Multicriteria Design of Plastic Recycling Based on Quality Information and Environmental Impacts

Jun Nakatani and Masahiko Hirao

Keywords:

industrial ecology
life cycle management (LCM)
mechanical recycling
mixed-integer linear programming (MILP)
polyethylene terephthalate (PET)
quality demand

:// Supporting information is available on the *JIE* Web site

Summary

In this study, we develop a framework for the multicriteria design of plastic recycling based on quality information and environmental impacts for the purpose of supporting collaborative decision making among consumers, municipalities, and recyclers. The subject of this article is the mechanical recycling of postconsumer polyethylene terephthalate (PET) bottles. We present a "quality conversion matrix," which links the quality of recycled PET resin to the quality of waste PET bottles and operational conditions, described in terms of the functions of modules constituting the entire recycling process. We estimate the quality of recycled PET resin and simulate the applicability to the intended products as the primary criterion by confirming whether the estimated quality of recycled resin satisfies the quality demands of PET resin users. The amounts of carbon dioxide (CO_2) emissions and fossil resource consumption are also estimated as the secondary criteria. An approach to collaborative decision making utilizing mixed-integer linear programming (MILP) and Monte Carlo simulation is proposed on the premise of different objectives of various stakeholders, where all the feasible optimal solutions for achieving the quality demands are obtained. The quality requirements of waste bottles, along with the CO_2 emissions and fossil resource consumption estimated for each solution, contribute to the collaborative multicriteria design of plastic recycling.

Address correspondence to
Jun Nakatani
The University of Tokyo—Urban Engineering
7-3-1 Hongo Bunkyo Tokyo 113-8656
Japan
nakatani@env.t.u-tokyo.ac.jp

DOI: 10.1111/j.1530-9290.2010.00316.x

Volume 15, Number 2

Introduction

In Japan, the recycling of postconsumer plastic packaging has been promoted under the national recycling law since 1997. The collection rate of postconsumer polyethylene terephthalate (PET) bottles for recycling purposes reached 88.4% in 2006 (Council for PET Bottle Recycling, Japan 2007). Plastic recycling is now expected to contribute to, besides the avoidance of landfilling, the alleviation of environmental impact and resource consumption.

The role of life cycle assessment (LCA) as a decision-support tool for the design of solid waste management, including plastic recycling, has been discussed in many papers (e.g., Finnveden and Ekvall 1998; Arena et al. 2003a; Askham-Nyland et al. 2003; Ekvall et al. 2007). Many LCA case studies have shown the effectiveness of the material recycling of plastics, particularly PET bottles, from the perspective of carbon dioxide (CO_2) emissions and energy consumption (Fukushima and Hirao 2000; Tokai and Furuichi 2000; Yasuda 2001; Arena et al. 2003b; Wada et al. 2004; Sugiyama et al. 2006; Matsuda and Kubota 2008). The crucial reason for the effectiveness of the mechanical recycling is that, as far as nonrenewable resources are concerned, recycling processes are often less resource-intensive than production processes for equivalent virgin products replaced by recycled products (Bjorklund and Finnveden 2005).

Nonetheless, some consumers still question the significance of PET bottle recycling. Such opinions arise in part from suspicions that waste PET bottles are not processed into valuable recycled products. In fact, material recycling by mechanical operations (mechanical recycling), which has a cost advantage over material recycling by chemical operations (chemical recycling), restricts the applications of recycled PET resin because of quality deterioration of the resin. It is difficult to take into account the issue of the quality deterioration of recycled materials within the framework of LCA, and none of the above-mentioned articles have considered quality issues. Some professionals in the field have intended to consider the issue of quality deterioration in plastic recycling by applying the concept of "substitution factor" or "performance ratio" within the LCA framework (Noda et al. 2001; Fujii et al. 2008). Still, researchers do not how to logically establish the value of the substitution factor or performance ratio.

Recycling systems for plastic waste should be designed with consideration of the quality of recycled materials as well as environmental impact and energy consumption (Røine and Brattebø 2003). Several studies have addressed the economic or environmental optimization of a recycling system utilizing linear programming, mixed-integer programming (MIP), or goal programming (Glassey and Gupta 1974; Hoshino et al. 1995; Bloemhof-Ruwaard et al. 1996; Stuart et al. 1999; Spengler et al. 2003; Lu et al. 2006; Hara et al. 2007; Williams et al. 2007; Tang et al. 2008; Tsai and Hung 2009). Another study presented a MILP model for the production of multi-grade virgin PET resin (Liberopoulos et al. 2010). Those studies maximized or minimized a single objective (multiple objectives in some studies), such as the recycler's profit or costs, recycling rate, and environmental impacts.

In reality, various stakeholders who have different objectives (i.e., consumers, municipalities, and recyclers) are involved in a recycling system of plastic waste, which means it is almost impossible for the objectives to be logically fixed on a single function. Several articles modeled the economics of recycling from the viewpoints of various stakeholders separately (e.g., Isaacs and Gupta 1997; Boon et al. 2000; Sodhi and Reimer 2001; Boon et al. 2003), but an approach to consensus building among stakeholders still remains an issue. Instead, examining all the feasible optimal solutions under constraints on the primary criterion, such as the quality demands, along with their evaluation from the viewpoint of the other criteria, such as environmental impacts, could lead to consensus building, or collaborative decision making, among stakeholders.

Our investigations into plastic mechanical recycling found that, at least in the case of postconsumer PET bottles, the quality of recycled resin (output from the process) largely depends on both the quality of plastic waste (input to the process) and the operational conditions of the process. Household plastic waste is presorted by consumers and collected and pretreated by waste collectors, who are employed by municipalities

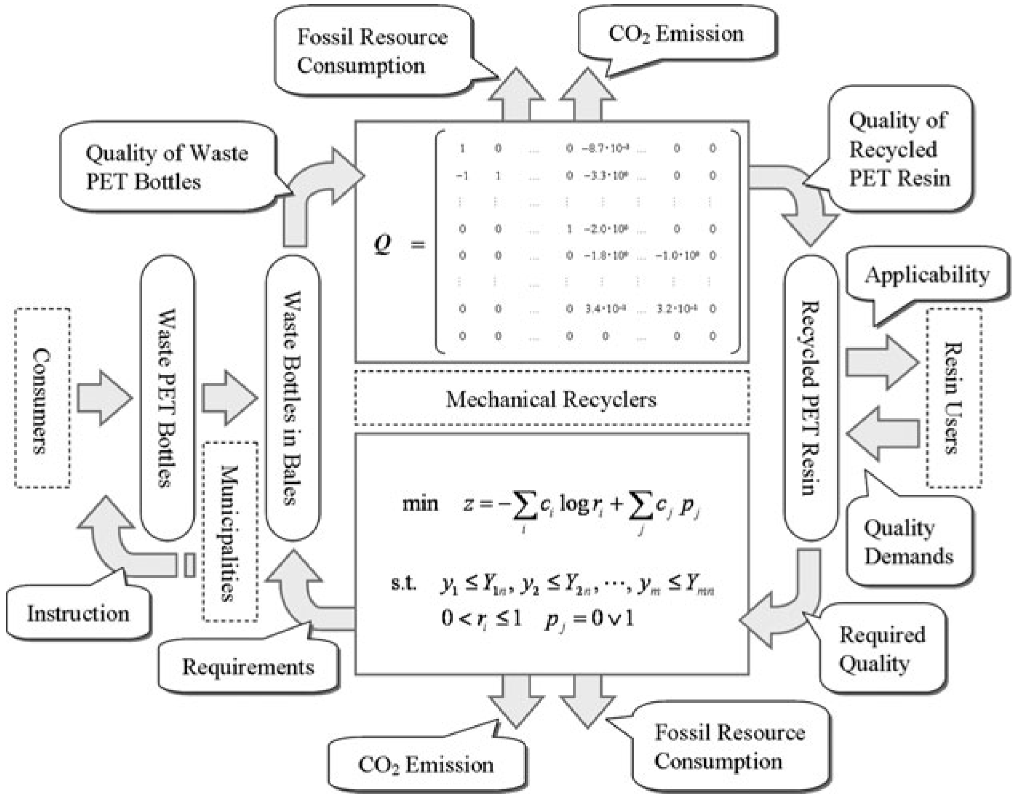

Figure 1 Information flow in the framework for the multicriteria design based on quality information and environmental impacts. Rounded boxes indicate waste or recycled materials, and dotted boxes indicate stakeholders involved in a recycling system. CO_2 = carbon dioxide; PET = polyethylene terephthalate; z = objective function; r_i = reduction rates for unwanted materials i of waste PET bottles; p_j = binary variables of module j; c_i and c_j = coefficients of the objective function; y_m = quality parameters of recycled PET resin; Y_{mn} = required levels for quality parameters m according to the applications n of recycled PET resin.

in Japan, and once collected, the recycling is outsourced to private recyclers. Hence, recyclers tend to accept the quality of plastic waste as a given and cannot fully control the quality of recycled materials. A modeling of the quality information, which describes the quality relation between the input and output of each module constituting the system, is required as a basis of collaborative decision making.

In this study, we develop a framework for the multicriteria design of plastic recycling based on quality information and environmental impacts for the purpose of supporting collaborative decision making among consumers, municipalities, and recyclers. The subject of this article is the mechanical recycling of postconsumer PET bottles in Japan. Figure 1 shows information flow in the proposed framework. The "quality conversion matrix" **Q**, which links the quality of recycled PET resin to the quality of waste PET bottles and operational conditions, is described on the basis of the functions of modules constituting the entire recycling process. We estimate the quality of recycled PET resin, the raw material for PET products, by multiplying the quality vector of waste bottles by the quality conversion matrix, and we simulate the applicability to the intended products as the primary criterion by confirming whether the estimated quality of recycled resin satisfies the quality demands of PET resin users (i.e., manufacturers of PET products). As the amounts of utilities to run the recycling process are attached to the quality conversion matrix, the amount of CO_2 emissions and fossil resource consumption are also estimated as the secondary criteria. In the case where the estimated quality does not satisfy the quality demands, the quality parameters of waste bottles that should be improved and the optional modules that should be included in the recycling process are specified by optimization under the required quality constraints according to MILP. As various stakeholders are involved in a recycling system and aim at different objectives, all the feasible optimal solutions for achieving the quality demands are obtained by Monte Carlo simulation. Then stakeholders (decision makers) collaborate on choosing the direction of improvement among the obtained solutions. The requirements for the quality of waste bottles, along with the CO_2 emissions and fossil resource consumption estimated for each solution, contribute to the collaborative multicriteria design of plastic recycling.

Modeling of Quality Information

Mechanical Recycling

Material recycling methods for postconsumer PET bottles in practical use in Japan are categorized into "mechanical recycling" and "chemical recycling." In mechanical recycling, waste PET bottles in bales are processed into recycled PET resin, flakes, or pellets, by mechanical operations such as shredding, washing, and melting, and recycled resin is used as a raw material for polyester filament products, polyester staple products, and sheet products, among others (Council for PET Bottle Recycling, Japan 2007). This is the so-called open-loop recycling. Conversely, in chemical recycling, waste PET bottles are decomposed into monomers of PET, either purified terephthalic acid (PTA) or bis (2-hydroxyethyl) terephthalate (BHET), and repolymerized into PET. Recycled PET resin processed by chemical recycling has been used as raw materials for beverage PET bottles in practice since 2004. This is the so-called closed-loop recycling or bottle-to-bottle recycling. The amount of recycled PET resin for bottle-to-bottle recycling was 12,600 tonnes[1] among the total amount of domestically recycled PET resin of 189,500 tons in 2006 (Council for PET Bottle Recycling, Japan 2007). Currently, mechanical recycling still predominates in the market of PET bottle recycling in Japan because of its cost advantage over chemical recycling.

Investigations into four mechanical recyclers of postconsumer PET bottles in Japan were conducted from 2006 to 2008. Such recyclers process incoming waste PET bottles in bales into PET flakes through a recycling process consisting of dozens of modules, or unit processes, such as the removal of unwanted materials by various kinds of separation, alkali washing with hot water and caustic soda, draining, and drying, among others. A portion of the flakes is processed into PET pellets by melt extrusion and pelletizing with the filtration of foreign particles. Utilities used for running the process are electricity and fuel oil. For one of the investigated recyclers, Recycler A, the modules shown in figure 2 constitute the recycling process. The other recyclers have no alkali washing, drying, fine separation (fine screening, third air separation, and sensor-based metal separation), or pelletizing module.

To effectively remove unwanted materials in recycling processes, the Council for PET Bottle Recycling in Japan (2001) has established an independent design guideline for PET bottles produced in Japan. This guideline provides, for example, that transparent PET bottles, adhesiveless polyolefin (PO) or polystyrene (PS) labels, and polyethylene (PE) or polypropylene (PP) caps shall be used (Council for PET Bottle Recycling, Japan 2001).

Required Quality

Plastic quality generally depends on several parameters. In this study, quality parameters were defined on the basis of the quality demands of resin users for recycled PET resin. The applications of mechanically recycled PET resin in practical use in Japan, as confirmed in our investigations, are as follows:

- Polyester filament products
- Polyester staple products: working wear, batting
- PET film products: trash bags
- PET sheet products: egg boxes, blister packs
- PET detergent bottles
- PET bands
- PET molded products.

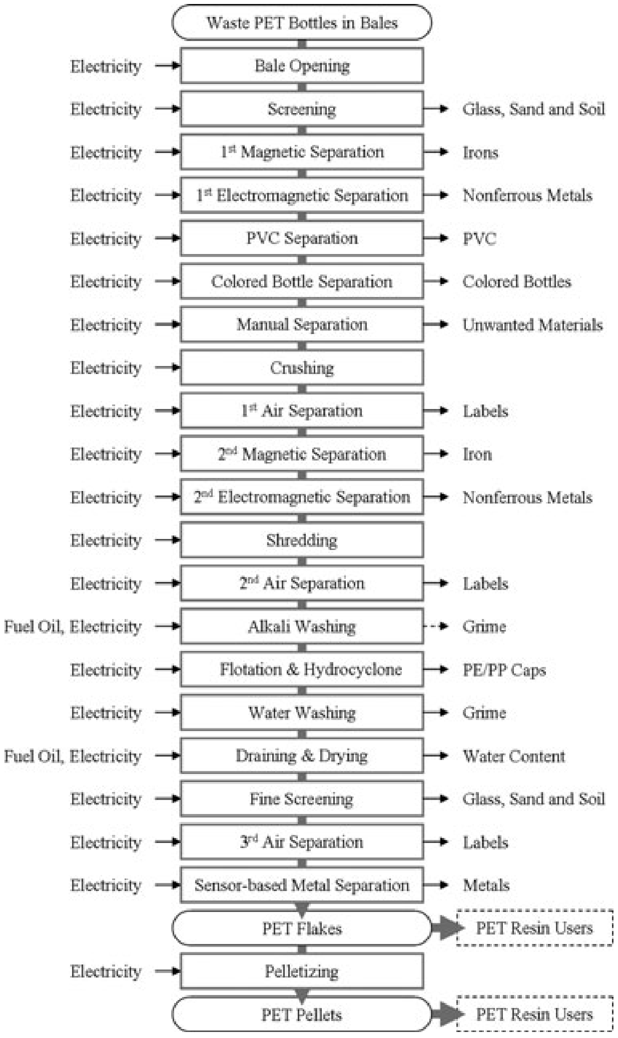

Figure 2 Mechanical recycling process of postconsumer polyethylene terephthalate (PET) bottles in Recycler A. Solid boxes indicate unit processes, and rounded boxes indicates waste or recycled materials. PVC = polyvinyl chloride; PE = polyethylene; PP = polypropylene.

The practice of quality control for recycled PET resin was investigated, and the following significant properties of recycled resin were specified: (1) intrinsic viscosity (IV), (2) color, (3) visible unwanted materials, and (4) invisible unwanted materials. Quality control parameters for such properties partly differed depending on whether recycled resin was used as a raw material of products in the shape of flakes or pellets.

In general, IV is emphasized as a substitute for the degree of polymerization. It is controlled by adjustment to either the water content of flakes, which promotes hydrolysis in melting processes of resin users, or the IV value (deciliter per gram [dL/g]) of pellets. The IV of virgin PET resin for beverage bottles is required to be 0.75 ± 0.02 dl/g by one of the major resin makers in Japan (Teijin Chemicals 2003).

The color of recycled PET resin is controlled on the basis of the L^*a^*b color system. The L value represents the brightness contrast between black and white by a value between 0 and 100. The a value and b value represent chromaticity (between green and red and between blue and yellow, respectively) by a value between −60 and 60.

The quality parameters for visible unwanted materials are quantity of (1) metals, (2) polyvinyl chloride (PVC), (3) colored PET, (4) PO, (5) adhesive-attached flakes, (6) labels, (7) other unwanted materials, and (8) sum of the unwanted materials (4) through (7) remaining in flakes (JCPRA 2007). Those unwanted materials remaining in the pellets are controlled on the basis of those remaining in the flakes fed into the pelletizing module.

Invisible unwanted materials are, as empirically observed by Recycler A, mainly composed of fine particles of silicon and aluminum components that are considered to come from glass, sand, and soil. According to Recycler A's analyses, the concentrations of such particles were 800 part per million (ppm) in average PET bottle flakes and 200 ppm in average pellets. For the pellets, because regular analyses of components are impractical, invisible unwanted materials are controlled on the basis of the number of meshes of filters per square inch used in the pelletizing module instead.

The required levels for the abovementioned quality parameters m, according to the applications n of recycled PET resin, Y_{mn} ($m = 1, \ldots, 14$; $n = 1, \ldots, 9$), are presented in table 1. The values in the table are primarily based on the actual condition of quality control in Recycler A, which sells its recycled resin for various kinds of products. Polyester filament products require raw materials (i.e., recycled resin) to be pelletized. As polyester batting, trash bags, and plastic bands have no requirements on the color of recycled resin, the required quality is defined as under 60, the maximum b value.

Quality Conversion Matrix

The modeling of the quality conversion matrix of mechanical recycling is based on the function of each module, or unit process, which, in aggregate, constitutes the entire recycling process. For example, the flotation and hydrocyclone modules aim at removing PE and PP, and the washing modules aim at eliminating grime.

The quality parameters of waste PET bottles, x_i, are defined as presented in the first line of table 2, in which x_i^{k-1} denotes the quality parameter i of the input to module k (i.e., output from module $k - 1$), and x_i^k denotes that of the output from module k. The quality parameters of the input to the first module, x_i^0, mean those of incoming waste PET bottles, x_i. The sum of x_i^{k-1} ($i = 0, \ldots, 10$) is the total amount of input to module k; hence, the sum of x_i ($i = 0, \ldots, 10$) means the number of incoming waste PET bottles. With regard to quality parameters i ($= 0, \ldots, 10$), the input and output of module k are linked by the residual ratio a_i^k ($0 < a_i^k \leq 1$) simply as $x_i^k = a_i^k \cdot x_i^{k-1}$, which can be rewritten as equation (1). The degree of grime ($i = 11$) measured in terms of the b value was formulated according to equation (2).

$$\log x_i^k = \log x_i^{k-1} + d^k \log a_i^k. \quad \left(\log a_i^k \geq 0\right) \tag{1}$$

$$x_{11}^k = x_{11}^{k-1} + d^k a_{11}^k. \tag{2}$$

Here, d^k is the dummy variable of module k (constituting the recycling process: 1; not constituting the recycling process: 0). The values of a_i^k presented in table 2 were based on the empirical quality data from incoming waste PET bottles and recycled PET resin for Recycler A. In some modules, such as air separation and sensor-based metal separation modules, a portion of transparent PET bottle flakes is inevitably removed in return for the effective removal of unwanted materials.

The water content of flakes ($i = 12$) does not depend on that of waste bottles, because flakes get soaked in the washing modules, but exclusively depends on the residual ratios of the draining and drying modules, a_{11}^{18} and a_{11}^{19}. The IV of pellets ($i = 13$) substantially depends on the water content of flakes fed into the pelletizing module, because the IV of incoming waste PET bottles is constant, on average. The water content of PET bottle flakes, x_{12}^{22}, and the IV (dL/g) of pellets, x_{13}^{23}, is formulated as

$$\log x_{12}^{22} = \log 1 + d^{18} \log a_{12}^{18} + d^{19} \log a_{12}^{19} \quad \left(0 < a_{12}^{18},\ a_{12}^{19} \leq 1\right), \tag{3}$$

$$x_{13}^{23} = b_0^{23} + b_1^{23} \log x_{12}^{22}. \tag{4}$$

The values of b_0^{23} and b_1^{23} were estimated by regression analysis with empirical data on the correspondence relation between the water content of PET bottle flakes before melting and the IV of PET pellets obtained in our investigations (table 3).

Among the modules constituting the entire process, alkali washing, drying, fine separation (fine screening, third air separation, and sensor-based metal separation) and pelletizing are optional modules, whereas the other modules are

Table 1 Required qualities for recycled polyethylene terephthalate (PET) resin according to the applications

			Polyester staple products			*PET sheet products*				
Quality parameter of recycled PET resin		*Polyester filament products* $n = 1$	*Working wear* $n = 2$	*Polyester batting* $n = 3$	*PET film products Trash bags* $n = 4$	*Egg boxes* $n = 5$	*Blister packs* $n = 6$	*PET detergent bottles* $n = 7$	*PET bands* $n = 8$	*PET molded products* $n = 9$
Visible unwanted materials (ppm)										
PO	Y_{1n}	≤30	≤30	≤30	≤30	≤30	≤30	≤30	≤30	≤30
Labels	Y_{2n}	≤10	≤10	≤20	≤20	≤20	≤10	≤10	≤20	≤20
PVC	Y_{3n}	≤20	≤20	≤40	≤40	≤40	≤20	≤20	≤40	≤40
Adhesive-attached flakes	Y_{4n}	≤100	≤100	≤1,200.0	≤1,200.0	≤1,200.0	≤100	≤100	≤1,200.0	≤1,200.0
Colored flakes	Y_{5n}	≤450	≤450	≤450	≤450	≤450	≤450	≤450	≤450	≤450
Metals	Y_{6n}	≤20	≤20	≤30	≤30	≤30	≤20	≤20	≤30	≤30
Sum of Y_1, Y_2, and Y_4	Y_{7n}	≤440	≤440	≤1,300.0	≤1,300.0	≤1,300.0	≤440	≤440	≤1,300.0	≤1,300.0
Other unwanted materials	Y_{8n}	≤280	≤280	≤280	≤280	≤280	≤280	≤280	≤280	≤280
Invisible unwanted materials (ppm)	Y_{9n}	–	≤800	≤1,600.0	≤800	≤1,600.0	≤400	≤400	≤1,600.0	≤400
Color										
b value	Y_{10n}	≤8	≤10	≤60	≤60	≤11	≤8	≤11	≤60	≤10
Water content	Y_{11n}	–	$\le 2.0 \cdot 10^{-2}$	$\le 2.0 \cdot 10^{-2}$	$\le 6.0 \cdot 10^{-3}$	$\le 3.0 \cdot 10^{-2}$	$\le 6.0 \cdot 10^{-3}$	$\le 6.0 \cdot 10^{-3}$	$\le 6.0 \cdot 10^{-3}$	$\le 6.0 \cdot 10^{-3}$
IV (dL/g)	Y_{12n}	≥0.65	≥0.64	≥0.66	≥0.66	≥0.62	≥0.66	≥0.66	≥0.66	≥0.66
Need to be pelletized?	Y_{13n}	Yes	No	No	No	No	No	No	No	No
No. meshes of filters per square inch	Y_{14n}	≥600	≥400	≥400	≥400	≥400	≥400	≥400	≥400	≥400

Note: ppm = parts per million; PO = polyolefin; PVC = polyvinyl chloride; IV = intrinsic viscosity; dL/g = deciliters per gram. Y_{mn} = required levels for quality parameters m according to the applications n of recycled PET resin.

Table 2 Residual ratios and amounts of utilities consumed for reprocessing 1 kilogram (kg) of waste polyethylene terephthalate (PET) bottles

Module		*Transparent PET* $i=0$	*Caps* $i=1$	*Labels* $i=2$	*PVC* $i=3$	*Adhesive-attached PET* $i=4$	*Colored PET* $i=5$	*Irons* $i=6$	*Nonferrous metals* $i=7$	*Others materials* $i=8$	*Glass* $i=9$	*Sand and soil* $i=10$	*Grime (b value)* $i=11$	*Water content* $i=12$	*Electricity (kWh)*	*Fuel oil (L)*
$k=1$	Bale opening	–	–	–	–	–	–	–	–	–	–	–	–	–	0.055	–
$k=2$	Screening	–	0.95	–	–	–	–	–	–	–	0.50	0.50	–	–	0.005	–
$k=3$	First magnetic separation	–	–	–	–	–	–	0.10	–	–	–	–	–	–	0.004	–
$k=4$	First electromagnetic separation	–	–	–	–	–	–	–	0.10	–	–	–	–	–	0.004	–
$k=5$	PVC separation	–	–	–	0.10	–	–	–	–	–	–	–	–	–	0.002	–
$k=6$	Colored bottle separation	–	–	–	–	–	0.25	–	–	–	–	–	–	–	0.000	–
$k=7$	Manual separation	–	–	–	0.25	–	0.10	–	–	0.10	–	–	–	–	0.001	–
$k=8$	Crashing	–	–	–	–	–	–	–	–	–	–	–	–	–	0.106	–
$k=9$	First air separation	0.99	–	0.10	–	–	–	–	–	–	–	–	–	–	0.011	–
$k=10$	Second magnetic separation	–	–	–	–	–	–	0.50	–	–	–	–	–	–	0.003	–
$k=11$	Second electromagnetic separation	–	–	–	–	–	–	–	0.50	–	–	–	–	–	0.003	–
$k=12$	Shredding	–	–	–	–	0.25	–	–	–	–	–	–	–	–	0.097	–
$k=13$	Second air separation	0.99	–	0.10	–	–	–	–	–	–	–	–	–	–	0.011	–
$k=14$	Alkali washing	–	–	–	–	–	–	–	–	–	–	–	−4	1.00	0.010	0.018
$k=15$	Flotation	–	0.01	0.50	–	–	–	–	–	–	–	–	–	1.00	0.014	–
$k=16$	Hydrocyclone	–	0.05	0.50	–	–	–	–	–	–	–	–	–	1.00	0.014	–
$k=17$	Water washing	–	–	–	–	–	–	–	–	–	–	–	−2	1.00	0.007	–
$k=18$	Draining	–	–	–	–	–	–	–	–	–	–	–	–	0.02	0.002	–
$k=19$	Drying	–	–	–	–	–	–	–	–	–	–	–	–	0.30	0.002	0.041
$k=20$	Fine screening	0.98	–	–	–	–	–	–	–	–	0.50	0.50	–	–	0.002	–
$k=21$	Third air separation	0.98	–	0.10	–	–	–	–	–	–	–	–	–	–	0.002	–
$k=22$	Sensor-based metal separation	0.99	–	–	–	–	–	0.50	0.50	–	–	–	–	–	0.000	–
$k=23$	Pelletizing	0.98	0.98	0.98	0.98	0.98	0.98	0.10	0.10	0.98	0.10	0.10	–	0.10	0.324	–

Note: i is the quality parameter's number of waste PET bottles, and k is the module's number. PVC = polyvinyl chloride; kWh = kilowatt-hour; L = liter.

Table 3 Correspondence relation between water content of polyethylene terephthalate (PET) bottle flakes and intrinsic viscosity (IV) of PET pellets

IV of PET pellets [dL/g]	*Water content of PET bottle flakes [–]*	*Notes*
0.62	$3.0 \cdot 10^{-2}$	Empirical data from Recycler B: the allowable minimum IV
0.65	$1.5 \cdot 10^{-2}$	Empirical data from Recycler B: the average case
0.68	$4.5 \cdot 10^{-3}$	Empirical data from Recycler A: the average case
b_0	0.515	Standard error: 0.021, p-value: 0.026
b_1	−0.071	Standard error: 0.011, p-value: 0.098
R^2	0.976	

Note: Recycler A sells its recycled PET resin for various kinds of products, and Recycler B sells its PET resin only for PET sheet products.

fundamental modules commonly included in the processes of most mechanical recyclers. To denote the operational conditions, we defined a constant of fundamental modules, $p_0 = 1$; binary variables of alkali washing, drying, fine separation, and pelletizing modules, $p_1, \ldots, p_4$; and the number of meshes of filters per square inch used in the pelletizing module, p_5, in place of the dummy variables d^k.

The quality conversion matrices of modules k, $\boldsymbol{q}^k$, change the quality and operations vectors of their inputs $[\log x_0^{k-1}, \ldots, \log x_{10}^{k-1}, x_{11}^{k-1}, p_0, \ldots, p_5]^T$ into those of their outputs $[\log x^k{}_0, \ldots, \log x^k{}_{10}, x^k{}_{11}, p_0, \ldots, p_5]^T$. For example, the quality conversion matrices of flotation (one of the fundamental modules), alkali washing, and pelletizing modules can be described by $\log a_i^k$ $(i = 0, \ldots, 10, 12)$ and $a^k{}_{11}$, as presented in Supplementary Tables S1–S3 in the Supporting Information on the Web, respectively.

The quality parameters from the last module, x_i^{23}, should be converted into quality parameters of recycled resin, y_m, to correspond to the required quality (see table 1). Equation (5) is applied to quality parameters in which the required quality is defined as the concentration, and equation (6) is applied to quality parameters in which the required quality is defined as the sum of two parameters, where the arithmetic mean is approximated by the geometric mean. The same is true of quality parameters on which the required quality is defined as the sum of three parameters. The following equations were organized in a "quality matrix" of recycled PET resin, $\boldsymbol{q}^R$ (see Supplementary Table S4 on the Web).

$$y_m = x_i^{23} / x_0^{23} \Leftrightarrow \log y_m = \log x_i^{23} - \log x_0^{23}. \quad (5)$$

$$y_m = \frac{x_i^{23} + x_{i+1}^{23}}{x_0^{23}} \cong \frac{2\sqrt{x_i^{23} x_{i+1}^{23}}}{x_0^{23}} \quad (6)$$

$$\Leftrightarrow \log y_m \cong \frac{1}{2}\left(\log x_i^{23} + \log x_{i+1}^{23}\right) + \log 2 - \log x_0^{23}.$$

The quality conversion matrix of the entire recycling process, $\mathbf{Q}$, is defined as the product of the quality conversion matrices of modules, $\boldsymbol{q}^k$ $(k = 1, \ldots, 23)$, and the quality matrix of recycled resin, $\boldsymbol{q}^R$. Consequently, the vector of the quality parameters of waste bottles and operational conditions $[\log x_0, \ldots, \log x_{10}, x_{11}, p_0, \ldots, p_5]^T$ and the quality vector of recycled resin $[\log y_0, \ldots, \log y_9, y_{10}, \log y_{11}, y_{12}, \ldots, y_{14}]^T$ were linearly linked by the quality conversion matrix $\mathbf{Q}$ (table 4).

As the amounts of utilities (i.e., electricity [kilowatt-hours] and fuel oil [liters]) consumed in each module k for reprocessing 1 kilogram (kg) of waste PET bottles, $u^k{}_1$ and $u^k{}_2$, respectively (see table 2), are attached to each $\boldsymbol{q}^k$, the amounts of electricity and fuel oil to run the entire recycling process for reprocessing 1 kg of waste bottles, U_1 and U_2, are also estimated by the quality conversion matrix $\mathbf{Q}$. The amount of recycled PET resin (kilograms), R, is calculated as $R = x_0^{23} + x_4^{23} + x_5^{23}$. Then the life cycle CO_2 emissions (kilograms) and life cycle fossil resource consumption (megajoules) of the recycling system for

Table 4 Quality conversion matrix of the mechanical recycling process, **Q**

Quality parameter of recycled PET resin	*Quality parameter of waste PET bottles*																	
	$\log x_0$	$\log x_1$	$\log x_2$	$\log x_3$	$\log x_4$	$\log x_5$	$\log x_6$	$\log x_7$	$\log x_8$	$\log x_9$	$\log x_{10}$	x_{11}	p_0	p_1	p_2	p_3	p_4	p_5
$\log y_0$	1	0	0	0	0	0	0	0	0	0	0	0	$-8.7 \cdot 10^{-3}$	0	0	$-2.6 \cdot 10^{-2}$	$-8.8 \cdot 10^{-3}$	0
$\log y_1$	−1	1	0	0	0	0	0	0	0	0	0	0	$2.7 \cdot 10^{0}$	0	0	$2.6 \cdot 10^{-2}$	0	0
$\log y_2$	−1	0	1	0	0	0	0	0	0	0	0	0	$3.4 \cdot 10^{0}$	0	0	$-9.7 \cdot 10^{-1}$	0	0
$\log y_3$	−1	0	0	1	0	0	0	0	0	0	0	0	$4.4 \cdot 10^{0}$	0	0	$2.6 \cdot 10^{-2}$	0	0
$\log y_4$	−1	0	0	0	1	0	0	0	0	0	0	0	$5.4 \cdot 10^{0}$	0	0	$2.6 \cdot 10^{-2}$	0	0
$\log y_5$	−1	0	0	0	0	1	0	0	0	0	0	0	$4.4 \cdot 10^{0}$	0	0	$2.6 \cdot 10^{-2}$	0	0
$\log y_6$	−1	0	0	0	0	0	$5.0 \cdot 10^{-1}$	$5.0 \cdot 10^{-1}$	0	0	0	0	$5.0 \cdot 10^{0}$	0	0	$-2.7 \cdot 10^{-1}$	$-1.0 \cdot 10^{0}$	0
$\log y_7$	−1	$3.3 \cdot 10^{-1}$	$3.3 \cdot 10^{-1}$	0	$3.3 \cdot 10^{-1}$	0	0	0	0	0	0	0	$4.3 \cdot 10^{0}$	0	0	$-3.1 \cdot 10^{-1}$	0	0
$\log y_8$	−1	0	0	0	0	0	0	0	1	0	0	0	$5.0 \cdot 10^{0}$	0	0	$2.6 \cdot 10^{-2}$	0	0
$\log y_9$	−1	0	0	0	0	0	0	0	0	$5.0 \cdot 10^{-1}$	$5.0 \cdot 10^{-1}$	0	$6.0 \cdot 10^{0}$	0	0	$-2.7 \cdot 10^{-1}$	$-1.0 \cdot 10^{0}$	0
y_{10}	0	0	0	0	0	0	0	0	0	0	0	$1.0 \cdot 10^{0}$	$-2.0 \cdot 10^{0}$	$-4.0 \cdot 10^{0}$	0	0	0	0
$\log y_{11}$	0	0	0	0	0	0	0	0	0	0	0	0	$-1.8 \cdot 10^{0}$	$0.0 \cdot 10^{0}$	$-5.2 \cdot 10^{-1}$	0	$-1.0 \cdot 10^{0}$	0
y_{12}	0	0	0	0	0	0	0	0	0	0	0	0	$8.8 \cdot 10^{-1}$	$0.0 \cdot 10^{0}$	$3.7 \cdot 10^{-2}$	0	$-2.3 \cdot 10^{-1}$	0
y_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
y_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U_1	0	0	0	0	0	0	0	0	0	0	0	0	$3.4 \cdot 10^{-1}$	$1.0 \cdot 10^{-2}$	$1.9 \cdot 10^{-3}$	$4.6 \cdot 10^{-3}$	$3.2 \cdot 10^{-1}$	0
U_2	0	0	0	0	0	0	0	0	0	0	0	0	0	$1.8 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	0	0	0

Note: x_i denotes the quality parameter i of waste PET bottles (see table 2). $p_0, \ldots, p_5$ denote the operational conditions (see table 5).
y_m denotes the quality parameter m of recycled PET resin (see table 7).
U_1 and U_2 indicate the amounts of electricity and fuel oil to run the entire recycling process for reprocessing 1 kilogram (kg) of waste bottles.

Table 5 Life cycle inventories for electricity supply, fuel oil consumption, and virgin polyethylene terephthalate (PET) resin production

Process	CO_2 *emission (kg/*)*	*Fossil resource consumption (MJ/*)*	*Notes*
Electricity supply (kWh)	0.39	5.7	Calculated on the basis of the data No. 000122 (JLCA 2008)
Fuel oil consumption (L)	2.79	37.7	Calculated on the basis of the data No. 000098 (JLCA 2008)
Virgin PET resin production (kg)	1.54	62.8	Calculated on the basis of the data No. 000055 (JLCA 2008)

Note: L = liter; kg = kilogram; kWh = kilowatt hour; kg/* = kilogram per kilowatt-hour, kilogram per liter, or kilogram per kilogram of PET resin; MJ/* = megajoule per kilowatt-hour, megajoule per liter, or megajoule per kilogram of PET resin.

reprocessing 1 kg of waste bottles, denoted by E and F, respectively, are evaluated as

$$\begin{aligned} E &= e_1U_1 + e_2U_2 - e_3R/W \\ &= e_1\sum_k d^k u_1^k + e_2\sum_k d^k u_2^k - e_3R/W, \end{aligned} \tag{7}$$

$$\begin{aligned} F &= f_1U_1 + f_2U_2 - f_3Y/X \\ &= f_1\sum_k d^k u_1^k + f_2\sum_k d^k u_2^k - f_3R/W, \end{aligned} \tag{8}$$

where e_1 and f_1 are respectively the life cycle inventories (CO_2 emissions and fossil resource consumption) for electricity supply, e_2 and f_2 are those for fuel oil consumption, e_3 and f_3 are those of the production processes for virgin PET resin replaced by recycled resin, and W is the amount of incoming waste PET bottles. The life cycle inventories presented in table 5 are calculated on the basis of the data from the Japanese Inventory Database (JLCA 2008). For more details on the life cycle inventories associated with PET bottle recycling, see the work of Nakatani and colleagues (2010).

Logistics, waste collection, and transportation are outside the scope of this framework because they have no impact on the quality of waste PET bottles. In addition, logistics have much less impact on CO_2 emissions and fossil resource consumption than recycling processes in the case of PET bottles recycling in Japan (Nakatani et al. 2010).

Design Based on Quality Information and Environmental Impacts

Applicability to Intended Products

The proposed framework makes it possible for decision makers to estimate the quality parameters of recycled PET resin $[\log y_0, \ldots, \log y_9, y_{10}, \log y_{11}, y_{12}, \ldots, y_{14}]^T$ by multiplying the quality and operations vector $[\log x_0, \ldots, \log x_{10}, x_{11}, p_0, \ldots, p_5]^T$ by the quality conversion matrix $\mathbf{Q}$ and to simulate the applicability of waste PET bottles to intended products as the primary criterion by confirming whether all the estimated quality parameters of recycled PET resin satisfy quality demands (see table 1). If the applicability is verified, then estimated CO_2 emissions and fossil resource consumption become the secondary criteria for decision making by examination of whether the estimated values are acceptable from the viewpoint of environmental impacts.

The approach described in the next section can be applied to collaborative decision making. In the case where the estimated quality of recycled PET resin does not satisfy the quality demands, the quality parameters of waste PET bottles that should be improved and the optional modules that should be included in the recycling process can be specified. In the case where the estimated quality satisfies the quality demands, unnecessary optional modules can be specified.

Specification of Requirements

Through MILP, the requirements for application to the intended products—that is, required improvements in the quality of waste PET bottles and required optional modules [$-\log r_0, \ldots, -\log r_{10}, -r_{11}, p_0, \ldots, p_5$]—are obtained as an optimal solution under the quality constraints required for recycled PET resin. The objective function and constraints are as follows:

$$\text{Objective function}: \quad \min z = -\sum_{i=1}^{10} c_i \log r_i - c_{11} r_{11} + \sum_{j=0}^{5} c_j p_j,$$

$$\text{Constraints}: \quad \log y_1 \leq \log Y_{1n}, \cdots, \log y_9 \leq \log Y_{9n}, y_{10} \leq Y_{10n}, \tag{9}$$

$$\log y_{11} \leq \log Y_{11n}, y_{12} \geq Y_{12n}, \cdots, y_{14} \geq Y_{14n}, \tag{10}$$

$$0 < r_i \leq 1 \quad (i = 1, \cdots, 10), \quad r_{11} \leq 0, \tag{11}$$

$$p_0 = 1, \quad p_1, \cdots, p_4 = 0 \vee 1, \tag{12}$$

where r_i ($i = 1, \ldots, 10$) are the reduction rates, running from 0 to 1, for unwanted materials i of waste PET bottles; r_{11} is the reduction range, zero or a negative value, for the degree of grime measured by the b value; and c_i, c_{11}, and c_j are coefficients of the objective function. $r_i = 1$ indicates that unwanted materials i are not reduced, whereas $r_i = 0$ indicates that unwanted materials i are completely presorted from waste PET bottles. $r_{11} = 0$ indicates that the degree of grime is unchanged, and $r_{11} < 0$ indicates that the degree of grime, measured by the b value, is reduced.

The objective function is the minimization of a linear combination of $-\log r_i$ ($i = 1, \ldots, 10$), $-r_{11}$, and p_j ($j = 0, \ldots, 5$), which indicates the minimum requirements for improvements in the quality of waste PET bottles and addition of optional modules to satisfy the required quality. The constraints consist of the required quality of recycled PET resin, the nonnegativity constraints on $-\log r_i$ ($i = 1, \ldots, 10$) and $-r_{11}$, a constant of fundamental modules $p_0 = 1$, and the binary constraints on operating conditions $p_1, \ldots, p_4$. There are no constraints for raw material demands of PET resin users—that is, unlimited demand for each application is presumed as far as quality constraints are satisfied.

For the decision making of a recycler, the primary objective may be to maximize the total profit by reprocessing plastic waste into recycled products, and all the quality parameters of waste bottles, which are noncontrollable for recyclers, become constants ($r_1, \ldots, r_{10} = 1$, $r_{11} = 0$). Then, given that recycled resin that satisfies the quality demands is sold at the same price, the objective function, equation (9), becomes the cost minimization of the recycling process, as follows:

$$\text{Objective function for a recycler}: \quad \min z = \sum_{j=0}^{5} c_j p_j, \tag{13}$$

where c_j means unit costs of optional modules. Constraints are the same as in equations (10) and (12). In contrast, for the decision making of consumers, the primary objective may be to minimize the burden of the quality improvements by presorting plastic waste, and all the operational conditions of a recycler, p_j, which are noncontrollable for consumers, become constants. Then the objective function is redefined as follows:

$$\text{Objective function for consumers}: \quad \min z = -\sum_{i=1}^{10} c_i \log r_i - c_{11} r_{11}, \tag{14}$$

and constraints are the same as in equations (10) and (11). Also, for the decision making of a municipality that wants to minimize the cost of pretreatment operations and instruction to consumers, the objective function is the same as in equation (14), but the weighting among the quality improvements, c_i ($i = 1, \ldots, 11$), may be different between consumers and a municipality.

In reality, various stakeholders (i.e., consumers, municipalities, and recyclers) are involved in a recycling system and aim at different objectives. For collaborative decision making among stakeholders, therefore, both the quality parameters of waste bottles and the operational conditions become design variables, but the coefficients of the objective function, which mean the weighting among the quality improvements and optional modules, can almost never be logically fixed on a single set of values. Instead, because of the properties of linear programming, the optimal solutions for a finite number of combinations of coefficients are aggregated into a limited number of solutions. By Monte Carlo simulation with sufficiently large sets of random numbers for the coefficients $c_i > 0$ and $c_j > 0$, all the feasible optimal solutions for achieving the quality demands can be obtained, along with the CO_2 emissions and fossil resource consumption estimated for each solution. Then, decision makers collaborate on choosing the direction of improvement among the obtained solutions considering the requirements for the quality of waste PET bottles, CO_2 emissions, and fossil resource consumption.

Case Study

The proposed framework was applied to a municipality, Ward C, in Tokyo as a case study. Quality parameters of waste bottles $[\log x_0, \ldots, \log x_{10}, x_{11}]^T$ were assumed on the basis of the published quality levels of waste PET bottles in Ward C (JCPRA 2007), as presented in table 6, and then the quality of recycled PET resin, CO_2 emissions, and fossil resource consumption were estimated as presented in table 7 under the operational conditions $[p_0, \ldots, p_5]^T = [1, 1, 1, 1, 0, 0]^T$. Comparing the estimated quality with the required quality in table 1, we found that the waste PET bottles of Ward C could be used for polyester batting, trash bags, egg boxes, and plastic bands but not for polyester filament products, working wear, blister packs, detergent bottles, or plastic molded products.

To obtain all the feasible optimal solutions for each application of recycled resin, we conducted Monte Carlo simulation with 1,000 sets of random numbers for the coefficients of the objective function. For example, there are four feasible optimal solutions for polyester filament products (table 8). The solutions for polyester filament products are characterized depending on whether the alkali washing module and the fine separation modules should be included in the recycling process or the number of labels and the degree of grime contained in the incoming waste PET bottles should be decreased. The drying and pelletizing modules are indispensable for applying recycled PET resin to the manufacture of polyester filament products. In the case of a recycler that is equipped with all the fundamental and optional modules, $p_0, \ldots, p_4$, such as

Table 6 Quality parameters of waste polyethylene terephthalate (PET) bottles in Ward C and operational conditions for the recycling process

Waste PET bottles (kg)	*Transparent PET (kg)*	*Caps (kg)*	*Labels (kg)*	*PVC (kg)*	*Adhesive-attached PET (kg)*	*Colored PET (kg)*	*Irons (kg)*	*Nonferrous metals (kg)*	*Other materials (kg)*	*Glass (kg)*	*Sand and soil (kg)*	*Grime (b value)*	*Fundamental modules*	*Alkali washing module*	*Drying module*	*Fine separation modules*	*Pelletizing module*	*No. meshes of filters per square inch*
W	x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	p_0	p_1	p_2	p_3	p_4	p_5
1.00	0.91	0.03	0.05	0.0010	0.0004	0.0025	0.0008	0.0003	0.0002	0.0010	0.0000	17	1	1	1	1	0	0

Note: kg = kilogram; PVC = polyvinyl chloride.

Table 7 Estimated qualities of recycled polyethylene terephthalate (PET) resin, carbon dioxide (CO_2) emissions, and fossil resource consumptions for reprocessing 1 kilogram (kg) of waste PET bottles in Ward C

Recycled PET resin (kg)	*Transparent PET (kg)*	*Visible unwanted materials (ppm)* PO	*Labels*	PVC	*Adhesive-attached flakes*	*Colored flakes*	*Metals*	*Sum of* y_1, y_2, *and* y_4	*Other unwanted materials*	*Invisible unwanted materials (ppm)*	*Color b value*	*Water content (-)*	*IV value (dL/g)*	*Pelletized? (Yes: 1, No: 0)*	*No. meshes of filters per square inch*	CO_2 *emissions (kg)*	*Fossil resource consumptions [MJ]*
R	y_0	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}	y_{13}	y_{14}	*E*	*F*
0.84	0.84	17	15	30	119	74	26	93	24	59	11	0.0045	0.92	0	0	−0.99	−48.7

Note: ppm = parts per million; IV = intrinsic viscosity; dL/g = deciliters per gram; PO = polyolefin; PVC = polyvinyl chloride.

Recycler A, all the obtained solutions are feasible. In the case of other recyclers that are unequipped with some optional modules, however, some of the obtained solutions are possibly infeasible. For example, in the case of a recycler that has no fine separation modules, Solutions 3 and 4 in table 8 are infeasible, and therefore decision makers have to choose either Solution 1 or 2. If a recycler is unequipped with both alkali washing and fine separation modules, only Solution 1 is feasible. Recyclers that are unequipped with either the drying or the pelletizing module are incapable of applying their recycled resin to polyester filament products.

The remaining tasks of decision makers are to choose the direction of improvement among the obtained feasible solutions. According to the requirements for the quality of waste PET bottles, municipalities have to reexamine the pretreatment operations and the instruction to consumers on presorting of waste PET bottles.

Conclusion

In this article, a framework for the multicriteria design of PET bottle recycling based on quality information and environmental impacts was developed for the purpose of supporting collaborative decision making among stakeholders. In this framework, we estimate the quality of recycled resin by multiplying the quality vector of waste bottles by the quality conversion matrix, and we simulate the applicability to the intended products by confirming whether the estimated quality of recycled resin satisfies the quality demands of PET resin users. As the amounts of utilities to run the recycling process are attached to the quality conversion matrix, the amounts of CO_2 emissions and fossil resource consumption are also estimated. An approach to collaborative decision making utilizing MILP and Monte Carlo simulation was proposed on the premise of different objectives of various stakeholders, in which all the feasible optimal solutions for achieving the quality demands were obtained. Then, decision makers collaborate on examining the direction of improvement on the basis of the obtained solutions considering the requirements on the quality of waste PET bottles, the CO_2 emissions, and

Table 8 Feasible optimal solutions for applying recycled polyethylene terephthalate (PET) resin to polyester filament products

Quality parameter of waste PET bottles		*Solution 1*	*Solution 2*	*Solution 3*	*Solution 4*
Caps	r_1	×1.0	×1.0	×1.0	×1.0
Labels	r_2	×0.1	×0.1	×0.7	×0.7
PVC	r_3	×0.7	×0.7	×0.7	×0.7
Adhesive-attached PET	r_4	×0.9	×0.9	×0.8	×0.8
Colored PET	r_5	×1.0	×1.0	×1.0	×1.0
Irons	r_6	×1.0	×1.0	×1.0	×1.0
Nonferrous metals	r_7	×1.0	×1.0	×1.0	×1.0
Other materials	r_8	×1.0	×1.0	×1.0	×1.0
Glass	r_9	×1.0	×1.0	×1.0	×1.0
Sand and soil	r_{10}	×1.0	×1.0	×1.0	×1.0
Grime (*b* value)	r_{11}	−7	−3	−7	−3
Fundamental modules	p_0	=1	=1	=1	=1
Alkali washing module	p_1	=0	=1	=0	=1
Drying module	p_2	=1	=1	=1	=1
Fine separation modules	p_3	=0	=0	=1	=1
Pelletizing module	p_4	=1	=1	=1	=1
No. meshes of filters per square inch	p_5	=600	=600	=600	=600
Recycled PET resin (kg)	R	0.88	0.88	0.83	0.83
CO$_2$ emissions (kg)	E	−0.97	−0.92	−0.89	−0.84
Fossil resource consumption (MJ)	F	−49.8	−49.1	−46.5	−45.8

Note: PVC = polyvinyl chloride; kg = kilograms; CO$_2$ = carbon dioxide; MJ = megajoules.

fossil resource consumption estimated for each solution, and thus the proposed framework contributes to the collaborative multicriteria design of plastic recycling.

This framework can be applied to recycling of other kinds of waste materials, at least to mechanical recycling of other kinds of postconsumer plastics, as long as the required quality and the quality conversion matrix for each recycling are specified. The major bottleneck of the proposed framework is the availability of data from recyclers on the quality relation between waste PET bottles and recycled PET resin. In this article, the input-output relation of each module, based on the empirical data of a single recycler, was simplified into linear formulation. In reality, the input-output relation of some modules might differ among recyclers, and the objective function or constraints might not even be modeled into linear formulation. If the formulation is nonlinear, a branch-and-bound scheme with fixed binary variables is preferred to make the most of the properties of linear programming (Sodhi and Reimer 2001). Further investigation on the mechanism of each module is required.

Acknowledgements

This research was supported by a Grant for Environmental Research Projects of the Sumitomo Foundation; the Alliance for Global Sustainability; and the Value Creation Initiative (Sumitomo Corporation), Research Into Artifacts, Center for Engineering, University of Tokyo. We are grateful to an anonymous Japanese recycler for providing much valuable information.

Note

1. One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short tons.

References

Arena, U., M. L. Mastellone, and F. Perugini. 2003a. The environmental performance of alternative solid waste management options: A life cycle assessment study. *Chemical Engineering Journal* 96(1–3): 207–222.

Arena, U., M. L. Mastellone, and F. Perugini. 2003b. Life cycle assessment of a plastic packaging recycling system. *International Journal of Life Cycle Assessment* 8(2): 92–98.

Askham-Nyland, C., I. S. Modahl, H. L. Raadal, and O. J. Hanssen. 2003. Application of LCA as a decision-making tool for waste management systems: Material flow modelling. *International Journal of Life Cycle Assessment* 8(6): 331–336.

Bjorklund, A. and G. Finnveden. 2005. Recycling revisited: Life cycle comparisons of global warming impact and total energy use of waste management strategies. *Resources, Conservation and Recycling* 44(4): 309–317.

Bloemhof-Ruwaard, J. M., M. Salomon, and L. N. V. Wassenhove. 1996. The capacitated distribution and waste disposal problem. *European Journal of Operational Research* 88: 490–503.

Boon, J. E., J. A. Isaacs, and S. M. Gupta. 2000. Economic impact of aluminum-intensive vehicles on the U.S. automotive recycling infrastructure. *Journal of Industrial Ecology* 4(2): 117–134.

Boon, J. E., J. A. Isaacs, and S. M. Gupta. 2003. End-of-life infrastructure economics for "clean vehicles" in the United States. *Journal of Industrial Ecology* 7(1): 25–45.

Council for PET Bottle Recycling, Japan. 2001. Shitei PET bottle no jishu sekkei guideline. [Independent design guideline for designated PET bottles.] www.petbottle-rec.gr.jp/more/mo_sitei_f.html. Accessed 14 December 2010.

Council for PET Bottle Recycling, Japan. 2007. *PET bottle recycle nenji houkoku-sho 2008 nendo-ban. [Annual report for PET bottle recycling 2007*] Tokyo, Japan: Council for PET Bottle Recycling.

Ekvall, T., G. Assefa, A. Bjorklund, O. Eriksson, and G. Finnveden. 2007. What life-cycle assessment does and does not do in assessments of waste management. *Waste Management* 27(8): 989–996.

Finnveden, G. and T. Ekvall. 1998. Life-cycle assessment as a decision-support tool: The case of recycling versus incineration of paper. *Resources, Conservation and Recycling* 24(3-4): 235–256.

Fujii, M., S. Hashimoto, K. Nansai, S. Murakami, R. Inaba, M. Osako, and Y. Moriguchi. 2008. Material recycle no LCI bunseki shuhou no seiri to hyouka jirei. [Evaluation method of mechanical recycling and case studies based on life cycle inventory analysis.] *Journal of Life Cycle Assessment, Japan* 4(1): 78–88.

Fukushima, Y. and M. Hirao. 2000. Life-cycle model ni-yoru PET bottle recycle system no hyouka. [Lifecycle model for PET bottle recycle system evaluation.] *Transaction of the Institute of Electrical Engineers of Japan* 118-C(9): 1250–1256.

Glassey, C. R. and V. K. Gupta. 1974. A linear programming analysis of paper recycling. *Management Science* 21(4): 392–408.

Hara, T., H. Shima, Y. Yoshida, and R. Matsuhashi. 2007. Model analysis of an inter-industrial and inter-regional waste recycling system in Japan. *Energy* 32: 609–618.

Hoshino, T., K. Yura, and K. Hitomi. 1995. Optimization analysis for recycle-oriented manufacturing systems. *International Journal of Production Research* 33(8): 2069–2078.

Isaacs, J. A. and S. M. Gupta. 1997. Economic consequences of increasing polymer content for the U.S. automobile recycling infrastructure. *Journal of Industrial Ecology* 1(4): 19–33.

JCPRA (Japan Containers and Packaging Recycling Association). 2007. PET bottle bunbetsu-kijun tekigou-butsu no hinshitsu tyousa kekka. [The results of quality surveys for adequately-sorted PET bottles.] www.jcpra.or.jp/gather/municipal/municipal03/01/index.html. Accessed 14 December 2010.

JLCA(Life Cycle Assessment Society of Japan). 2008. JLCA-LCA Database 2010 nendo 3 ban. [JLCA LCA database 2008, third ed]. www.jemai.or.jp/lcaforum/db/01_01.cfm. Accessed 28 December 2008.

Liberopoulos, G., G. Kozanidis, and O. Hatzikonstantinou. 2010. Production scheduling of a multi-grade PET resin plant. *Computers and Chemical Engineering* 34: 387–400.

Lu, Q., J. A. S. Williams, M. Posner, W. Bonawi-tan, and X. Qu. 2006. Model-based analysis of capacity and service fees for electronics recyclers. *Journal of Manufacturing Systems* 25 (1): 45–57.

Matsuda, S. and H. Kubota. 2008. Shakai energy shouhi-ryou wo shihyou to-shita PET bottle recycle no LCA kaiseki. [LCA analysis of PET bottle recycling by using proposed concept of social energy consumption]. *Journal of Life Cycle Assessment, Japan* 4(1): 67–77.

Nakatani, J., M. Fujii, Y. Moriguchi, and M. Hirao. 2010. Life-cycle assessment of domestic and transboundary recycling of post-consumer PET bottles. *International Journal of Life Cycle Assessment* 15(6): 590–597.

Noda, R., M. Komatsu, and E. Sumi. 2001. Evaluation of material recycling for plastics: Environmental aspects. *Journal of Material Cycles and Waste Management* 3(2): 118–125.

Røine, K. and H. Brattebø. 2003. Towards a methodology for assessing effectiveness of recovery systems: A process system approach. In *Perspectives on industrial ecology*, edited by D. Bourg and S. Erkman. Sheffield, U.K.: Greenleaf Publishing.

Sodhi, M. S. and B. Reimer. 2001. Models for recycling electronics end-of-life products. *OR Spectrum* 23: 97–115.

Spengler, T., M. Ploog, and M. Schroter. 2003. Integrated planning of acquisition, disassembly and bulk recycling: a case study on electronic scrap recovery. *OR Spectrum* 25: 413–442.

Stuart, J. A., J. C. Ammons, and L. J. Turbini. 1999. A product and process selection model with multidisciplinary environmental considerations. *Operations Research* 47(2): 221–234.

Sugiyama, H., M. Hirao, R. Mendivil, U. Fischer, and K. Hungerbuhler. 2006. A hierarchical activity model of chemical process design based on life cycle assessment. *Process Safety and Environmental Protection* 84(B1): 63–74.

Tang, J., Y. Liu, R. Y. K. Fung, and X. Luo. 2008. Industrial waste recycling strategies optimization problem: mixed integer programming model and heuristics. *Engineering Optimization* 40 (12): 1085–1100.

Teijin Chemicals Ltd. 2003. Recycle PET no inryou bottle tou heno riyou ni-kakaru shokuhin kenkou eikyou-hyouka shiryou. [Food safety assessment on applying recycled PET resin to beverage bottles.] www.fsc.go.jp/senmon/kiguyouki/k-dai1/index.html. Accessed 28 December 2008.

Tokai, A. and T. Furuichi. 2000. Evaluation of recycling policies for PET bottles based on multiattribute utility indices. *Journal of Material Cycles and Waste Management* 2(2): 70–79.

Tsai, W. H. and S. J. Hung. 2009. Treatment and recycling system optimization with activity-cased costing in WEEE reverse logistics management: an environmental supply chain perspective. *International Journal of Production Research* 47 (19): 5391–5420.

Wada, Y., K. Nakano, T. Ozaki, and A. Iwamoto. 2004. Shimin no ukeire-ishi wo kouryo shita inryou-you PET bottle recycle no hyouka. [Evaluation of recycling system of beverage polyethylene terephthalate bottle in citizens' acceptance intention.] *Journal of the Japan Society of Civil Engineers* 769: 43–54.

Williams, J. A. S., S. Wongweragiat, X. Qu, J. B. McGlinch, W. Bonawi-tan, J. K. Choi, and J. Schiff. 2007. An automotive bulk recycling planning model. *European Journal of Operational Research* 177: 969–981.

Yasuda, Y. 2001. PET bottle no recycle system nikansuru hyouka to seisaku-bunseki. [Evaluation and policy analysis on the recycling system of PET bottles.] *Journal of the Japan Society of Waste Management Experts* 12(5): 229–234.

About the Authors

Jun Nakatani is an assistant professor in the Department of Urban Engineering and **Masahiko Hirao** is a professor in the Department of Chemical System Engineering at the University of Tokyo, Japan.

Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: This supplement contains Supplementary Tables S1–S3, which provide the quality conversion matrices for the flotation, alkali washing, and pelletizing module that change the quality and operations vectors of their inputs into those of their outputs, and Supplementary Table S4, which provides the quality matrix of recycled PET resin that converts quality parameters to correspond to the required quality presented in table 1 in the main text.