level of *Control*, i.e., the efficiency of collection deteriorates by 50% relative to *Control*. This case may be of relevance, for example, to large Japanese cities where an increase in transport activities for the collection of waste could contribute to congestion.

For each of these scenarios we computed its impact on production (including recycling, collection of waste, and waste management) and the emission of CO_2 by use of (7) and the realized value of final demand in 1992. It was not possible to compute the second-order effect in the form given by the second term of the right hand side of (7), because information on the composition of waste was not available. We therefore computed not the 'full second effect' but a part of it that refers to the decrease in old paper to be treated in the waste management that resulted from the increased recycling. In particular, we replaced the expression inside the rightmost { } of (7) by $-X_z$. Accordingly, the second effect always has a negative impact on industrial production.

3.3.2 Results

Table 5 shows computation results, with figures referring to the rate of change in industrial production, collection activity, and emission of CO_2. The way the rate is defined differs among production, collection activity, and emission. The figures for the industry sector refer to the rate of change relative to the realized values. The figures for the collection of old paper, however, refer to the rate of change relative to *Control*, because we assumed the amount of collection of old paper for recycling to be zero in the realized data. Since the realized value was available for the emission of CO_2, we computed the rate of change relative to both the realized value and the *Control*. Corresponding to each scenario are two columns of figures, the first of which refers to the first effect, and the second to the total effect, including the partial second effect as mentioned above.

Effects of recycling We first compare the *Control* with the realized value to see the effects of recycling. As far as the first effect is concerned, recycling increases the production of petroleum and transport & storage due to the collection of waste, but decreases the production in all the other sectors, in particular in paper and wood & products. The emission of CO_2 decreases relative to the realized level. When the second effect is included, we observe a reduction in the level of production in all the industry sectors including petroleum and transport & storage, and a further reduction in CO_2 emission. A further increase in the proportion of recycled input increases the amount of old paper collected by 44 percent. It is noteworthy that, even for the first effect, both the rate of increase in petroleum and transport & storage and in CO_2 emission decline relative to the realized level. We thus cannot observe any net increase in CO_2 emission due to the increased transport activity for recycling.

Efficiency of collection When the efficiency of collection deteriorates by 50 percent, its first effect takes the form of an increase in the production of petroleum, transport, construction, and in CO_2 emission relative to the realized level. As for the total effect, including the 2nd effect, however, the level

Scenario	*Control*		*A*		*B*	
Parameters	θ: 0.2, β: 1, a_{zr}: 1.2		θ: 0.4, β: 1 a_{zr}: 1.2		θ: 0.2, β: 1.5, a_{zr}: 1.2	
sector	first effect	total effect	first effect	total effect	first effect	total effect
Agriculture	-0.00008	-0.00024	-0.00020	-0.00043	-0.00004	-0.00020
Crude petroleum	-0.00046	-0.00162	-0.00100	-0.00267	-0.00039	-0.00155
Other mining	-0.00011	-0.00082	-0.00033	-0.00136	-0.00002	-0.00074
Food	-0.00008	-0.00018	-0.00018	-0.00032	-0.00006	-0.00016
Textile & products	-0.00023	-0.00076	-0.00050	-0.00126	-0.00019	-0.00072
Wood & products	-0.00202	-0.00297	-0.00393	-0.00529	-0.00197	-0.00292
Paper & products	-0.04456	-0.04523	-0.08542	-0.08634	-0.04448	-0.04515
Petroleum	0.00024	-0.00159	0.00019	-0.00243	0.00046	-0.00136
Chemical	-0.00045	-0.00145	-0.00101	-0.00244	-0.00041	-0.00141
Rubber	-0.00039	-0.00137	-0.00089	-0.00229	-0.00036	-0.00134
Building materials	-0.00028	-0.00114	-0.00066	-0.00191	-0.00022	-0.00108
Basic metals	-0.00009	-0.00081	-0.00028	-0.00131	-0.00003	-0.00075
Metal products & machinery	-0.00013	-0.00100	-0.00039	-0.00165	-0.00004	-0.00092
Manufacturing n.e.c.	-0.00010	-0.00086	-0.00032	-0.00141	-0.00003	-0.00079
Electricity	-0.00043	-0.00434	-0.00118	-0.00680	-0.00024	-0.00415
Other public utilities	-0.00017	-0.00182	-0.00045	-0.00282	-0.00011	-0.00176
Construction	-0.00002	-0.00088	-0.00014	-0.00138	0.00005	-0.00081
Transport & storage	0.00018	-0.00066	0.00009	-0.00113	0.00040	-0.00045
Environmental cleansing	-0.00051	-0.00409	-0.00127	-0.00641	-0.00037	-0.00396
Other services	-0.00019	-0.00092	-0.00055	-0.00159	-0.00010	-0.00082
old paper: relative to *Control*			0.43585	0.43541	0.00008	0.00008
CO_2: relative to actual data	-0.00013	-0.00202	-0.00080	-0.00352	0.00024	-0.00165
CO_2: relative to *Control*			-0.00067	-0.00150	0.00037	0.00037

Scenario	*C*		*D*		*E*: Combination of *A* and *B*	
Parameters	θ: 02., β: .5, a_{zr}: 1.2		θ: 0.2, β: 1 a_{zr}: 1.8		θ: 0.4, β: 1.5, a_{zr}: 1.2	
sector	first effect	total effect	first effect	total effect	first effect	total effect
Agriculture	-0.00012	-0.00028	-0.00004	-0.00028	-0.00014	-0.00038
Crude petroleum	-0.00053	-0.00170	-0.00039	-0.00213	-0.00089	-0.00257
Other mining	-0.00020	-0.00091	-0.00002	-0.00109	-0.00020	-0.00123
Food	-0.00010	-0.00020	-0.00006	-0.00021	-0.00015	-0.00029
Textile & products	-0.00028	-0.00081	-0.00019	-0.00099	-0.00044	-0.00120
Wood & products	-0.00206	-0.00301	-0.00197	-0.00340	-0.00387	-0.00523
Paper & products	-0.04464	-0.04530	-0.04448	-0.04548	-0.08532	-0.08623
Petroleum	0.00001	-0.00181	0.00046	-0.00227	0.00051	-0.00210
Chemical	-0.00049	-0.00148	-0.00041	-0.00191	-0.00095	-0.00239
Rubber	-0.00043	-0.00140	-0.00036	-0.00182	-0.00084	-0.00224
Building materials	-0.00033	-0.00120	-0.00022	-0.00152	-0.00058	-0.00183
Basic metals	-0.00015	-0.00087	-0.00003	-0.00111	-0.00020	-0.00123
Metal products & machinery	-0.00021	-0.00109	-0.00004	-0.00136	-0.00027	-0.00153
Manufacturing n.e.c.	-0.00018	-0.00094	-0.00003	-0.00117	-0.00021	-0.00131
Electricity	-0.00062	-0.00453	-0.00024	-0.00611	-0.00091	-0.00653
Other public utilities	-0.00023	-0.00188	-0.00011	-0.00259	-0.00036	-0.00273
Construction	-0.00009	-0.00095	0.00005	-0.00125	-0.00004	-0.00128
Transport & storage	-0.00003	-0.00088	0.00040	-0.00087	0.00040	-0.00082
Environmental cleansing	-0.00064	-0.00422	-0.00037	-0.00574	-0.00108	-0.00622
Other services	-0.00029	-0.00102	-0.00010	-0.00119	-0.00041	-0.00145
old paper: relative to *Control*	-0.00008	-0.00008	0.50012	0.49960	0.43601	0.43558
CO_2: relative to actual data	-0.00050	-0.00239	0.00024	-0.00260	-0.00027	-0.00299
CO_2: relative to *Control*	-0.00037	-0.00037	0.00037	-0.00058	-0.00014	-0.00096

(Except for when otherwise stated, the figures refer to the rate of change relative to the actual value.
θ: share of 2nd pulp in pulp input, β: efficiency of collection (inverse), a_{zr}: recycling efficiency)

Table 5: Effects of recycling on industrial production and CO_2 emission under several scenarios

of production declines in each of the industry sectors, and CO_2 emission also decreases relative to the realized level while slightly increases relative to the *Control*. It appears that a reduction of waste to be treated in waste management contributes to a decline in CO_2 emission even when the efficiency of collection declines. When a deterioration in the efficiency of collection is accompanied with an increase in the of use of recycled input, CO_2 emission declines relative to the *Control* even for the first effect.

Efficiency of recycling technology When the efficiency of recycling technology declines, a greater amount of waste is needed to produce the same amount of output. In its first effect, this results in an increase in the production of petroleum, transport, and construction, and in CO_2 emission relative to the realized level. As for the total effect, CO_2 emission decreases relative to the realized level, due mainly to the reduction in the activity of the waste management sector. On the other hand, an increase in the efficiency of recycling technology reduces the collection of waste, and slightly increases CO_2 emission relative to the *Control*, while the emission still decreases relative to the realized level. Given this result, one might conclude that a reduction in the efficiency of recycling technology could be an effective way of achieving a reduction in both the amount of waste and CO_2 emission. This conclusion is wrong, even allowing for the fact that our exercise is based on a simple numerical prototype, and not on a fully-fledged empirical model. This is because a reduction in the efficiency of recycling technology results in an increase in the amount of waste that is not recycled, i.e., to an increase in the generation of waste in the recycling sector. Since our model does not deal with the generation of waste, we do not take account of this aspect.

4 Concluding remarks

We extended the environmental input-output model of Leontief and Duchin for analyzing the economic and environmental impact of the collection, recycling, and waste management of a given stock of waste under consideration of interdependence among different sectors of an economy. As an empirical illustration of the model, I constructed a numerical prototype for the recycling of old paper based on the Dutch NAMEA data set and information on waste management and the recycling of old paper in Japan.

According to the results of the scenario analysis based on the numerical model, the recycling of old paper not only reduces the amount of waste but also reduces the total emission of CO_2. An increase in the proportion of the use of old paper as a material for pulp in place of log chips further strengthens this tendency. Given the nature of the model as a numerical prototype, it is unwarranted to derive real implications.

It is often argued that an increase in recycling, while certainly contributing to saving virgin materials, may increase the total emission of CO_2 because of the increased need for transporting waste to recycling centers. It is hoped that the model presented in this paper will provide useful information for this sort of discussion that can only be settled by quantitative information based on a solid theoretical model. The model presented above is merely a numerical prototype. More detailed information on the composition of waste, on technology of collection, recycling and waste management, as well as emission of CO_2 at a level of at least 100 sectors will be necessary for constructing an empirical model that is suitable for actual analysis.

In our scenario analysis, the proportion of the use of recycled input(s) was exogenously given as a parameter. In reality, however, this magnitude is determined by, among others, the extent to which recycled goods and virgin materials are substitutable for each other. Their relative prices and quality as well as the technology of sectors using them are important determinants of this extent. The price of recycled goods in turn largely depends on the efficiency of collection and recycling technology. The model presented above, by its nature, is a quantity model that can be effective for evaluating quantitative effects of an exogenously given proportion of recycled goods. For economically explaining the proportion, one needs a price model that is dual to the quantity model, a sketch of which is given in Nakamura (1996). These are issues for future research.

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A Detailed Set Up of the Numerical Model

A.1 Substitution between secondary and virgin pulp

Secondary pulp is an input to the paper industry, and is supposed to be a substitute for the output of the paper industry, that is used as an input to to the paper industry, and for wood & products. Let $\theta \in [0, 1]$ be an exogenously given parameter that indicates the proportion of the use of secondary pulp. We regard $(a_{6,7} + a_{7,7})(1 - \theta)$ as the amount of input of virgin pulp, and $a_{r,7}\theta$ as that of secondary pulp.

A.2 Recycling Technology

Our estimate of the recycling technology (manufacturing of secondary pulp from old paper) is based on the input structure of the paper industry given by the Dutch input-output table, except for the input of old paper that has to be estimated from other sources. Secondary pulp can be produced using less input in general than virgin pulp, and almost without using any virgin materials in particular. We therefore modified the original column vector of input coefficients by setting the input from the sectors related to natural resources (sectors one to six) equal to zero, and by multiplying the input from the other sectors by 0.5.

We now turn to the estimate of a_{zr} that refers to the amount of old paper in 1000 tonnes that is needed to produce one monetary unit (million guilders) of secondary pulp. According to Morisawa et al (1993), the production of 1 tonne of secondary pulp requires 1.07 to 1.25 tonnes of old paper depending on the quality of the latter. As the standard case in our exercise (*Control*), we choose that 1.2 tonnes of old paper is needed to produce 1 tonne of secondary pulp. We still have to convert the unit of production of secondary pulp from physical to monetary units. The 1992 value of 1 tonne of paper and paper board was about 1400 Dutch guilders (Ministry of International Trade and Industry, 1992. The amount in Japanese yen was converted to Dutch guilders using the monthly mean value of the exchange rate for May 1992). For analytical convenience, we assumed that the value of 1000 tonnes of secondary pulp was 1000 guilders, and obtained $a_{zr} = 1.2$ (recall that the monetary unit of the Dutch table is one million guilders and the physical unit is 1000 tonnes).

A.3 Collection

Our estimate of the input structure of the collection of waste for recycling is based on the input structure of the transportation industry given by the Dutch input-output table. Its level of activity has to be converted to the level corresponding to the collection of 1000 tonnes of waste. According to Tanaka (1996, p.426, Table7), the collection of 1000 tonnes of waste costs about 238000 guilders (conversion from Japanese yen to Dutch guilders by the exchange rate as mentioned above). We therefore multiplied the input coefficients of the transport sector by .238 to obtain the coefficients that correspond to the collection of 1000 tonnes.

A.4 Waste management

We used the column of input coefficients of the environmental cleansing sector (sector 19) as the input structure of waste management after having transformed it to the level that corresponds to the treatment of 1000 tonnes of waste. Since the Dutch table gives the amount of waste treated in 1000 tonnes, this transformation was straightforward.