Waste PC Recycling Policy Formulation by Fuzzy Optimization Techniques

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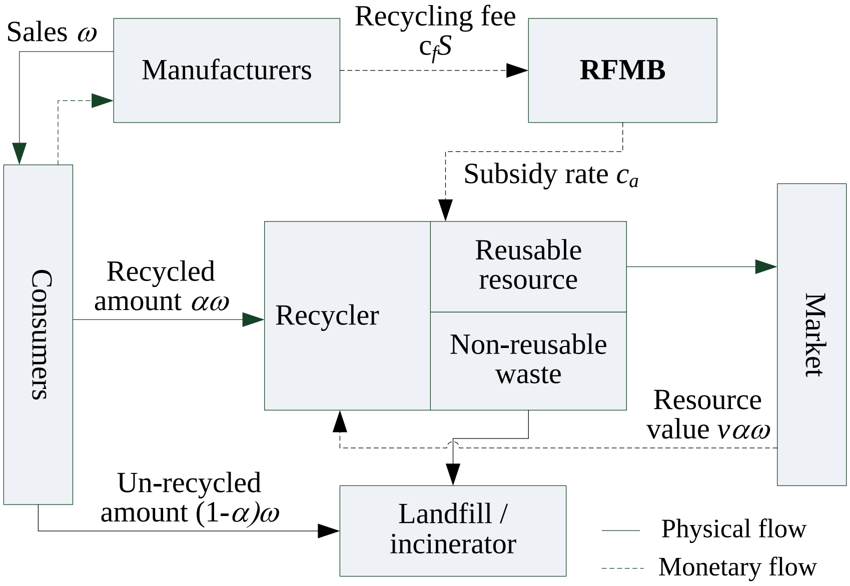
Abstract. *As the fast growth of information technology and the short life cycle of PC, environmental concerns regarding the disposal of waste PCs are increasing. Government regulation has played an important role in the management and recycling of electronic waste. This study attempts to formulate the recycling fee and subsidy rate for an organization which is in charge of the waste PC recycling policies in Taiwan. Fuzzy mathematical programming is used to model the decision, and a solution procedure based on intuitionistic fuzzy optimization is employed to solve the problem. The result obtained by this study is compared with the current operations by the organization.*

1. Introduction

The dramatic development of telecommunication and information technology during the last two decades has accelerated the mass production, mass consumption, and mass disposal of waste personal computers (PCs). The consequence is the great environmental impacts brought by PC manufacturing and disposal. As the life cycle of PC becomes shorter, environmental concerns regarding the disposal of end-of-life (EoL) PCs are increasing (Choi et al. 2006).

Government regulation has played an important role in the management and recycling of electronic waste. Using Taiwan as an example, to prevent and solve the environmental pollution problems caused by waste materials, the Environmental Protection Administration (EPA) of Taiwan established the Recycling Fund Management Board (RFMB) in 1998 to monitor and manage the operations of the recycling and reuse of waste materials, and to enhance recycling efficiency. The RFMB's operations are conducted through the joint participation of industry representatives, the fee rate inspection committee, an auditing and verifying organization, the recycling industry, the government, and the general public. Manufacturers, importers, and sellers (MISs) of designated products pay recycling fees (i.e. product charge) based on fee rates derived by the fee rate inspection committee. The money is then channeled into the recycling management fund and used to promote recycling incentives, part of which is used as the subsidy given to recycling industries to enhance their recycling ratio. Confirmation of the amount of resources actually recycled is conducted by an auditing and verifying organization selected by the EPA. The above-mentioned interrelations between RFMB, MISs, and recyclers are depicted in Figure 1.

It is noted that recycling rate improvement ought to be one of the primary objectives for the establishment of RFMB. However, the current fee rate decision by RFMB does not take such an objective into account. Hong and Ke (2011) also questioned the appropriateness of the fund balance concept adopted by RFMB, and investigated the use of other objectives in determining recycling fees. The efficient use of the fund is also missed in the current recycling fee determination. Hong and Ke (2011) suggested the maximization of social welfare should be considered in the recycling fee decision process. This study adopts a similar concept where the minimization of recycling fee is considered in the decision. A lower recycling fee charged to the MISs would reduce the product price, and hence the surpluses of both MISs and consumers are increase. This study attempts to determine the recycling fee and the subsidy rate for RFMB with the objectives of minimizing the recycling fee while maximizing the recycling rate at the same time. These two objectives are conflict in nature, where the maximization of recycling rate would require the increasing of subsidy rate, which will in turn boost the recycling fee. The exact relation how subsidy rate affects recycling rate is difficult to identify due to the complicated factors and limited data involving in this problem. To alleviate such a difficulty, this study uses fuzzy regression analysis to model the relation. For the convenience in dealing with the fuzzy equation in our multi-objective optimization problem, a fuzzy approach based on intuitionistic fuzzy sets is adopted to solve the problem.



c_a: Subsidy rate
c_f: Recycling fee rate
ω: Estimated amount of waste PC
v: Unit resource recycling value
S: Sales amount
α: Recycling rate

Figure 1. Waste PC recycling system

2. Recycling Fee and Subsidy Rate Decision Model

The main objective of RFMB is to maximize the recycling rate so as to reduce the environmental impacts caused by EoL products. The sole income of RFMB is the recycling fees collected from MISs. Efficient use of this single resource is an obligation of RFMB. When the recycling fee is set to high by RFMB, it may harm the competiveness of the MISs, and the increased cost of MISs may also be transferred to consumers. In such a case, the surpluses of both MISs and consumers are reduced. Thus, it is also important for RFMB to minimize the recycling fee. Consequently, the recycling fee and subsidy rate decision considered in this study is a multi-objective optimization problem. The mean by RFMB to improve the recycling rate is via the incentive of subsidy given to recyclers. Though this study does not explicitly consider the decision of recyclers, the influence of subsidy on the recycling rate is modeled by fuzzy regression analysis.

2.1. Fuzzy regression on recycling rate

The factors that determine the recycling rate of EoL PCs are complicated and are not easy to be fully identified. Though it is believed that subsidy is a decisive factor among them, there are not abundant data to support the identification of the regression function of the recycling rate on subsidy rate. The distribution of the recycling rates with respect to different levels of subsidy rate in the past 10 years also reveals that the statistical regression analysis is not suitable in this case.

Though historical data regarding recycling rate are scarce, estimates of recycling rate based on different levels of subsidy are possible to be obtained from experts in the recycling industry. Instead of statistical regression, this study adopts fuzzy regression analysis to model the recycling rate based on estimated data due to its capability of handling incomplete, insufficient, and subjective data. The estimates of recycling rate under different levels of subsidy are requested from five recyclers. Their responses are presented in Table 1. At the same level of subsidy, recyclers have different estimates of the expected recycling rate. Such deviations are considered stemming from incomplete information and subjective judgment. Fuzzy regression analysis is suitable for dealing with observations with incomplete information and subjective judgment.

To conduct the fuzzy regression analysis on the data in Table 1, the estimates by the five recyclers at the same subsidy rate level are aggregated to a single fuzzy number. This aggregation is done by the fuzzy number construction method proposed by Cheng (2005). The resulting fuzzy aggregation of individual estimates is shown in the last column of Table 1. A fuzzy number is denoted by (l, m, r), where l indicates its left endpoint, m the mode, and r the right endpoint. Figure 3 illustrates the fuzzy number (l, m, r), where the triangular-shaped function describes the certainty degree of numbers in the interval [l, r].

The fuzzy regression function of the recycling rate on the subsidy rate is defined as:

$$\hat{\alpha} = \hat{a} + \hat{b} c_a \,, \tag{1}$$

where $\hat{\alpha}$ is the fuzzy recycling rate, $\hat{a}$ is a fuzzy intercept, and $\hat{b}$ is a fuzzy coefficient. The solutions of $\hat{a}$ and $\hat{b}$ can be obtained by employing the concept of Cheng (2005), which is mainly based the approaches of Tanaka (1987) and Lee and Tanaka (1999). The idea is to find the minimum fuzziness of the regression model that can comprise the fuzziness of all aggregated ratings under a β-level set concept. The β-level set of a fuzzy set A is defined as $[A]_\beta=\{x|\mu_A(x) \geq \beta\}$.

Let $\hat{f}_i = (l_i, m_i, r_i)$, i=1,…,9, denote the fuzzy aggregated ratings at the nine subsidy levels (denoted by c_a^i, i=1,…,9) in Table 1, and define $\hat{a} = (a^L, a^M, a^R)$ and $\hat{b} = (b^L, b^M, b^R)$. The fuzzy regression parameters of Eq. (2) can be identified by the optimization problem below:

$$\text{Minimize } \sum_{i=1}^{9}(a^R - a^L) + (b^R - b^L)c_a^i \qquad (3)$$

Subject to:

$$(a^L + c_a^i b^L) + \beta((a^M + c_a^i b^M) - (a^L + c_a^i b^L)) \leq l_i + \beta(m_i - l_i),\ i=1,\ldots,9 \qquad (4)$$

$$(a^R + c_a^i b^R) + \beta((a^M + c_a^i b^M) - (a^R + c_a^i b^R)) \leq r_i + \beta(m_i - r_i),\ i=1,\ldots,9 \qquad (5)$$

The objective function (3) is to minimize the fuzziness of the regression model, which is defined as the distance between the right and the left endpoints. Constraints (4) and (5) together ensure that the fuzziness of data is within the fuzziness of the model.

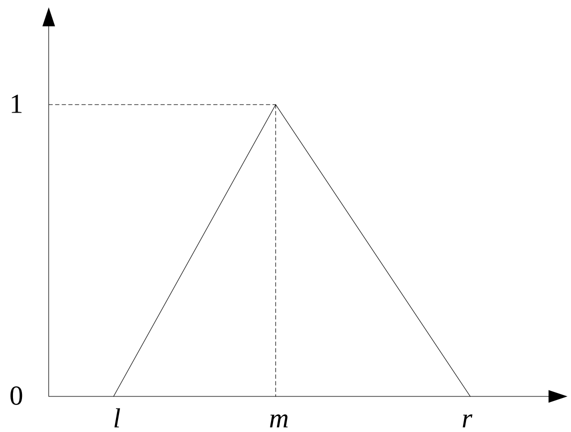


Figure 2. Graphic presentation of the fuzzy number

2.2. Multi-Objective Optimization Model

The main goal of the RFMB is to maximize the recycling rate of waste PCs, and the tool of this agent is the subsidy given to recyclers to enhance their motivations. As discussed earlier, the solely resource of RFMB is the recycling fees charged from manufacturers. However, manufacturers would transfer the recycling fee to their customers and hence raise the product price, which reduces the social welfare. Thus, in our subsidy rate decision model we consider two goals for the RFMB. The notations used in the model are described as follows.

Decision variables:

c_a Subsidy rate to recycling industry for waste recycling and treatment (NT$/PC).

c_f recycling fee charged to manufacturers (NT$/PC).

γ The ratio of administration expense over the fund of RFMB (%).

Parameters:

ω Estimated amount of waste PCs in the coming year.

S Sales of PCs reported by manufacturers.

B Balance of the fund; it could be a deficit or surplus.

v Unit resource recycling value of waste PCs (NT$/PC).

c_E Unit cost of environmental affection (NT$/PC).

F Fixed recycling cost (NT$).

c_V Variable recycling cost (NT$/PC).

A Auditing cost of RFMB allocated to PC recycling per year (NT$/yr).

f^U The upper limit of recycling fee.

γ^L, γ^U The lower and the upper limits of γ.

The optimization mode is then formulated as follows.

$$\text{Maximize } z_1=\alpha \tag{6}$$

$$\text{Minimize } z_2=c_f \tag{7}$$

Subject to:

$$c_f S + B \geq c_a \alpha\omega + \gamma c_f S \tag{8}$$

$$c_a \alpha\omega + v\alpha\omega \geq F + c_V \alpha\omega \tag{9}$$

$$\gamma c_f S \geq A + c_E (1-\alpha)\omega \tag{10}$$

$$\gamma^L \leq \gamma \leq \gamma^U \tag{11}$$

$$c_f \leq f^U \tag{12}$$

$$0 \leq \alpha \leq 1 \tag{13}$$

Eq. (2), c_a, $c_f \geq 0$

The objective (6) is to maximize the recycling rate of waste PCs, while objective (7) is to minimize the recycling fee rate charged to manufacturers. These two objectives are apparently conflict, since the enhancement of the recycling rate would require an increment on the subsidy given to recyclers, however, the increment of subsidy implies the raise of recycling fees. Constraint (8) is to ensure that the net income of RFMB has to cover its expenses, including the subsidy given to recyclers and the administrative expense to support its operations. Constraint (9) confirms that the recycler is able to break-even at least to stay in the business, where the income of a recycler includes the subsidy it receives and the revenue of selling the recycled material in the market, while its costs are the fixed and the variable costs of the recycling operations. The administration expense of the RFMB is spent on the audit process and the disposal of the waste PCs which do not enter the recycling system as described by constraint (10). A reasonable range of the administration expense is also imposed by constraint (11). The purpose of constraint (12) is to avoid an unexpectedly high recycling fee, where the upper limit f^U is set as the highest record in the history. Constraint (13) is the feasible range of the recycling rate. The equation (2) discussed earlier is contained in the model to describe the possible recycling rate resulting from a certain subsidy. With a given a ρ-level set, Eq. (2) can be rewritten as:

$$\rho(a^M + b^M c_a) + (1-\rho)(a^L + b^L c_a) \le \alpha \le \rho(a^M + b^M c_a) + (1-\rho)(a^R + b^R c_a) \quad (14)$$

Recycling fee is charged to manufacturers on the basis of their future sales, *S*, which is predicted by a moving average method. The amount of waste PCs in the coming year is estimated based on the probability distribution of the life of a PC. This study assumes that the maximum life of a PC is six years, and adopts the Kaplan-Meier method to estimate the survival probabilities of a PC over the past six years. The resource recycling value is obtained by computing the market values of recycled components and materials of the PC.

Table 1. Top 10 researchers with the greatest closeness scores

Parameter	Value	Description
B	NT$22,216,583	Fund balance at the end of 2012, reported by RFMB
f^U	NT$352	The highest recycling fee rate in history
S	2,152,960	Predicted sales of PCs in 2013
ω	2,055,880	Estimated amount of waste PCs in 2013
v	NT$188.75	Unit recycling value, estimated by this study
F	NT$11,133,806	Fixed cost per year, estimated by this study
c_V	NT$140.7	Unit variable cost (Wen 2008)
c_E	NT$23.43	Unit environmental cost (Wen 2008)
A	NT$6,267,011	Auditing cost, reported by RFMB
$[\gamma^L, \gamma^U]$	[0.036, 0.090]	Suggested by this study

The unit environmental affection cost c_E was computed by Wen (2008) based on the budget subsidized to local governments for garbage reduction, waste disposal, and resource recycling. The feasible interval of the ratio of the administrative expense over the income of RFMB (i.e. the recycling fee) is to maintain it within a reasonable range. Currently, this ratio is around 9%, and manufacturers generally consider it is too high (Wen 2008). By referring to the similar institutes in European countries, such expense is around 3.6% of their recycling cost. Thus, [3.6%, 9%] is considered as a suitable interval of γ in this study. The estimates of the parameters used in the model are summarized in Table 1.

3. Solution Procedure

The optimization model presented in the previous section contains two objectives and a fuzzy constraint, and thus results in a fuzzy multi-objective optimization problem. Traditional fuzzy optimization algorithms have been used to solve the fuzzy multi-objective optimization problems. This study considers the available information is not sufficient to define the imprecise concepts used in our model by means of conventional fuzzy sets, and hence adopts the intuitionistic fuzzy set (IFS) as an alternative to model the imprecise decision.

In a conventional fuzzy set, the degree of belief through a membership function is used to define the imprecise concept. Extending the concept of fuzzy sets, IFS is characterized by both a membership function and a non-membership function to express the decision maker's uncertainty. IFS was first introduced by Atanassov (2000) and has been found to be well suited for dealing with problems concerning vagueness. Mahapatra et al. (2010) proposed an IFS multi-objective optimization algorithm for solving an LCD display unit reliability problem. This study adopts the solution procedure of Mahapatra et al. (2010) to solve the recycling fee and subsidy rate decision problem presented in the previous section.

The steps of the solution procedure are described as follows.

Step 1: Ideal solutions of individual objectives

Consider one objective at a time, ignoring others, and solve the original multi-objective problem as a single-objective problem. This step results in a set of ideal solutions corresponding to the set of objectives. Assume there are *K* objective and let $\mathbf{x}_i$ denote the ideal solution of the *i*-th objective.

Step 2: Construct the pay-off matrix

The objective values of the multi-objective problem with respect to each ideal solution is presented in the following pay-off matrix:

$$P = \begin{bmatrix} z_1^*(\mathbf{x}_1) & z_2(\mathbf{x}_1) & \dots & z_K(\mathbf{x}_1) \\ z_1(\mathbf{x}_2) & z_2^*(\mathbf{x}_2) & \dots & z_K(\mathbf{x}_2) \\ \vdots & & \ddots & \vdots \\ z_1(\mathbf{x}_K) & z_2(\mathbf{x}_K) & \dots & z_K^*(\mathbf{x}_K) \end{bmatrix}, \tag{15}$$

where $z_i^*(\mathbf{x}_i)$ is the ideal objective value of the *i*-th objective.

Step 3: Construct membership and non-membership functions

The degree of acceptance of an individual objective can be established based on the pay-off matrix (14). For the case of maximization, it is readily to set the level of the absolutely accepted objective value of the *i*-th objective as $U_i^{acc} = z_i^*(\mathbf{x}_i)$, and the least accepted value as $L_i^{acc} = \min_{\forall k, k \neq i}\{z_i(\mathbf{x}_k)\}$. The range of the degree of rejection uses the acceptable range as the reference. Let L_i^{rej} and U_i^{rej} denote the absolutely rejected and not-rejected points of the *i*-th objective, it is assumed $L_i^{acc} \leq L_i^{rej} \leq U_i^{rej} \leq U_i^{acc}$. The membership and the non-membership functions, $\mu_i(z_i(\mathbf{x}))$ and $\nu_i(z_i(\mathbf{x}))$, correspond to the degrees of acceptance and rejection of an objective are depicted in Figure 3.

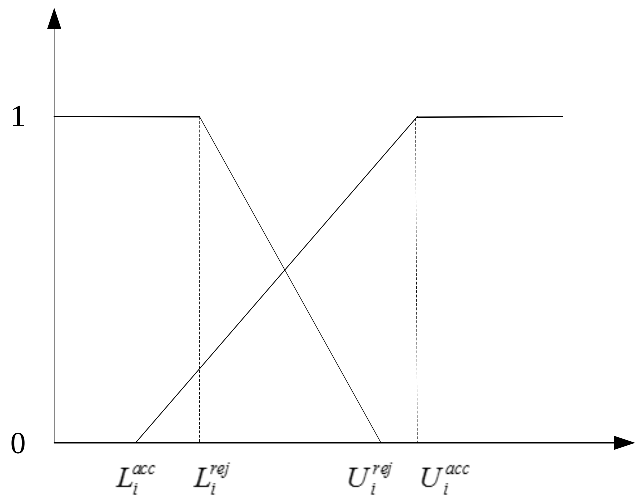


Figure 3. Membership and non-membership functions of an objective

Step 4: Re-formulation of the multi-objective problem

The original multi-objective problem becomes to maximize the overall membership values of all objectives and to minimize the overall non-membership values of all objectives. Assume the additive operator is used by the decision maker, the multi-objective problem is reformulated as:

$$\text{Maximize } \sum_{i=1}^{K} \mu_i(z_i(\mathbf{x}) - \nu_i(z_i(\mathbf{x})) \qquad (16)$$

Subject to:

$$\mu_i(z_i(\mathbf{x})) \geq \nu_i(z_i(\mathbf{x})),\ \forall i \qquad (17)$$

$$\mu_i(z_i(\mathbf{x})) + \nu_i(z_i(\mathbf{x})) < 1,\ \forall i \qquad (18)$$

$$\nu_i(z_i(\mathbf{x})) \geq 0,\ \forall i \qquad (19)$$

$$\mathbf{x} \in G \qquad (20)$$

The acceptance degree must be greater than the rejection degree to have a reasonable solution as expressed by constraint (17). Constraint (18) impose the sum of the membership and the non-membership to be less than the unity as defined by Atanassov (1995), otherwise the use of non-membership becomes redundant when they compensate to each other. (19) is the non-negative constraint, and G in constraint (20) is the feasible space constructed by the constraints in the original multi-objective problem. The above intuitionistic fuzzy optimization problem can be solved by available solvers.

4. Computational Result

The recycling fee and subsidy rate decision problem is solved by following the solution procedure described in the previous section.

Step 1: Optimize one objective at a time for the multi-objective problem, and obtain optimum solutions $\mathbf{x}_1$ and $\mathbf{x}_2$ of the two single objective problems as $\mathbf{x}_1 = (c_{f1}, c_{r1}, \gamma_1) = (286.366, 286.7999, 0.08)$ for the first objective, and $\mathbf{x}_2 = (c_{f2}, c_{r2}, \gamma_2) = (61.99168, 108.9355, 0.2)$ for the second objective.

Step 2: The pay-off matrix is then constructed accordingly as $\begin{bmatrix} 1 & 286.7999 \\ 0.5759 & 61.9916 \end{bmatrix}$.

Step 3: The membership function of each objective is constructed based on the pay-off matrix. It is readily obtained that $L_1^{acc} = 0.5759$, $U_1^{acc} = 1$, $L_2^{acc} = 286.7999$, and $U_2^{acc} = 61.9916$. The non-membership function of each objective is determined based on the expectation of the improvement of the decision in the previous year. For simplicity, we set $L_1^{rej} = L_1^{acc}$ and $L_2^{rej} = L_2^{acc}$. The goal of RFMB is to promote the recycling rate to 70%, thus we set $U_1^{rej} = 0.7$. The recycling fee in the previous year is NT$114.8. With an expectation of reducing this fee, we set $U_2^{rej} = 114.8$.

Step 4: With different levels of ρ, we solve the intuitionistic fuzzy optimization problem and obtain the solution in Table 2, where the comparison to the current operations by RFMB is also provided. The ρ-level defines the belief degree (i.e. 1-ρ) of the range of the recycling rate under a certain subsidy rate. It can also be interpreted as the possibility degree (i.e. ρ) of the resulting solution.

Table 2. Solutions with different ρ-level

	Recycling fee (c_f)	Subsidy rate (c_a)	Administration (γ)	Recycling rate (α)
Current	114.80	182.00	0.200	56.7%
ρ=0.1	120.83	181.81	0.080	70.0%
ρ=0.2	136.03	204.54	0.071	70.0%
ρ=0.3	152.67	229.44	0.063	70.0%
ρ=0.4	170.98	256.83	0.056	70.0%
ρ=0.5	189.35	285.47	0.051	69.7%
ρ=0.6	189.35	299.38	0.055	66.2%
ρ=0.7	189.35	314.88	0.059	62.7%
ρ=0.8	189.35	332.26	0.064	59.1%
ρ=0.9	189.35	351.90	0.068	55.6%

The current recycling fee is NT$114.8, subsidy rate is NT$182, and the administration expense ratio is 0.2, which result in a recycling rate of 56.7%. Our approach generally suggests the raise of recycling fee and subsidy rate to improve the recycling rate. At the same time, the solutions indicate that the administration expense can be greatly reduced without harming the operations of RFMB. It is noted that the subsidy rate increases but recycling rate decreases when the levels of ρ is increased.

When the value of ρ increases, the fuzziness of the recycling rate regression function is reduced which also narrows the possible range of the recycling rate, and thus the subsidy rate is magnified to maximize the recycling rate.

5. Concluding Remarks

This study models the recycling fee and subsidy rate decision for waste PC recycling operations by fuzzy multi-objective programming, and solves the problem by an intuitionistic fuzzy optimization solution procedure. With practical data, the proposed approach generally suggests the raise of recycling fee and subsidy rate to improve the recycling rate.

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