A General Equilibrium Analysis of Environmental and Economic Interaction with Material Circulation - A CGE-modeling Approach –

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Introduction

Waste has been throwing a serious issue to our present society. To cope with this issue, a terminology "zero-emissions" has very often been used at various phases. As this name suggests, the concept of zero-emissions implies a social system where no waste is discharged ultimately. This concept was initially advocated by United Nations University in 1995 (Capra and Pauli, 1995), and since its initiation, study of zero-emissions has attracted many researchers, in particular, in Japan (Suzuki, 2000).

Looking at the current study situation , however, it has still stayed at an initial stage. For example, studies have been concentrated on the kind of materials used, or the kind of waste generated in a specific production system (Suzuki, 2000).

Besides the natural science or engineering approach, study of zero-emissions has been a considerably unexplored field in environmental economics despite the fact of potentially attractive and important theme. For example, it would be significantly worth examined how the economic impacts of promotion and realization of a zero-emissions oriented society would be. But there have been little attempts for this topic in environmental economics.

Taking these backgrounds into account, this article aims to extend the authors' previous study concerning this field (Miyata and Pang, 1999a and 1999b), and then to evaluate the possibility and economic impacts of the zero-emissions oriented society taking Aichi Prefecture in Japan as a study region. More concretely, this paper emphasizes a *CGE*-modeling approach to evaluate the following contents: reduction in the volume of final unused materials due to improvement of recycling rates resulting from technological progress, changes in the scale of waste recycling and abatement activities, industrial structural change towards a zero-emissions society, and impacts of environmental subsidies for promotion of a zero-emissions oriented society.

Economic and Material Circulation Accounting Matrix

The authors have already proposed an economic-waste accounting matrix in their previous studies (Miyata and Pang, 1999a and 1999b). Instead of the former concept, the present paper introduces a significantly extended new accounting matrix. The structure of this new matrix is illustrated in Table 2. In the new accounting matrix, waste generated by each industry is classified into more detailed categories i.e. 26 types. And then recycling, internal and external abatements are considered for each type of waste of each industry.

Table 1 Classification of Recycled Commodities

recycled commodities	abbreviation	corresponding waste	6 digit classification in I/O table	2 digit classification in I/O table
recycled construction materials Ⅰ	RC Ⅰ	cinder and slag	other non-metallic ore	mining
recycled construction materials Ⅱ	RC Ⅱ	organic sludge, inorganic sludge, and construction waste	gravel and quarrying	mining
recycled construction materials Ⅲ	RC Ⅲ	soot and dust	other non-metallic ore	mining
compost	COM	animal waste	organic fertilizers	beverage and feed
recycled organic fertilizers	ROF	organic sludge	organic fertilizers	beverage and feed
recycled organic fertilizers and feeds	ROFF	animal and vegetable residue	organic fertilizers and feeds	beverage and feed
recycled fiber	RF	waste fiber	fabrics	fabric and textile
recycled wooden products	RW	waste wood	timber, plywood, and wooden chip	wooden product
recycled pulp and paper	RPP	waste paper	pulp and paper	pulp and paper
recycled chemical fertilizers	RCF	cinder, inorganic sludge	chemical fertilizer	chemical
recycled acid and alkali	RAA	waste acid and alkali	inorganic chemicals basic products	chemical
recycled oils	RO	waste oil	petroleum refinery products	petroleum refinery and coal
recycled plastics	RP	waste plastic	plastic products	plastic
recycled tires	RT	waste tire	tires and inner tubes	rubber
recycled rubber	RR	waste rubber	rubber products	rubber
recycled glass and construction materials Ⅳ	RG	waste glass and porcelain	glass, and miscellaneous ceramic, stone and clay products	ceramic, stone, and clay
recycled iron	RI	slag and waste metal	crude steel	iron and steel
recycled non-ferrous metals	RNF	slag and waste metal	non-ferrous metals	non-ferrous metal

Moreover, waste recycling , internal and external abatement activities are explicitly specified with their factor inputs, i.e. intermediate, labor, and capital inputs. Recycled materials are discriminated from virgin commodities, being in turn used as intermediate and final goods. Table 1 depicts the classification of recycled materials.

Table 3 shows an estimation result of the new economic and material circulation accounting matrix in anaggregate format. The original format of this matrix is composed of 34 industries, 18 recycling activities (*R*-activities), 34 internal waste abatement activities (*S*-activities), one external waste abatement activity (*C*-activity), the government, aggregate household, capital, labor, capital account, and the external sector. Industries, *R*- and *S*-activities are aggregated into respective sectors yielding Table 3. Here, *C*-activity is defined as an aggregate activity that is composed of waste abatement firms and public waste abatement activities.

From this table, one can see that industries in Aichi Prefecture totally produce 66 trillion and 75.95 billion yen of output in 1994, generating 16.84 million tons of waste (including industrial general waste). Households earn 26 trillion and 63.04 billion yen of income, consume 15 trillion and 16.23 billion yen, and discharge 2.14 million tons of waste.

2.80 million tons of industrial waste is disposed by *S*-activities at the cost of 3.9 billion yen. 5.92

million tons of industrial and household waste is treated by *C*-activities at the cost of 16.1 million yen. Finally, 10.25 million tons of waste is recycled costing 24.02 million yen.

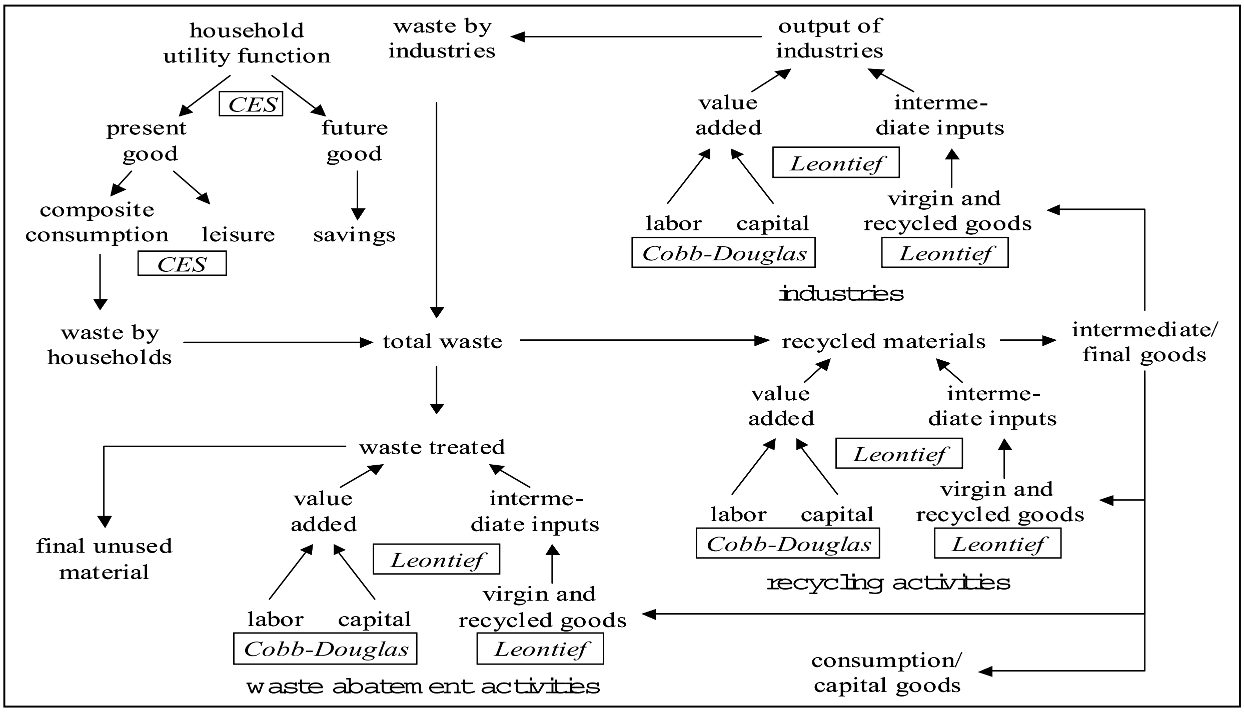

Figure 1 Hierarchical Structure of the Economic and Material Circulation CGE Model

		production activities	recycling activities		waste abatement activities		final demand	total
		34 industries	recycled construction materials	recycled metals	self-abatement	consigned abtement		
production activities	34 industries	intermediate inputs in industries; recycled goods	intermediate inputs in recycling; virgin goods		intermediate inputs in waste abatement			demand for virgin goods
recycling activities	recycled construction materials : recycled metals	purchase of recycled goods	supply of recycled goods		purchase of recycled goods			demand for recycled goods
waste abatement activities	self-abatement	???????? waste; payment to waste abatement	material transformation		?			demand for waste abatement
	consigned abtement						household waste	
value added								
total		supply of virgin goods	supply of recycled goods		total waste abated		total	

Table 2 Structure of Economic-Material Circulation Accounting Matrix

Table 3 Estimated Economic and Material Circulation Accounting Matrix of 1994 Aichi's Economy

		production activities	recycling activities	waste abatement activities		institution		production factors		capital accumulation	external sector	total
		34 industries	18 recycling activies	self-abatement	consigned abatement	government	households	capital	labor			
production activities	34 industries	35,476,581	172,849	2,669	29,541	1,962,981	15,162,063	0	0	7,337,704	6,615,136	66,759,524
recycling activies	18 recycling activies	239,846	55	0	8	0	227	0	0	31	0	240,167
waste abatement activities	self-abatement	3,875	0	0	0	0	0	0	0	0	0	3,875
	consigned abatement	96,280	0	0	0	57,085	7,643	0	0	0	0	161,008
institution	government	2,285,022	9,166	0	3,152	0	6,118,189	0	0	0	1,324,915	9,740,444
	households	0	0	0	0	2,149,822	0	8,008,547	16,197,355	0	274,696	26,630,420
production factors	capital	7,518,146	28,719	91	13,483	0	0	0	0	0	448,107	8,008,547
	labor	16,672,090	17,411	629	103,499	0	0	0	0	0	253,257	17,046,886
capital finance		4,467,684	11,967	486	11,324	1,753,243	5,342,298	0	0	0	232,738	11,819,740
external sector		0	0	0	0	3,817,313	0	0	849,531	4,482,005	0	9,148,849
total		66,759,525	240,167	3,875	161,008	9,740,444	26,630,420	8,008,547	17,046,886	11,819,740	9,148,849	149,559,461
waste generation /recycling/abatement		16,837	−10,250	−2,800	−5,923	0	2,136	0	0	0	0	0

Note: Figures in transaction of econmic sectors are in million yen, while waste generation/recycling/abatement are in thousand tons

The Model

The proposed model in this study is static one similar to our previous model. Figure 1 graphically illustrates its hierarchical structure. This section explains details of the model.

A. Main Assumptions of the Model

Main assumptions made for the model are summarized here, however, there are many additional assumptions made in the model. Those will be explained at appropriate places to avoid unnecessary complexity.

(1) 1994 Aichi's economy is examined. Economic agents are households, 34 industries, 18 *R*-activities, 34 *S*-activities, *C*-activity, the government, and the external sector. Waste discharged by industries and households are classified into 26 types.

(2) *R*-activities process a part of industries' and households' waste, and supply recycled goods as intermediate and final commodities. *R*-activities are assumed to take firm's behavior.

(3) Each industry is equipped with its own *S*-activity. Each *S*-activity is assumed to abate only waste which is discharged by its associated industry. Operation of each *S*-activity is managed by its industry.

(4) *C*-activity is composed of public and private abatement activities, and disposes of industrial and household wastes that are neither recycled nor self-abated. *C*-activity is assumed to take firm's behavior.

(5) Recycled goods are discriminated from virgin goods.

(6) 55 markets are considered in the model. They are 34 virgin commodity, 18 recycled commodity, one external waste abatement service, labor, and capital markets. These are assumed to be perfectly competitive, and in equilibrium in 1994.

Table 4 Classification of Industries

industry	abbreviation	Industry	abbreviation
1. agriculture and forestry	AF	18. metal product	MT
2. fishery	FS	19. general machinery	GM
3. mining	MI	20. electric machinery	EM
4. food	FO	21. transportation equipment	TE
5. beverage and feed	BF	22. precision machinery	PM
6. fabric and textile	FT	23. other manufacturing	OM
7. wooden product	WD	24. construction	CO
8. furniture	FU	25. electric power	EP
9. pulp and paper	PP	26. gas, steam, and hot water supply	GS
10. chemical	CH	27. water supply and sewage disposal	WS
11. petroleum refinery and coal	PC	28. trade	TR
12. plastic	PL	29. financial service, insurance, and real estate	FI
13. rubber	RB	30. land transport	LT
14. leather	LE	31. other transport	OT
15. ceramic, stone, and clay	CS	32. communication and broadcasting	CB
16. iron and steel	IS	33. car repairing	CR
17. non-ferrous metal	NF	34. other services	OS

B. Industries and Waste Self-abatement Activities

Each industry produces its commodities inputting intermediate goods, labor, and capital, while it generates waste. Waste is recycled by *R*-activities, disposed by the industry itself employing its associated *S*-activity, and treated by *C*-activity. Portions of wastes recycled, internally and externally abated to the total waste generated by each industry and household are fixed. Each industry pays internal and external waste abatement costs.

Leontief technology is assumed in intermediate inputs, while *Cobb-Douglas* technology is applied in labor and capital inputs. Constant returns to scale are assumed in the technology of each industry. The technology in *S*-activities is also *Leontief* and *Cobb-Douglas* with respect to intermediate inputs, and labor and capital inputs, respectively, with constant returns to scale.

Profit maximization in industry's behavior becomes cost minimization given its output, due to linear homogeneity in the production technology. Note that each intermediate input in each industry is specified as a composite of virgin and recycled goods considerably differing from our previous study. In what follows, every intermediate input is specified as a composite of virgin and recycled commodities for general expression. For notational convenience, virgin and recycled goods are abbreviated by *V*- and

R-goods, respectively, and a composite of *V*- and *R*-commodities by *V*/*R*-composite hereafter.

$$\begin{aligned} & min \quad \sum_{i=1}^{34} p_{ij}^{V} x_{ij}^{V} + (1+tp_{Vj})(w \cdot L_{Vj} + r \cdot K_{Vj}) + \sum_{i=1}^{34} p_{ij}^{T} x_{ij}^{T} + (1+tp_{Tj})(w \cdot L_{Tj} + r \cdot K_{Tj}) + q_C WC_j \\ & with\ respect\ to \quad x_{ij}^{V}, L_{Vj}, K_{Vj}, x_{ij}^{T}, L_{Tj}, K_{Tj}, WC_j \qquad (j=1,\ldots,34) \end{aligned} \tag{1}$$

subject to

$$X_j = min\,\{ \frac{1}{a_{V0j}} f_{Vj}(L_{Vj}, K_{Vj}), \frac{x_{1j}^{V}}{a_{1j}^{V}}, \ldots, \frac{x_{34j}^{V}}{a_{34j}^{V}} \} \tag{2}$$

$$x_{ij}^{V} \equiv x_{Vij}^{\alpha_{Vij}} \prod_{k=1}^{18} z_{Vkij}^{\alpha_{Vkij}} \quad (\alpha_{Vij} + \sum_{k=1}^{18} \alpha_{Vkij} = 1) \tag{3}$$

$$WG_{kj} \equiv \varsigma_{kj} X_j \quad (k=1,\ldots,26,\ j=1,\ldots,34) \tag{4}$$

$$WT_j \equiv \sum_{k=1}^{26} \eta_{kj} WG_{kj} \tag{5}$$

$$WT_j = min\,\{ \frac{1}{a_{T0j}} f_{Tj}(L_{Tj}, K_{Tj}), \frac{x_{1j}^{T}}{a_{1j}^{T}}, \ldots, \frac{x_{34j}^{T}}{a_{34j}^{T}} \} \tag{6}$$

$$x_{ij}^{T} \equiv x_{Tij}^{\alpha_{Tij}} \prod_{k=1}^{18} z_{Tkij}^{\alpha_{Tkij}} \quad (\alpha_{Tij} + \sum_{k=1}^{18} \alpha_{Tkij} = 1) \tag{7}$$

$$WC_j \equiv \sum_{k=1}^{26} \theta_{kj} WG_{kj} \tag{8}$$

$$f_{Vj}(L_{Vj}, K_{Vj}) \equiv A_{Vj} L_{Vj}^{\alpha_{Vj}} K_{Vj}^{1-\alpha_{Vj}} \tag{9}$$

$$f_{Tj}(L_{Tj}, K_{Tj}) \equiv A_{Tj} L_{Tj}^{\alpha_{Tj}} K_{Tj}^{1-\alpha_{Tj}} \tag{10}$$

where

p^{V}_{ij} : price index of intermediate input of *V*/*R*-composite *i* in industry *j*

x^{V}_{ij} : intermediate input of *V*/*R*-composite *i* in industry *j*

tp_{Vj} : net indirect tax rate on industry *j*

w: wage rate

L_{Vj} : labor input in industry *j*

r : capital return rate

K_{Vj} : capital input in industry *j*

p^{T}_{ij} : price index of intermediate input of *V*/*R*-composite *i* in *S*-activity *j*

x^T_{ij} : intermediate V/R-composite input i in S-activity j

tp_{Tj} : net indirect tax rate on S-activity j

L_{Tj} : labor input in S-activity j

K_{Tj} : capital input in S-activity j

q_C : price of service of C-activity

WC_j : volume of waste discharged by industry j and disposed by C-activity

X_j : output of industry j

a_{V0j} : value added rate in industry j

a^V_{ij} : intermediate input coefficient of V/R-composite i in industry j

x_{Vij} : virgin commodity i in intermediate V/R-composite i in industry j

α_{Vij} : share parameter on virgin commodity i in intermediate V/R-composite i in industry j

z_{Vkij} : recycled commodity k in intermediate V/R-composite i in industry j

α_{Vkij} : share parameter on recycled good k in intermediate V/R-composite i in industry j

WG_{kj} : volume of waste of type k discharged by industry j

ζ_{kj} : marginal waste discharge of type k in industry j

WT_j : volume of waste disposed by S-activity j

η_{kj} : rate of internal abatement on waste of type k discharged by industry j

a_{T0j} : value added rate in industry j

a^T_{ij} : intermediate input coefficient of V/R-composite i in S-activity j

x_{Tij} : virgin commodity i in intermediate V/R-composite i in S-activity j

α_{Tij} : share parameter on virgin commodity i in intermediate V/R-composite i in S-activity j

z_{Tkij} : recycled commodity k in intermediate V/R-composite i in S-activity j

α_{Tkij} : share parameter on recycled commodity k in intermediate V/R-composite i in S-activity j

θ_{kj} : rate of external abatement on waste of type k discharged by industry j

A_{Vj} : efficiency parameter in industry j's production function

α_{Vj} : share parameter on labor input in industry j's production function

A_{Tj} : efficiency parameter in S-activity j's production function

α_{Tj} : share parameter on labor input in S-activity j's production function

Solving cost minimization problem expressed by equations (1) to (10) given an output X_j, conditional demands for intermediate goods, labor, and capital are derived with price indices of intermediate V/R-composites.

Conditional demands for intermediate goods, labor, and capital, and price indices of intermediate *V*/*R*-composites.

$$x_{ij}^{V} = a_{ij}^{V} X_{j}$$

$$z_{Vkij} = x_{ij}^{V} \frac{\alpha_{Vkij}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Vij}} \right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Vlij}} \right]^{\alpha_{Vlij}}$$

$$x_{Vij} = x_{ij}^{V} \frac{\alpha_{Vij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Vij}} \right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Vlij}} \right]^{\alpha_{Vlij}}$$

$$L_{Vj} = \left[\frac{a_{Vj} r}{(1 - a_{Vj}) w} \right]^{1-\alpha_{Vj}} \frac{a_{V0j} X_{j}}{A_{Vj}}$$

$$K_{Vj} = \left[\frac{(1 - a_{Vj}) w}{a_{Vj} r} \right]^{\alpha_{Vj}} \frac{a_{V0j} X_{j}}{A_{Vj}}$$

$$x_{Tij} = a_{ij}^{T} WT_{j}$$

$$x_{Tij} = x_{ij}^{T} \frac{\alpha_{Tij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Tij}} \right]^{\alpha_{Tij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Tlij}} \right]^{\alpha_{Tlij}}$$

Conditional demands for intermediate goods, labor, and capital, and price indices of intermediate *V*/*R*-composites.

$$x_{ij}^{V} = a_{ij}^{V} X_{j}$$

$$z_{Vkij} = x_{ij}^{V} \frac{\alpha_{Vkij}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Vij}} \right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Vlij}} \right]^{\alpha_{Vlij}}$$

$$x_{Vij} = x_{ij}^{V} \frac{\alpha_{Vij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Vij}} \right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Vlij}} \right]^{\alpha_{Vlij}}$$

$$L_{Vj} = \left[\frac{a_{Vj} r}{(1 - a_{Vj}) w} \right]^{1-\alpha_{Vj}} \frac{a_{V0j} X_{j}}{A_{Vj}}$$

$$K_{Vj} = \left[\frac{(1 - a_{Vj}) w}{a_{Vj} r} \right]^{\alpha_{Vj}} \frac{a_{V0j} X_{j}}{A_{Vj}}$$

$$x_{Tij} = a_{ij}^{T} WT_{j}$$

$$x_{Tij} = x_{ij}^{T} \frac{\alpha_{Tij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Tij}} \right]^{\alpha_{Tij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Tlij}} \right]^{\alpha_{Tlij}}$$

$$z_{Tkij} = x_{ij}^{T} \frac{\alpha_{Tkij}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Tij}} \right]^{\alpha_{Tij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Tlij}} \right]^{\alpha_{Tlij}}$$

$$L_{Tj} = \left[\frac{\alpha_{Tj} r}{(1-\alpha_{Tj}) w} \right]^{1-\alpha_{Tj}} \frac{a_{T0j} WT_j}{A_{Tj}}$$

$$K_{Tj} = \left[\frac{(1-\alpha_{Tj}) w}{\alpha_{Tj} r} \right]^{\alpha_{Tj}} \frac{a_{T0j} WT_j}{A_{Tj}}$$

$$p_{ij}^{V} = \left[\frac{p_{Vi}}{\alpha_{Vij}} \right]^{\alpha_{Vij}} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{Vkij}} \right]^{\alpha_{Vkij}}$$

$$p_{ij}^{T} = \left[\frac{p_{Vi}}{\alpha_{Tij}} \right]^{\alpha_{Tij}} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{Tkij}} \right]^{\alpha_{Tkij}}$$

where

p_{Vi} : price of virgin commodity *i*

p_{Rk} : price of recycled commodity *k*

Free entry assumption ensures zero profit condition in every industry, yielding a supply function.

$$p_{Vj} X_j = \sum_{i=1}^{34} p_{Vi} x_{Vij} + \sum_{i=1}^{34} \sum_{k=1}^{18} p_{Rk} z_{Vkij} + (1+tp_{Vj})[w \cdot L_{Vj} + r \cdot K_{Vj}]$$

$$+ \sum_{i=1}^{34} p_{Vi} x_{Tij} + \sum_{i=1}^{34} \sum_{k=1}^{18} p_{Rk} z_{Tkij} + (1+tp_{Tj})[w \cdot L_{Tj} + r \cdot K_{Tj}] + q_C WC_j$$

The shadow price of *S*-activity *j*' s service, q_j, is calculated from the *Lagrangian* multiplier associated with the technological constraint (6).

$$q_j = \sum_{i=1}^{34} p_{Vi} a_{Tij} + \sum_{i=1}^{34} \sum_{k=1}^{18} p_{Rk} c_{Tkij} + w \cdot l_{Tj} + r \cdot k_{Tj}$$

$a_{Tij} \equiv \partial x_{Tij} / \partial WT_j$, $c_{Tkij} \equiv \partial z_{Tkij} / \partial WT_j$,
$l_{Tj} \equiv \partial L_{Tj} / \partial WT_j$, $k_{Tj} \equiv \partial K_{Tj} / \partial WT_j$

where

q_j : shadow price of *S*-activity *j*'s service

C. External Waste Abatement Activity

C-activity actually disposes of both industrial and household waste. In the model, *C*-activity is assumed to abate waste which is neither self-treated nor recycled. The technology in *C*-activity is assumed to be the same as that in *S*-activities, but this activity is supposed to take firm's behavior. That is, cost minimizing is the optimal behavior of *C*-activity under given industries' and households' waste to be reduced.

$$min\sum_{i=1}^{34} p_i^C x_i^C + (1+tp_C)(w\cdot L_C + r\cdot K_C) \tag{26}$$

with respect to x^C_i, L_C, K_C

subject to

$$WC \equiv \sum_{j=1}^{34}\sum_{k=1}^{26}\theta_{kj} WG_{kj} + (1-\sum_{k=1}^{26}\mu_k)WH \tag{27}$$

$$WC = min\{\frac{1}{a_{C0}} f_C(L_C, K_C), \frac{x_1^C}{a_1^C}, \ldots, \frac{x_{34}^C}{a_{34}^C}\} \tag{28}$$

$$f_C(L_C, K_C) \equiv A_C L_C^{\alpha_C} K_C^{1-\alpha_C} \tag{29}$$

$$x_i^C \equiv x_{Ci}^{\alpha_{Ci}} \prod_{k=1}^{18} z_{Cki}^{\alpha_{Cki}} \quad (\alpha_{Ci} + \sum_{k=1}^{18}\alpha_{Cki} = 1) \tag{30}$$

where

p^C_i: price index of intermediate input of *V*/*R*-composite *i* in *C*-activity

x^C_i: intermediate input of *V*/*R*-composite *i* in *C*-activity

tp_C: net indirect tax rate on *C*-activity

L_C: labor input in *C*-activity

K_C: capital input in *C*-activity

WC: total volume of waste disposed by *C*-activity

μ_k: recycling rate on household waste of type *k*

WH: household waste

a_{C0}: value added rate in *C*-activity

a^C_i: intermediate input coefficient of *V*/*R*-composite *i* in *C*-activity

A_C: efficiency parameter in production function in *C*-activity

α_C: share parameter on labor input in production function in *C*-activity

x_{Ci}: virgin commodity *i* in intermediate *V*/*R*-composite *i* in *C*-activity

α_{Ci}: share parameter on virgin commodity *i* in intermediate *V*/*R*-composite *i* in *C*-activity

z_{Ckj} : recycled commodity *k* in intermediate *V*/*R*-composite *i* in *C*-activity

α_{Cki} : share parameter on recycled good *k* in intermediate *V*/*R*-composite *i* in *C*-activity

From the above-stated optimization problem, we obtain conditional demands for intermediate goods, labor, and capital with the price indices of intermediate *V*/*R*-composites.

$$x_i^C = a_i^C WC \tag{31}$$

$$x_{Ci} = x_i^C \frac{\alpha_{Ci}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Ci}} \right]^{\alpha_{Ci}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Cli}} \right]^{\alpha_{Cli}} \tag{32}$$

$$z_{Cki} = x_i^C \frac{\alpha_{Cki}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Ci}} \right]^{\alpha_{Ci}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Cli}} \right]^{\alpha_{Cli}} \tag{33}$$

$$L_C = \left[\frac{\alpha_C r}{(1-\alpha_C) w} \right]^{1-\alpha_C} \frac{a_{C0} WC}{A_C} \tag{34}$$

$$K_C = \left[\frac{(1-\alpha_C) w}{\alpha_C r} \right]^{\alpha_C} \frac{a_{C0} WC}{A_C} \tag{35}$$

$$p_i^C = \left[\frac{p_{Vi}}{\alpha_{Ci}} \right]^{\alpha_{Ci}} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{Cki}} \right]^{\alpha_{Cki}} \tag{36}$$

Zero profit condition is also realized in equilibrium yielding a supply function of *C*-activity.

$$q_C WC = \sum_{i=1}^{34} p_{Vi} x_{Ci} + \sum_{i=1}^{34} \sum_{k=1}^{18} p_{Rk} z_{Cki} + (1 + tp_C)[w \cdot L_C + r \cdot K_C] \tag{37}$$

D. Recycling Activities

R-activities process a part of industrial and household wastes, and supply recycled goods. It is assumed that waste transformed by *R*-activities is purchased free of cost from industries and households, but the quantity of waste inputted in *R*-activities imposes a technological constraint on the quantity of recycled commodities produced by *R*-activities.

R-activities are also assumed to take firm's behavior implying cost minimization of production costs under a given volume of waste to be recycled.

$$min \sum_{i=1}^{34} p_{ij}^R x_{ij}^R + (1 + tp_{Rj})(w \cdot L_{Rj} + r \cdot K_{Rj}) \qquad (j = 1, \ldots, 18) \tag{38}$$

with respect to x^R_{ij}, L_{Rj}, K_{Rj}

subject to

$$Z_j = min\{\frac{1}{a_{R0j}} f_R(L_{Rj}, K_{Rj}), \frac{x^R_{1j}}{a^R_{1j}}, \cdots, \frac{x^R_{34j}}{a^R_{34j}}, \frac{WZ_j}{a^R_{Zj}}\} \quad (39)$$

$$WR_k \equiv \sum_{j=1}^{34} \xi_{kj} \varsigma_{kj} X_j + \mu_k \cdot \kappa \cdot CC \quad (40)$$

$$WZ_j \equiv \sum_{k=1}^{26} \phi_{jk} WR_k \quad (41)$$

$$f_{Rj}(L_{Rj}, K_{Rj}) \equiv A_{Rj} L_{Rj}^{\alpha_{Rj}} K_{Rj}^{1-\alpha_{Rj}} \quad (42)$$

$$x^R_{ij} \equiv x_{Rij}^{\alpha_{Rij}} \prod_{k=1}^{26} z_{Rkij}^{\alpha_{Rkij}} \quad (\alpha_{Rij} + \sum_{k=1}^{18} \alpha_{Rkij} = 1) \quad (43)$$

where

p^R_{ij}: price index of intermediate input of *V*/*R*-composite *i* in *R*-activity *j*

x^R_{ij}: intermediate input of *V*/*R*-composite *i* in *R*-activity *j*

tp_{Rj}: net indirect tax rate on *R*-activity *j*

L_{Rj}: labor input in *R*-activity *j*

K_{Rj}: capital input in *R*-activity *j*

Z_j: recycled good supplied by *R*-activity *j*

a_{R0j}: value added rate in *R*-activity *j*

a^R_{ij}: intermediate input coefficient of *V*/*R*-composite *i* in *R*-activity *j*

WZ_j: waste input in *R*-activity *j*

a^R_{Zj}: waste input coefficient in *R*-activity *j*

WR_{kj}: waste recycled of type *k* discharged by industry *j*

ξ_{kj}: recycling rate on waste of type *k* discharged by industry *j*

κ: household marginal waste generation

CC: household composite consumption

ϕ_{jk}: proportion of waste of type *k* inputted to recycling activity *j*

A_{Rj}: efficiency parameter in production function in *R*-activity *j*

α_{Rj}: share parameter on labor input in production function in *R*-activity *j*

x_{Rij}: virgin commodity *i* in intermediate *V*/*R*-composite *i* in *R*-activity *j*

α_{Rij}: share parameter on virgin commodity *i* in intermediate *V*/*R*-composite *i* in *R*-activity *j*

z_{Rkij}: recycled commodity *k* in intermediate *V*/*R*-composite *i* in *R*-activity *j*

α_{Rkij}: share parameter on recycled good *k* in intermediate *V*/*R*-composite *i* in *R*-activity *j*

Conditional demands for intermediate, labor, capital, and waste inputs associated with the supply of recycled good Z_j are derived from the optimization problem described by equations (38) to (43). Similar to the other activities, price indices of intermediate *V*/*R*-composites and zero profit condition are also obtained.

$$x_{ij}^R = a_{ij}^R Z_j \quad @ \tag{44}$$

$$x_{Rij} = x_{ij}^R \frac{\alpha_{Rij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Rij}} \right]^{\alpha_{Rij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Rlij}} \right]^{\alpha_{Rlij}} \tag{45}$$

$$z_{Rkij} = x_{ij}^R \frac{\alpha_{Rkij}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Rij}} \right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Rlij}} \right]^{\alpha_{Rlij}} \tag{46}$$

$$L_{Rj} = \left[\frac{a_{Rj} r}{(1 - a_{Rj}) w} \right]^{1-\alpha_{Rj}} \frac{a_{R0j} Z_j}{A_{Rj}} \tag{47}$$

$$K_{Rj} = \left[\frac{(1 - a_{Rj}) w}{a_{Rj} r} \right]^{\alpha_{Rj}} \frac{a_{R0j} Z_j}{A_{Rj}} \tag{48}$$

$$WZ_j = a_{Zj}^R Z_j \quad @ \tag{49}$$

$$p_{ij}^R = \left[\frac{p_{Vi}}{\alpha_{Rij}} \right]^{\alpha_{Rij}} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{Rkij}} \right]^{\alpha_{Rkij}} \tag{50}$$

$$p_{Rj} Z_j = \sum_{i=1}^{34} p_{Vi} x_{Rij} + \sum_{i=1}^{34} \sum_{k=1}^{18} p_{Rk} z_{Rkij} + (1 + tp_{Rj})[w \cdot L_{Rj} + r \cdot K_{Rj}] \tag{51}$$

Note that the volume of waste processed in producing recycled goods (49) must coincide with the volume of waste in generation side (41). This point will be referred again in a later part.

E. Households

Households are assumed to be homogeneous with the fixed number of households. Thus one can consider that households share an aggregate single utility function. Households share a *CES* utility function of the present and future goods. Here, the present good is defined as a *CES* composite of present consumption goods and leisure time, while the future good is derived from saving.

Households choose a bundle of the present and future goods so as to maximize the utility function with a budget constraint. Then the present good is divided into a composite consumption good and a leisure time, being further disaggregated into virgin and recycled commodities. Household behavior is now described as follows:

$$\max_{G,H}\ u(G,H) \equiv \{\alpha^{1/\nu_1} G^{(\nu_1-1)/\nu_1} + (1-\alpha)^{1/\nu_1} H^{(\nu_1-1)/\nu_1}\}^{\nu_1/(\nu_1-1)} \tag{52}$$

subject to

$$p_G \cdot G + p_H \cdot H = (1-ty)FI - TrHO \tag{53}$$

$$FI \equiv (1-l_o)w \cdot E + LI + (1-k_o)(1-k_r)r \cdot KS + KI + TrGH + TrOH \tag{54}$$

where

G: household present consumption

H: household future consumption

α: share parameter in utility function

ν_1: elasticity of substitution between present and future goods

p_G: price index of present good

p_H: price index of future good

ty: direct tax rate on households

FI: household full income

$TrHO$: current transfers from households to the external sector

l_o: rate of labor income transferred to the external sector

E: household initial labor endowment

LI: labor income transfers from the external sector to households (exogenous variable)

k_o: rate of capital income transferred to the external sector

k_r: capital depreciation rate

KS: initial capital stock endowed by households

KI: property income transferred from the external sector (exogenous variable)

$TrGH$: government current transfers to households

$TrOH$: current transfers from the external sector to households

Solving this utility maximization problem, demand functions for present and future goods are obtained yielding a household saving function.

$$G = \frac{\alpha[(1-ty)FI - TrHO]}{p_G^{\nu_1} \cdot \Delta} \tag{55}$$

$$H = \frac{(1-\alpha)[(1-ty)FI - TrHO]}{p_H^{v_1} \cdot \Delta} \tag{56}$$

$$S = p_H H / p_s \tag{57}$$

$$\Delta \equiv \alpha p_G^{1-v_1} + (1-\alpha) p_H^{1-v_1} \tag{58}$$

where

S: household real saving

p_s: price of saving good

Then maximizing the demand for present good (55) with a budget constraint yields a composite consumption and a leisure demand functions.

$$\max_{CC,F} \ G \equiv \{\beta^{1/v_2} CC^{(v_2-1)/v_2} + (1-\beta)^{1/v_2} F^{(v_2-1)/v_2}\}^{v_2/(v_2-1)} \tag{59}$$

subject to

$$p \cdot CC + (1-ty)(1-l_o)w \cdot F = (1-ty)FI - TrHO - SH \tag{60}$$

$$SH \equiv P_S \cdot S \tag{61}$$

where

β: share parameter in sub-utility function

ν_2: elasticity of substitution between composite consumption and leisure time

F: leisure time

p: price index of composite consumption good

SH: household nominal savings

$$CC = \frac{\beta[(1-ty)FI - TrHO - SH]}{p^{v_2} \cdot \Omega} \tag{62}$$

$$F = \frac{(1-\beta)[(1-ty)FI - TrHO]}{[(1-ty)(1-l_o)w]^{v_2} \cdot \Omega} \tag{63}$$

$$LS = E - F \tag{64}$$

$$\Omega \equiv \beta p^{(1-v_2)} + (1-\beta)[(1-ty)(1-l_o)w]^{(1-v_2)} \tag{65}$$

where LS : household labor supply

Substituting composite consumption (62) and leisure time (63) into (59), the price index of the present good is derived as follows:

$$p_G = \{\beta\, p^{1-\nu_2} + (1-\beta)[(1-ty)(1-l_o)w]^{1-\nu_2}\}^{1/(\nu_2-1)} \tag{66}$$

Moreover, the composite consumption is disaggregated into *V*/*R*-composites by type through maximizing a *Cobb-Douglas* sub-sub utility function given household income and leisure time.

$$max\ CC \equiv \prod_{i=1}^{34} C_i^{C\gamma_i} \qquad (\sum_{i=1}^{34} \gamma_i = 1) \tag{67}$$

subject to

$$\sum_{i=1}^{34} p_i^D \cdot C_i^C = (1-ty)Y - TrHO - SH \tag{68}$$

$$Y \equiv (1\text{-}l_0)w \cdot LS + LI + (1\text{-}k_0)(1\text{-}k_r)r \cdot KS + KI + TrGH + TrOH \tag{69}$$

where

C^C_i: household consumption of *V*/*R*-composite good *i*

γ_i: share parameter in sub-sub-utility function

p^D_i: price index of *V*/*R*-composite consumption good *i*

Y: household income

From this optimization problem, *V*/*R*-composites by type are derived with the price index of *CC*.

$$C_i^C = \frac{\gamma_i}{p_i^D}[(1-ty)Y - TrHO - SH], \quad p \equiv \prod_{i=1}^{34} [\frac{p_i^D}{\gamma_i}]^{\gamma_i} \tag{70}$$

Finally, *V*/*R*-composites are further disaggregated into virgin and recycled goods with a budget constraint.

$$max\ C_i^C \equiv C_i^{\alpha_i} \prod_{k=1}^{18} Z_{Cki}^{\alpha_{ki}} \qquad (\alpha_i + \sum_{k=1}^{18} \alpha_{ki} = 1) \tag{71}$$

subject to

$$p_i^D C_i^C = p_{Vi} C_i + \sum_{k=1}^{18} p_{Rk} Z_{Cki} \tag{72}$$

where

C_i: household consumption of virgin good *i*

α_i: share parameter on virgin good *i* in *V*/*R*-composite *i*

Z_{Cki} : household consumption of recycled good k

α_{ki} : share parameter on recycled good k in V/R-composite i

Therefore we have;

$$C_i = C_i^C \frac{\alpha_i}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_i}\right]^{\alpha_i} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{ki}}\right]^{\alpha_{ki}} \tag{73}$$

$$Z_{Cki} = C_i^C \frac{\alpha_{ki}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_i}\right]^{\alpha_i} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{li}}\right]^{\alpha_{li}} \tag{74}$$

$$p_i^D = \left[\frac{p_{Vi}}{\alpha_i}\right]^{\alpha_{Rij}} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{ki}}\right]^{\alpha_{Rkij}} \tag{75}$$

F. The Government, the External Sector, and Saving/Investment Balance

These are specified as the following balances of payments.

government sector

$$\begin{aligned} & ty \cdot Y + \sum_{j=1}^{34} tp_{Vj}(w \cdot L_{Vj} + r \cdot K_{Vj}) + \sum_{k=1}^{18} tp_{Rk}(w \cdot L_{Rk} + r \cdot K_{Rk}) \\ & + \sum_{j=1}^{34} tp_{Tj}(w \cdot L_{Tj} + r \cdot K_{Tj}) + tp_C(w \cdot L_C + r \cdot K_C) + TrOG \\ & \equiv \sum_{i=1}^{34} p_{Vi} \cdot CG_i + \sum_{k=1}^{18} p_{Rk} \cdot Z_{Gk} + TrGH + WTC + TrGO + SG \end{aligned} \tag{76}$$

$$WTC \equiv q_C \sum_{k=1}^{26} (1-\mu_k) WH \tag{77}$$

where

$TrOG$: current transfers from the external sector to the government (exogenous variable)

CG_i : government consumption of virgin good i

Z_{Gk} : government consumption of recycled good k

$TrGH$: government current transfers to households

WTC : government expenditures on C-activity

$TrGO$: government current transfers to the external sector

SG : government nominal savings

external sector

$$\sum_{i=1}^{34} p_i \cdot EM_i + TrHO + TrGO + KIO + LIO = \sum_{i=1}^{34} p_i \cdot EX_i + TrOH + TrOG + KI + LI + SO \qquad (78)$$

$$LIO \equiv l_o \cdot w \cdot LS, \quad KIO \equiv k_o \cdot r \cdot KS \qquad (79)$$

where

EM_i : import of virgin commodity i

KIO : property income transfers from households to the external sector

LIO : labor income transfers from households to the external sector

EX_i : export of virgin commodity i (exogenous variable)

KI : property income transfers from the external sector to households (exogenous variable)

LI : labor income transfers from the external sector to households (exogenous variable)

SO : savings of the external sector (= - prefectural current surplus)

balance of saving and investment

$$SH + SG + SO + \sum_{j=1}^{34} DR_{Vj} + \sum_{k=1}^{18} DR_{Rk} + \sum_{j=1}^{34} DR_{Tj} + DR_C = \sum_{i=1}^{34} p_{Vi} \cdot I_i + \sum_{k=1}^{18} p_{Rk} \cdot Z_{Ik} \qquad (80)$$

where

DR_{Vi} : capital depreciation in industry j

DR_{Ri} : capital depreciation in R-activity j

DR_{Ti} : capital depreciation in S-activity j

R_C : capital depreciation in C-activity

I_i : virgin good i used in investment

Z_{Ik} : recycled good k used in investment

In the above specifications, nominal government consumption expenditures, $p_{Vi} \cdot CG_i$ and $p_{Rk} \cdot Z_{Gk}$, current transfers from the government to households, *TrGH*, and current transfers from the government to the external sector, *TrGO*, are assumed to be proportional to the government total revenue. Proportions of virgin and recycled goods in government consumption expenditures and capital investment are fixed at nominal term.

Exports of each commodity are fixed at a real value, while imports are assumed to be proportional to prefectural domestic demand for each good. Exports and imports are assumed to exclude recycled commodities since this study emphasizes intraregional material circulation.

G. Supply Functions

Differentiating the zero profit conditions in industries, *R*-activities, and *C*-activity with respect to supply quantity, supply functions are respectively derived. Industries’ and *R*-activities’ supply functions can be expressed by matrix representation as in equation (81).

$$
\begin{aligned}
\begin{bmatrix} p_{V1} \\ \vdots \\ p_{V34} \\ p_{R1} \\ \vdots \\ p_{R18} \end{bmatrix}
&= \left[\begin{array}{ccc|ccc} a_{V11} & \cdots & a_{V341} & c_{V11} & \cdots & c_{V181} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a_{V134} & \cdots & a_{V3434} & c_{V134} & \cdots & c_{V1834} \\ \hline b_{R11} & \cdots & b_{R341} & d_{R11} & \cdots & d_{R181} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ b_{R118} & \cdots & b_{R3418} & d_{R118} & \cdots & d_{R1818} \end{array}\right]
\begin{bmatrix} p_{V1} \\ \vdots \\ p_{V34} \\ p_{R1} \\ \vdots \\ p_{R18} \end{bmatrix} \\
&+ \left[\begin{array}{ccc|c} \sum_{k=1}^{26}\eta_{k1}\zeta_{k1} & \cdots & 0 & \\ \vdots & \ddots & \vdots & 0 \\ 0 & \cdots & \sum_{k=1}^{26}\eta_{k34}\zeta_{k34} & \\ \hline & 0 & & 0 \end{array}\right]
\left[\begin{array}{ccc|ccc} a_{T11} & \cdots & a_{T341} & c_{T11} & \cdots & c_{T181} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a_{T134} & \cdots & a_{T3434} & c_{T134} & \cdots & c_{T1834} \\ \hline & 0 & & & 0 & \end{array}\right]
\begin{bmatrix} p_{V1} \\ \vdots \\ p_{V34} \\ p_{R1} \\ \vdots \\ p_{R18} \end{bmatrix} \\
&+ \left[\begin{array}{ccc|c} \sum_{k=1}^{26}\theta_{k1}\zeta_{k1} & \cdots & 0 & \\ \vdots & \ddots & \vdots & 0 \\ 0 & \cdots & \sum_{k=1}^{26}\theta_{k34}\zeta_{k34} & \\ \hline & 0 & & 0 \end{array}\right]
\left[\begin{array}{ccc|ccc} a_{C1} & \cdots & a_{C35} & c_{C1} & \cdots & c_{C18} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a_{C1} & \cdots & a_{C35} & c_{C1} & \cdots & c_{C18} \\ \hline & 0 & & & 0 & \end{array}\right]
\begin{bmatrix} p_{V1} \\ \vdots \\ p_{V34} \\ p_{R1} \\ \vdots \\ p_{R18} \end{bmatrix} \\
&+ \begin{bmatrix} (1+tp_{V1})(w\cdot l_{V1}+r\cdot k_{V1})+(1+tp_{T1})(w\cdot l_{T1}+r\cdot k_{T1})+(1+tp_{C})(w\cdot l_{C}+r\cdot k_{C}) \\ \vdots \\ (1+tp_{V34})(w\cdot l_{V34}+r\cdot k_{V34})+(1+tp_{T34})(w\cdot l_{T34}+r\cdot k_{T34})+(1+tp_{C})(w\cdot l_{C}+r\cdot k_{C}) \\ (1+tp_{R1})(w\cdot l_{R1}+r\cdot k_{R1}) \\ \vdots \\ (1+tp_{R18})(w\cdot l_{R18}+r\cdot k_{R18}) \end{bmatrix}
\end{aligned} \tag{81}
$$

$$a_{Vij} \equiv \frac{\partial x_{Vij}}{\partial X_j} = \frac{\alpha_{Vij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Vij}}\right]^{\alpha_{Vij}} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{Vkij}}\right]^{\alpha_{Vkij}} a_{ij}^{V} \tag{82}$$

$$b_{Rij} \equiv \frac{\partial x_{Rij}}{\partial X_j} = \frac{\alpha_{Rij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Rij}}\right]^{\alpha_{Rij}} \prod_{k=1}^{18} \left[\frac{p_{Rk}}{\alpha_{Rkij}}\right]^{\alpha_{Rkij}} a_{ij}^{R} \tag{83}$$

$$c_{Vkj} \equiv \sum_{i=1}^{34} \frac{\partial z_{Vkij}}{\partial X_j} = \sum_{i=1}^{34} \frac{\alpha_{Vkij}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Vij}}\right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Vlij}}\right]^{\alpha_{Vlij}} a_{ij}^{V} \tag{84}$$

$$d_{Rkj} \equiv \sum_{i=1}^{34} \frac{\partial z_{Rkij}}{\partial Z_j} = \sum_{i=1}^{34} \frac{\alpha_{Rkij}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Rij}}\right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Rlij}}\right]^{\alpha_{Rlij}} a_{ij}^{R} \tag{85}$$

$$a_{Tij} \equiv \frac{\partial x_{Tij}}{\partial WT_j} = \frac{\alpha_{Tij}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Tij}}\right]^{\alpha_{Tij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Tlij}}\right]^{\alpha_{Tlij}} a_{ij}^{T} \tag{86}$$

$$c_{Tkj} \equiv \sum_{i=1}^{34} \frac{\partial z_{Tkij}}{\partial WT_j} = \sum_{i=1}^{34} \frac{\alpha_{Tkij}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Tij}}\right]^{\alpha_{Vij}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Tlij}}\right]^{\alpha_{Tlij}} a_{ij}^{T} \tag{87}$$

$$a_{Ci} \equiv \frac{\partial x_{Ci}}{\partial WC} = \frac{\alpha_{Ci}}{p_{Vi}} \left[\frac{p_{Vi}}{\alpha_{Ci}}\right]^{\alpha_{Ci}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Cli}}\right]^{\alpha_{Cli}} a_{i}^{C} \tag{88}$$

$$c_{Ck} \equiv \sum_{i=1}^{34} \frac{\partial z_{Cki}}{\partial WC} = \sum_{i=1}^{34} \frac{\alpha_{Cki}}{p_{Rk}} \left[\frac{p_{Vi}}{\alpha_{Ci}}\right]^{\alpha_{Ci}} \prod_{l=1}^{18} \left[\frac{p_{Rl}}{\alpha_{Cli}}\right]^{\alpha_{Cli}} a_{i}^{C} \tag{89}$$

$$l_{Vj} \equiv \partial L_{Vj} / \partial X_j \ , \ k_{Vj} \equiv \partial K_{Vj} / \partial X_j \ , \ l_{Tj} \equiv \partial L_{Tj} / \partial WT_j \ , \ k_{Tj} \equiv \partial K_{Tj} / \partial WT_j \tag{90}$$

$$l_C \equiv \partial L_C / \partial WC \ , \ k_C \equiv \partial K_C / \partial WC \ , \ l_{Rj} \equiv \partial L_{Rj} / \partial Z_j \ , \ k_{Rj} \equiv \partial K_{Rj} / \partial Z_j \tag{91}$$

The supply function of C-activity is given by the following equation.

$$q_C = \sum_{i=1}^{34} p_{Vi} a_{Ci} + \sum_{k=1}^{18} p_{Rk} c_{Ck} + (1 + tp_C)[w \cdot L_C + r \cdot K_C] \tag{92}$$

Therefore given a price system satisfying equations (81) and (92), all the demands including demands for virgin and recycled commodities, and production factors are determined. Then outputs of industries, R-, and C-activities are determined to meet the respective demand levels.

Equilibrium Conditions

Summarizing the demand and supply functions mentioned above, the equilibrium conditions in the present model are described as follows:

virgin and recycled commodity market equilibrium

$$
\begin{aligned}
&\begin{bmatrix} X_1 \\ \vdots \\ X_{34} \\ Z_1 \\ \vdots \\ Z_{18} \end{bmatrix} + \begin{bmatrix} EM_1 \\ \vdots \\ EM_{34} \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \left[\begin{array}{ccc|ccc} a_{V11} & \cdots & a_{V134} & b_{R11} & \cdots & b_{R118} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a_{V341} & \cdots & a_{V3434} & b_{R341} & \cdots & b_{R3418} \\ \hline c_{V11} & \cdots & c_{V134} & d_{R11} & \cdots & d_{R118} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ c_{V181} & \cdots & c_{V1834} & d_{R181} & \cdots & d_{R1818} \end{array}\right] \begin{bmatrix} X_1 \\ \vdots \\ X_{34} \\ Z_1 \\ \vdots \\ Z_{18} \end{bmatrix} \\
&+ \left[\begin{array}{ccc|c} a_{T11} & \cdots & a_{T134} & \\ \vdots & \ddots & \vdots & 0 \\ a_{T341} & \cdots & a_{T3434} & \\ \hline c_{T11} & \cdots & c_{T134} & \\ \vdots & \ddots & \vdots & 0 \\ c_{T181} & \cdots & c_{T1834} & \end{array}\right] \left[\begin{array}{ccc|c} \sum_{k=1}^{26}\eta_{k1}\zeta_{k1} & \cdots & 0 & \\ \vdots & \ddots & \vdots & 0 \\ 0 & \cdots & \sum_{k=1}^{26}\eta_{k34}\zeta_{k34} & \\ \hline & 0 & & 0 \end{array}\right] \begin{bmatrix} X_1 \\ \vdots \\ X_{34} \\ Z_1 \\ \vdots \\ Z_{18} \end{bmatrix} \\
&+ \left[\begin{array}{ccc|c} a_{C1} & \cdots & a_{C1} & \\ \vdots & \ddots & \vdots & 0 \\ a_{C35} & \cdots & a_{C35} & \\ \hline c_{C1} & \cdots & c_{C1} & \\ \vdots & \ddots & \vdots & 0 \\ c_{C18} & \cdots & c_{C18} & \end{array}\right] \left[\begin{array}{ccc|c} \sum_{k=1}^{26}\theta_{k1}\zeta_{k1} & \cdots & 0 & \\ \vdots & \ddots & \vdots & 0 \\ 0 & \cdots & \sum_{k=1}^{26}\theta_{k34}\zeta_{k34} & \\ \hline & 0 & & 0 \end{array}\right] \begin{bmatrix} X_1 \\ \vdots \\ X_{34} \\ Z_1 \\ \vdots \\ Z_{18} \end{bmatrix} \\
&+ \begin{bmatrix} a_{C1} \\ \vdots \\ a_{C35} \\ c_{C1} \\ \vdots \\ c_{C18} \end{bmatrix} (1-\sum_{k=1}^{26}\mu_k)\cdot\kappa\cdot CC + \begin{bmatrix} C_1 \\ \vdots \\ C_{34} \\ Z_{C1} \\ \vdots \\ Z_{C18} \end{bmatrix} + \begin{bmatrix} CG_1 \\ \vdots \\ CG_{34} \\ Z_{G1} \\ \vdots \\ Z_{G18} \end{bmatrix} + \begin{bmatrix} I_1 \\ \vdots \\ I_{34} \\ Z_{I1} \\ \vdots \\ Z_{I18} \end{bmatrix} + \begin{bmatrix} EX_1 \\ \vdots \\ EX_{34} \\ 0 \\ \vdots \\ 0 \end{bmatrix}
\end{aligned} \tag{93}
$$

waste recycling equilibrium

$$Z_i = \sum_{k=1}^{26} \phi_{ik} (\sum_{j=1}^{34} \xi_{kj} \cdot \zeta_{kj} \cdot X_j + \mu_k \cdot CC) @ \quad (i = 1,...,18) \tag{94}$$

waste self-abatement equilibrium

$$WT_j = \sum_{k=1}^{26} \eta_{ki} \cdot \zeta_{kj} \cdot X_j \quad (j = 1,...,34) \tag{95}$$

waste external consigned abatement equilibrium

$$WC = \sum_{j=1}^{34} \sum_{k=1}^{26} \theta_{kj} \cdot \zeta_{kj} \cdot X_j + (1 - \sum_{k=1}^{26} \mu_k) \cdot \kappa \cdot CC \tag{96}$$

labor market equilibrium

$$LS = \sum_{j=1}^{34} L_{Vj} + \sum_{j=1}^{18} L_{Rj} + \sum_{j=1}^{34} L_{Tj} + L_C \tag{97}$$

capital market equilibrium

$$\overline{KS} = \sum_{j=1}^{34} K_{Vj} + \sum_{j=1}^{18} K_{Rj} + \sum_{j=1}^{34} K_{Tj} + K_C \tag{98}$$

In these conditions, commodities are supplied to meet the demand, and waste abatement services are provided to treat wastes described by equations (95) and (96). However, the volume of waste to be recycled, Z_i , is determined by equation (93) derived from waste demand side as well as by the condition (94) imposed by waste generation side. To realize both the conditions, in this study, net indirect tax rates on *R*-activities, tp_{Ri} , are adjusted to satisfy equation (94) from waste demand side, while recycling rates, ξ_{kj} and μ_k , are adjusted from waste generation side.

In addition, the above-mentioned equilibrium conditions are, of course, insufficient to solve the model implying that all the equations in the model are necessary. However if equation (94) is satisfied, the *Walras* law, that is, *value of excess demand for labor* + *value of excess demand for capital* = 0 will be realized. This implies that if either labor or capital market is cleared, the equilibrium solution of the model can be obtained.

Thus letting labor be a numeraire (w=1), capital return rate is computed to clear the capital rental market by using *Newton-Raphson* method. Moreover, net indirect tax rates on *R*-activities, tp_{Ri} , or recycling rates, ξ_{kj} and μ_k , are calibrated feedbacking a gap in equation (94) to obtain the full equilibrium solution.

Parameter Setting

For numerical experiment, it is necessary to estimate parameters in functions specified in the model. Since the technological parameters in the production functions in industries, *R*-, *S*-, and *C*-activities are specified as *Leontief-Cobb-Douglas* type, they can easily be estimated by applying the economic and material balance accounting matrix as a benchmark dataset in a usual *CGE*-modeling framework (Shoven and Whalley, 1992). The detailed results of parameter estimation is beyond the scope of this paper, therefore, they are skipped here.

For the parameters in the utility function, estimation of them is made in a standard way with results shown in Table 4 though the description of the estimation method is skipped as well.

Marginal waste generations, waste recycling rates, and waste abatement rates were estimated by employing Research Report on Industrial Waste in Aichi Prefecture (1996). Waste is expressed in physical term in this study, but recycled goods are modeled in both physical and monetary terms. Prices of recycled commodities are estimated by applying Japan’s I/O Tables (1999) and Research Report on Cost of Waste Disposal (1998).

Table 4 Parameters in Utility Function

Commodities	share parameter
present goods	0.77824
future goods	0.22176
composite consumption	0.58506
leisure time	0.41494
elasticity of substitution between present and future goods	1.11908
elasticity of substitution between composite consumption and leisure time	1.07054

Simulation Analysis

A. Simulation Cases

As described in the model specification, optimization is made to derive the demand and supply equilibrium of virgin commodities, implying that virgin commodity equilibrium is a result of economic agent purposive behavior. But the demand and supply of recycled materials are linked to by-products of industries, implying that disequilibrium in recycled commodity market is prone and inevitable under fixed parameters relating to recycling. Figure 2 graphically illustrates this situation.

Therefore if some waste program is to be implemented, the following conditions must hold to equilibrate the demand and supply of virgin and recycled goods.

(1) Recycling rates must rise when the demand for recycled goods is intended to increase.

(2) Prices of recycled goods must decline when the supply of recycled commodities is intended to increase. Taking these conditions into account, 6 cases presented in Table 5 will be simulated and comparatively examined. Exgogenous changes in parameters in cases 1 to 3 are shown in Tables 6 and 7, which are set up referring to targets made by the government or some industrial associations (National Environmental Planning Agency, 1993) .

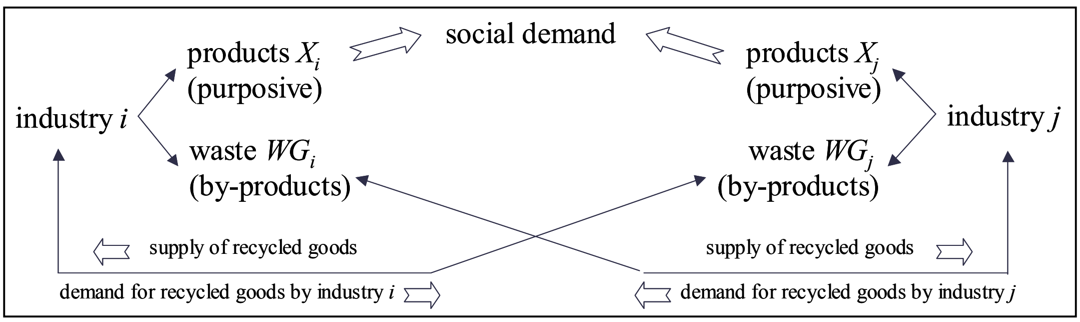

Figure 2 Concept of Simulation Analysis

Table 5 Simulation Cases

case	description
base case	Business as usual case.
case 1	Recycling of waste is expanded in demand side by rising share parameters on recycled goods in intermediate *V*/*R*-composite inputs in industries, *R*-, *S*-, and *C*- activities. To equilibrate demand for and supply of recycled goods, recycling rates are endogenously calibrated. Rates of increase in share parameters are shown in Table 6.
case 2	Recycling of waste is promoted in supply side by increasing recycling rates. *R*-activities are subsidized by the government to equilibrate demand and supply of recycled goods through lowering prices of recycled goods. Rates of increase in recycling rates are presented in Table 7.
case 3	In addition to case 2, additional government subsidies are equivalently financed by rising household direct tax rate.
case 4	Recycling rate on every waste is increased to 100%. Similar to case 2, additional government subsidies for *R*-activities are considered.
case 5	In addition to case 4, household direct tax rate is internalized to equivalently compensate the additional government subsidies in case 4.

Table 6 Assumed Rates of Increase in Share Parameters on Recycled Commodities in Case 1

recycled goods	rate of increase in share parameter	recycled goods	rate of increase in share parameter
recycled construction materials I	3	recycled chemical fertilizers	40
recycled construction materials II	5	recycled acid and alkali	20
recycled construction materials III	10	recycled oils	10
compost	10	recycled plastics	20
recycled organic fertilizers	40	recycled tires	20
recycled organic fertilizers/feeds	10	recycled rubber	10
recycled fiber	20	recycled glass and construction materials IV	40
recycled wooden products	20	recycled iron	1
recycled pulp and paper	10	recycled non-ferrous metals	1

Table 7 Assumed Rates of Increase in Recycling Rates in Case 2

Waste	rate of increase in recycling rate	Waste	rate of increase in recycling rate	waste	rate of increase in recycling rate
Cinder	30	waste plastic	20	waste glass and porcelain	40
organic sludge	40	waste tire	10	slag	3
inorganic sludge	40	shredder dust	0	waste concrete	10
general waste oil	10	waste paper	10	waste asphalt	10
waste solvent	10	waste wood	20	other construction waste	10
solid waste	10	waste fiber	20	soot and dust	10
oil sludge	10	animal and vegetable residue	10	animal waste	10
waste acid	20	waste rubber	(50)	other industrial waste	--
waste alkali	20	waste metal	0		

Note: The recycling rate on waste rubber in case 2 is assumed to be 50% since it is 0% in the base case.

B. Simulation Results

Simulation results of the 6 cases are shown in Figures 2 to 9 where variational ratios of cases 2 to 5 relative to the base case are illustrated. Monetary values are indicated in terms of the relative price system in the base case.

(a) case 1

Although share parameters on recycled materials are increased implying expansion of use of recycled commodities in demand side, impacts of the scenario in this case are estimated to be very small.

Looking at industrial outputs in Figure 4, negative impacts are relatively large on rubber and beverage and feed with impact rate of -0.1%, and plastic with -0.04%. Industries suffered from negative impact can be identified as those suffered from substitution effect where virgin goods are substituted by recycled goods. Positive impacts are found in assembling manufactures and consumption related industries. As use of recycled goods are promoted, price indices of *V*/*R*-composites slightly fall resulting in a moderate expansion in household consumption with a positive equivalent variation of 4.1 billion yen. Moreover, imports of virgin commodities substituted by recycled goods show a decrease as expected.

(b) case 2

In this case, recycling rates are increased endogenously adjusting government subsidies to equilibrate demand and supply of recycled goods. Since small increases in recycling rates are assumed, significant impacts of the scenario of this case are not found as well.

However, government subsidies considerably depreciate prices of recycled goods. There can be observed many recycled commodities with over 10% down in their prices, specifically prices of recycled rubber, recycled organic fertilizer, and recycled pulp and paper show falls of exceeding 30%. This result suggests that a significant decline in recycled commodity prices must be necessary even in a realistic and feasible recycling program.

The additional expense of subsidies is estimated as 9.8 billion yen which straightforwardly reduces government revenues since no additional tax is assumed to compensate the expenditures. On the other hand, since household waste is promoted by 60% up in the recycling rate, government expenditures on *C*-activity are saved by 5.9 billion yen yielding an increase in government savings of 4.7 billion yen.

Substitution effect is observed in imports of several commodities, but the total import increases due to expansion effect in industries and income effect in households.

Households consumption expenditures and savings grow due to income effect of falls in recycled commodity prices leading to a welfare improvement as *EV* shows 14.2 billion yen.

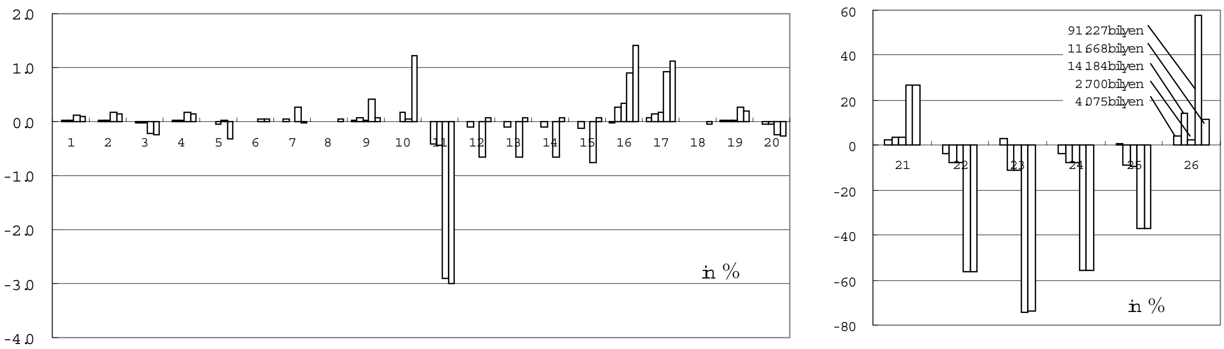

Figure 3 Changes in Key Variables

Note: 1. total output, 2. total industrial output, 3. prefectural gross product, 4. gross product of industries, 5. household full income, 6. household income, 7. household composite consumption, 8. leisure time, 9. household savings, 10. direct taxes, 11. net indirect taxes, 12. government income, 13. government consumption, 14. government current transfers to households, 15. government current transfers to the external sector, 16. government savings, 17. investment, 18. labor demand, 19. capital return rate, 20. price index of composite consumption, 21. total output of *R*-activities, 22. total output of *S*-activities 23. gross product of *R*-activities, 24. gross product of *S*- and *C*-activities, 25. government expenditures on *C*-activity, 26. equivalent variation.

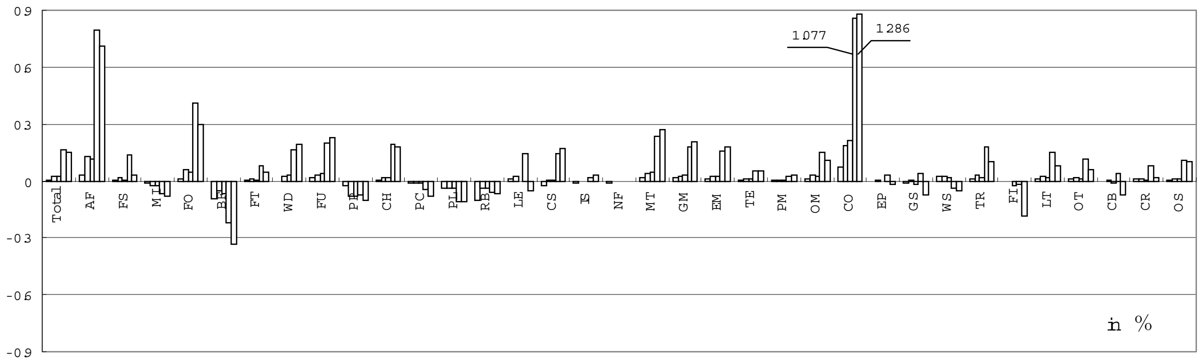

Figure 4 Changes in Outputs of Industries

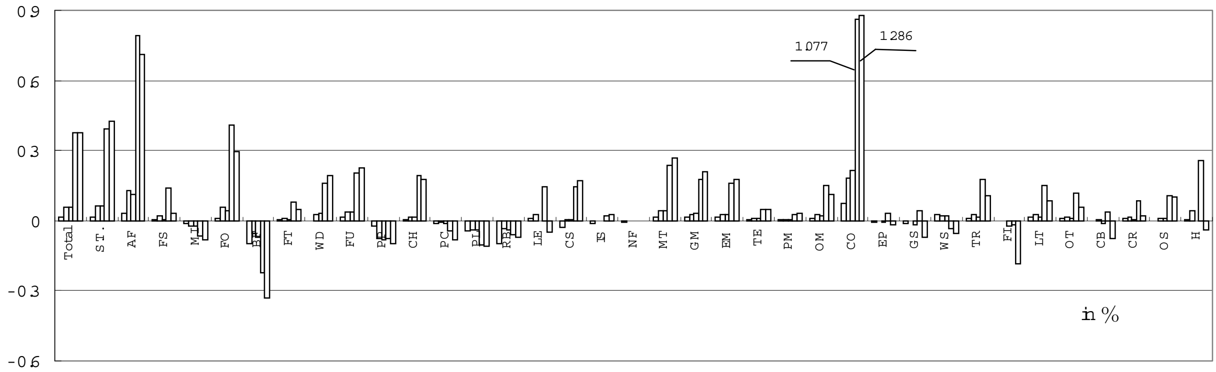

Figure 5 Changes in Waste Generation

Note: S.T.: total volume of industrial waste, H : households

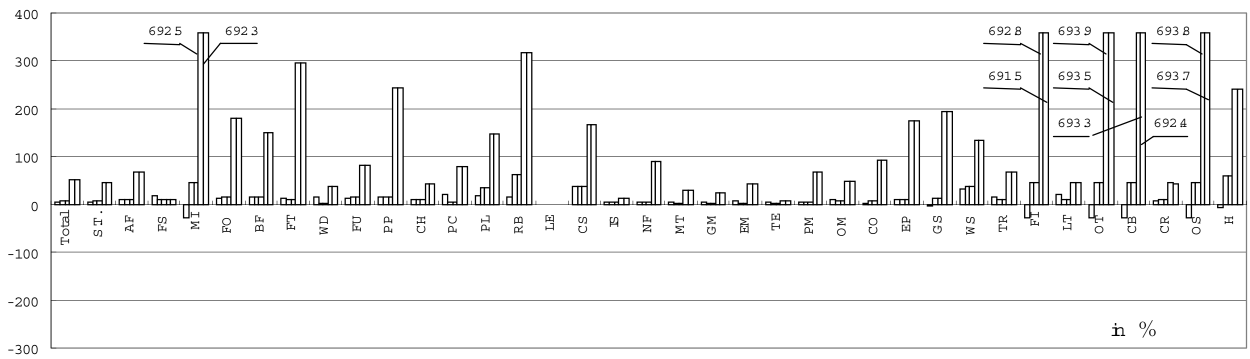

Figure 6 Changes in Recycled Waste

Note: S.T.: total volume of industrial waste, H : households

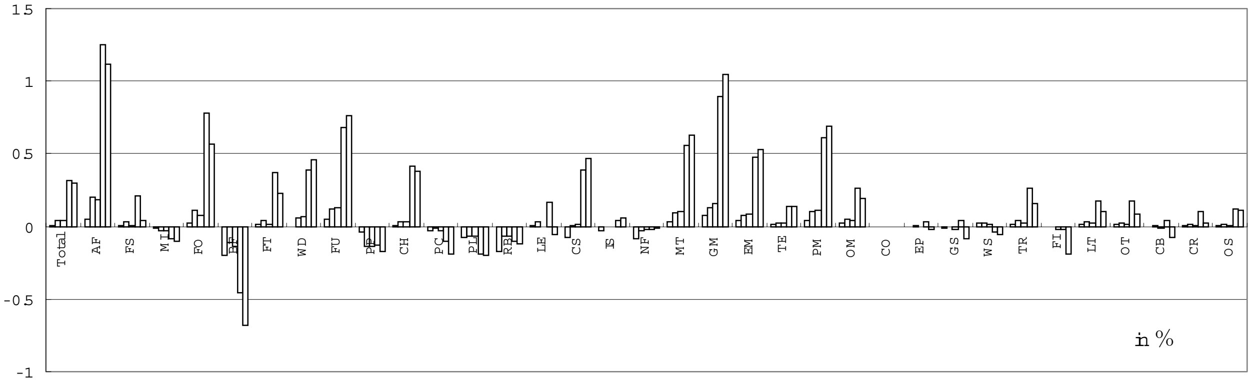

Figure 7 Changes in Imports of Virgin Commodities

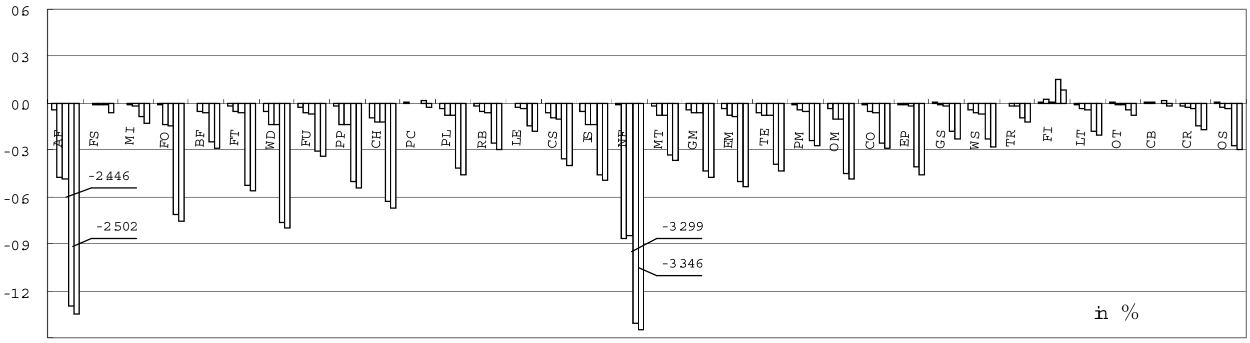

Figure 8 Changes in Prices of Virgin Commodities

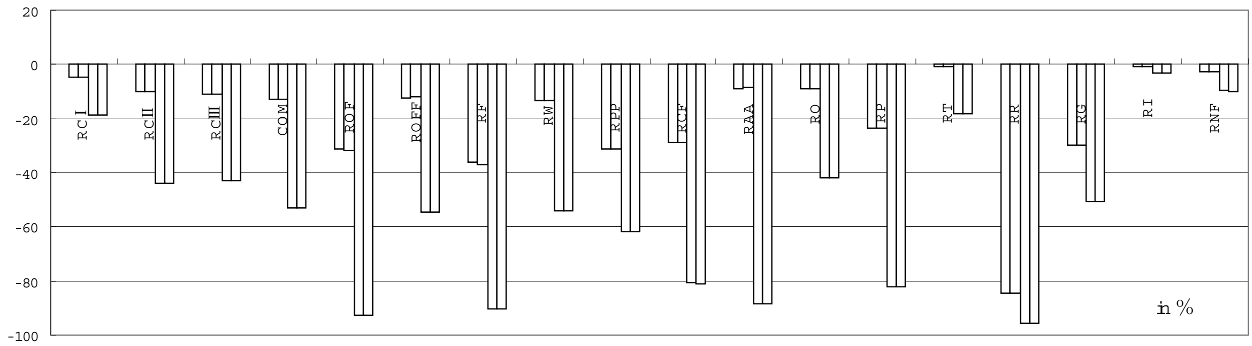

Figure 9 Changes in Prices of Recycled Commodities

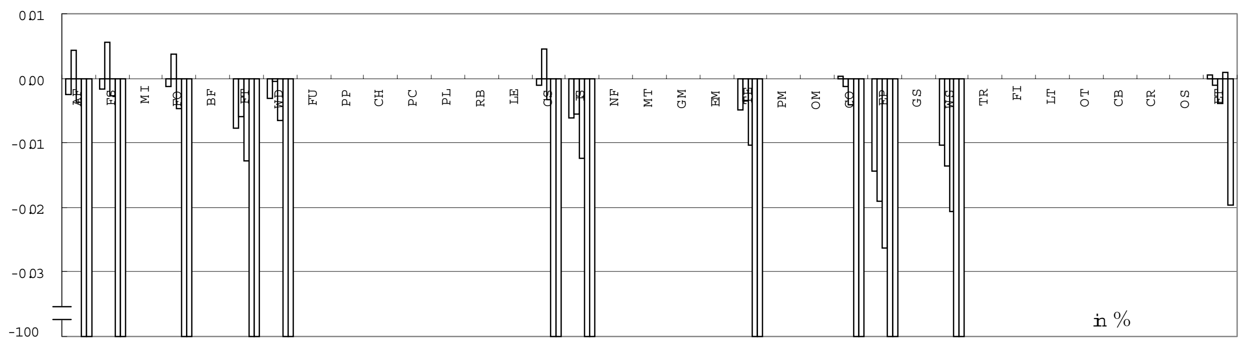

Figure 10 Changes in Prices of Waste Abatement Services

Note: ET: external waste abatement

(c) case 3

In this case, it is assumed that the additional government subsidies on recycling activities are equivalently financed by raising the household direct tax rate. As a result, only direct effects such as a decrease in household disposable income, increases in revenues, consumption expenditures, and savings in the government sector are significant with small indirect repercussive impacts. Although a decrease in household consumption affects a negative impact on household utility, it is compensated by increases in household leisure time and savings leading to a welfare improvement as *EV* depicts 2.7 billion yen.

(d) case 4

This case assumes perfect recycling, i.e. 100% recycling rates on every waste (except household food residue aiming) at realizing a zero-emissions oriented society in Aichi Prefecture. Similar to case 3, additional government subsidies on recycling activities are considered to depreciate prices of recycled commodities.

By assumption, one can see that there are a number of types of waste whose recycled volumes become several times as compared to the base case, yielding significant impacts on the prefectural whole economy. Looking at industrial activities in Figure 4, significant reductions in their outputs can be found due to substitution effect particularly in beverage and feed with impact rate of -0.2%, plastic with -0.1%, pulp and paper with -0.08%, and rubber with -0.06%.

On the other hand, construction, agriculture and forestry, and food industries show increases in output with positive impact rates of 1.1%, 0.8%, and 0.4%, respectively. Assembling industries such as general machinery, electric machinery, and transportation equipment industries expand suggesting an industrial structural change from raw material based industries to assembling industries in the prefectural economy.

Relating to this structural change, imports show a similar manner to industrial outputs, however, their magnitudes are larger than in outputs resulting from impacts on household consumption expenditures and capital investment.

Government subsidies on recycling activities considerably depreciate prices of recycled commodities ranging from 18% to 95% except recycled iron and non-ferrous metals, since they have already been recycled at high recycling rates. Government additional burden on budget resulting from the subsidies is estimated as 66.8 billion yen, yielding a decrease of 13 billion yen in government consumption expenditures. However, public expenditures on *C*-activity are reduced by 23.9 billion yen which in turn increases government savings by 15.6 billion yen.

For households, income effect is significant due to the fall in commodity prices deriving expansions in consumption and savings with welfare improvement of 91.2 billion yen in EV.

(e) case 5

Like case 3, this case also supposes that the additional government subsidies for promotion of recycling in case 4 is equivalently compensated by endogenously raising the household direct tax rate. Similar to the results in case 3, significant impacts are particularly found in households and in the government. Household disposal income is reduced by an increase in direct taxes, but their consumption expenditures do not show a large decrease with impact rate of only -0.04% being offset by the income effect of commodity price depreciation.

In the government budget balance, government expenditures on *C*-activities are reduced by 24 billion yen in addition to an increase in direct tax revenues leading to an increase of 24.8 billion yen in government savings with an expansion in capital investment. Despite household consumption expenditures decrease, *EV* shows 11.7 billion yen followed by an increase in household leisure time and savings.

Concluding Remarks

This study has significantly extended our previous paper on this topic internalizing waste recycling activities as economic agents, and specifying detailed recycling and waste abatement rates. Even in Japan, data collection is very difficult in waste studies. This article has also attempted to improve the data reliability as far as the authors could. Assuming realization of a zero-emissions society in this study, numerical simulations of the general equilibrium effects of it is highlighted since they have not been examined and reported in the literature.

On the other hand, the actual waste problem has been throwing us various difficulties including recyclability of specific materials, complexity of physical distribution system of waste recycling, and recyclability of materials already accumulated in our society for long time. These are our new targets in the future studies.

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