JCC: The Business and Economics Research Journal • Volume 5, Issue 2, 2012 • 207-223

JCC
Journal of
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Evaluating Recycling Sustainability Performance of E-waste Products

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Abstract

This paper develops a new performance evaluation approach for evaluating the relative recycling sustainability performance of e-waste products in terms of their contribution to the corporate sustainability of an e-recycling company. A fuzzy pairwise comparison process is used to help make comparative assessments. A fuzzy technique for order preference by similarity to ideal solution (TOPSIS) is used to give an overall sustainability performance score to each e-waste product, relative to others. A new optimal weighting model is developed to determine the optimal weights for the environmental, economic, and social sustainability dimensions that reflect the best sustainability interests of the e-recycling company. An empirical study is conducted to illustrate the approach.

Keywords: Performance evaluation, sustainability, e-waste recycling, fuzzy pairwise comparison, fuzzy multicriteria decision making (MCDM), optimization, TOPSIS

JEL Classification codes: C61, D81, Q53, Q56

E-recycling is the recycling of end-of-life electrical and electronic products, such as household appliances, information and communication technology equipment, and consumer electronics, including their assembly, components, and consumables. These end-of-life products are often referred to as e-waste. E-waste contains more than 1000 different hazardous and non hazardous substances, such as ferrous and nonferrous metals, plastics, glass, wood, printed circuit boards, concrete and ceramics, rubber, and other materials (Pinto, 2008).

Many of the e-waste products can be reused, refurbished, or recycled to obtain economic value from considerable quantities of the valuable materials and precious metals they contain. However, toxic chemicals such as lead, mercury, arsenic, cadmium, selenium, hexavalent chromium, and flame retardants will cause an adverse impact on the environment and on human health if the disposal of the e-waste is not handled properly. To ensure the e-waste products are recycled in an economically viable and socially responsible manner with minimal environmental impacts, e-recycling companies need to evaluate and manage the recycling performance of their e-waste products in order to maximize the corporate sustainability performance.

As defined by Elkington (1998), corporate sustainability is achieved by delivering environmental, economic, and social benefits simultaneously, as these are the three dimensions of sustainable development. To assess the environmental, economic, and social performance, a set of sustainability criteria needs to be properly identified.

The identification of the sustainability criteria for the e-waste recycling industry has been well addressed in sustainability research (e.g., Atlee & Kirchain, 2006; Rahman & Subramanian, 2011; Widmer, Oswald-Krapf, Sinha-Khetriwal, Schnellmann, & Böni, 2005; Williams et al., 2008). When identifying the appropriate sustainability criteria, e-recycling companies should be aware of the corporate sustainability interests and concerns prevalent in their current business context.

The corporate sustainability performance of e-recycling companies is affected by the diversity of e-waste product types due to their differences in the collection, processing, and disposal processes. Thus, it is important for the e-recycling companies to evaluate the relative sustainability performance of their e-waste products with respect to the identified sustainability criteria under the three sustainability dimensions. For a given e-recycling company, the relative sustainability performance of an e-waste product represents the degree to which it contributes to the corporate sustainability performance of the e-recycling company, relative to other e-waste products processed by the e-recycling company. In this paper, we develop a new approach for addressing this sustainability performance evaluation problem, using fuzzy MCDM and optimization-based models.

The sustainability performance evaluation problem to be addressed is a typical MCDM problem, rather than a data envelopment analysis (DEA) problem. MCDM is a technique for evaluating a finite set of decision alternatives with respect to a set of multiple, usually conflicting criteria (Hwang & Yoon, 1981), whereas DEA is a technique for measuring the relative efficiency of a finite set of decision-making units with multiple inputs and multiple outputs (Kao & Liu, 2011; Zhu, 2011). MCDM has been widely used to address practical performance evaluation problems (e.g., Belton & Stewart, 2002; Chiou, Tzeng, & Cheng, 2005; Geldermann et al., 2009; Kirkwood, 1997; Kuo & Liang, 2012; Xu & Yeh, 2012; Yeh, Deng, & Chang, 2000). The common characteristics of MCDM problems include: (a) the measurement of performance ratings of the alternatives for each criterion, (b) the criteria weights for representing the relative importance of each criterion, (c) the aggregation of performance ratings of the alternatives with the criteria weights, and (d) the resultant performance ranking of the alternatives (Chang, Yeh, & Liu, 2006; Hwang & Yoon, 1981).

Decision makers involved in an MCDM problem may need to make comparative assessments regarding the performance ratings of the alternatives and the criteria weights for representing their relative importance (Saaty, 1980). As there are limitations to the amount of information that human beings can effectively handle, a pairwise comparison process is commonly used to facilitate comparative assessments (Yeh & Chang, 2009). The concept of pairwise comparison has been known since the work of Thurstone (1927) and has been implemented in the analytic hierarchy process (AHP) of Saaty (1980). As the decision makers usually find that it is more comfortable to give interval judgments rather than fixed value judgments, fuzzy set theory is widely used in pairwise comparison to deal with the imprecision and uncertainty of human decisions (Chen & Hwang, 1992; Kaya, 2012).

To reflect the decision makers' imprecise assessments about the sustainability performance of e-waste products, we use the fuzzy pairwise comparison technique to carry out the process of assessing the relative performance ratings of e-waste products on sustainability criteria and the relative weights of sustainability criteria. In particular, we allow the decision makers to specify their confidence level about the fuzzy assessment and use the corresponding fuzzy number accordingly. To give each e-waste product processed by an e-recycling company an overall sustainability performance score relative to other e-waste products, we apply a widely used MCDM method called TOPSIS. With the fuzzy assessment data, we use a fuzzy TOPSIS evaluation model with optimal weights obtained from an optimization model.

The concept of TOPSIS is that the most preferred alternative should have not only the shortest distance from the positive ideal solution, but also the longest distance from the negative ideal solution (Hwang & Yoon, 1981). In our approach, we apply the concept of TOPSIS together with fuzzy set theory for evaluating the e-waste products of an e-recycling company in terms of their overall sustainability performance. The reasons for this choice are that: (a) the concept is rational and comprehensible, (b) the computation involved is simple, (c) the concept is capable of depicting the pursuit of the best performance of an e-waste product for each sustainability criterion in a simple mathematical form, and (d) the concept allows the criteria weights to be incorporated into the comparison process (Deng, Yeh, & Willis, 2000).

In evaluating the overall sustainability performance of e-waste products for an e-recycling company, we develop a new optimal weighting model to determine the optimal weights for the environmental, economic, and social dimensions of the company's corporate sustainability. The optimal weighting model objectively assigns weights to the three sustainability dimensions to reflect the best sustainability interests of the e-recycling company, in consideration of the decision maker's subjective assessments of the sustainability dimension weights based on the current practice and concerns of the e-recycling company. In particular, we use the concept of α-cut on the decision maker's fuzzy assessments of the relative importance of the environmental, economic, and social dimensions to determine their subjective weight ranges, which are used as the dimension weight constraints for the optimal weighting model.

In subsequent sections, we first describe the sustainability performance evaluation approach, including the fuzzy pairwise comparison assessments, the fuzzy TOPSIS evaluation model, and the optimal weighting model. We then conduct an empirical study to demonstrate the effectiveness of the approach and discuss the practical implications of the study outcomes.

The Sustainability Performance Evaluation Approach

Fuzzy Pairwise Comparison Assessments

For pairwise comparison assessments, the AHP technique suggests the use of a 1-9 ratio scale to compare two alternatives (e.g., sustainability criteria or e-waste products) to indicate the strength of their relative importance or performance (Saaty, 1980). In this study, we use the 1-9 ratio scale in pairwise comparison as it has proved to be an effective measurement scale to reflect the qualitative information of a decision problem and to enable the approximation of the unknown weights (Yeh & Chang, 2009).

To reflect the subjectivity and vagueness involved in the comparative assessment, the ratio value given by the decision maker is represented by a corresponding triangular fuzzy number $\tilde{a} = (a_1, a_2, a_3)$. A triangular fuzzy number is a convex fuzzy set (Zadeh, 1965) with its membership function defined as:

$$\mu_A(x) = \begin{cases} (x - a_1)/(a_2 - a_1), & a_1 \le x \le a_3 \\ (a_3 - x)/(a_3 - a_2), & a_2 \le x \le a_3 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where a_2 is the highest possible value, and a_1 and a_3 are the lower and upper bounds respectively used to reflect the fuzziness of the assessment.

In this study, we use triangular fuzzy numbers to represent the approximate value range of the linguistic terms used in pairwise comparisons. Figures 1 and 2 show the membership functions of the five linguistic terms used in pairwise comparisons to assess the relative importance of the sustainability criteria and the sustainability dimensions and the relative performance of e-waste products with respect to each sustainability criterion respectively.

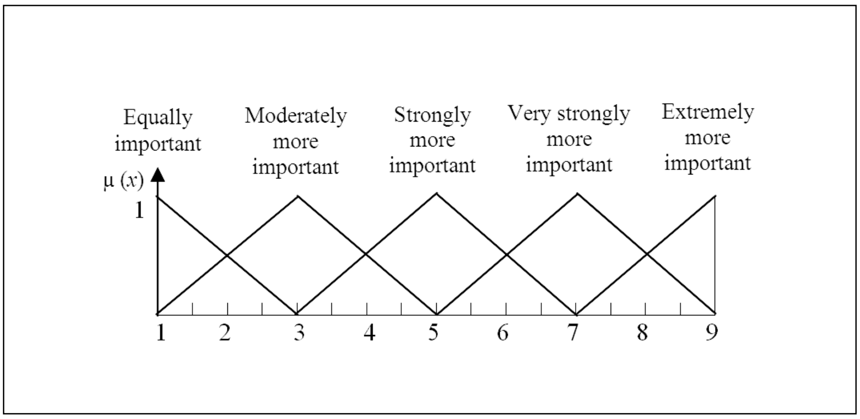

Figure 1. Membership functions of linguistic terms for assessing the relative importance of sustainability criteria and sustainability dimensions.

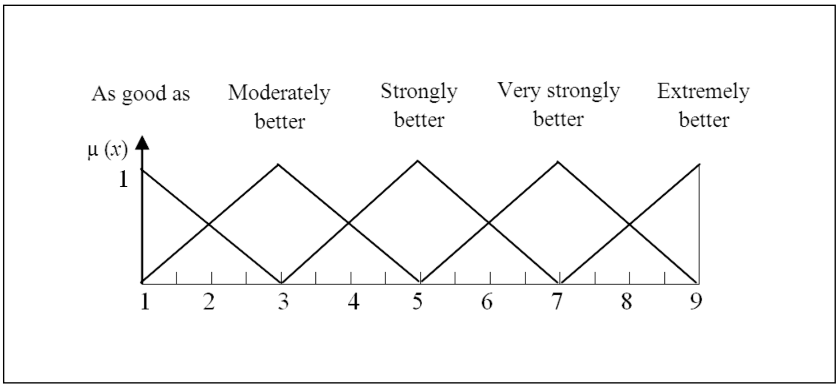

Figure 2. Membership functions of linguistic terms for assessing the relative performance of e-waste products.

With reference to the two sets of five linguistic terms given in Figures 1 and 2 respectively, the decision maker can specify the most proper linguistic term or specify only the highest possible value for the fuzzy assessment. Tables 1 and 2 illustrate how a triangular fuzzy number is generated to represent the fuzzy assessment of relative importance and the relative performance respectively from a linguistic term or a numeric ratio value assessed by the decision maker. For instance, if the linguistic term "Strongly more important" or a ratio value 5 is specified, the fuzzy assessment represented as a triangular fuzzy number is (3, 5, 7), whose membership function is defined as in Equation 1 and shown in Figure 1. This implies that the assessment is "about 5" to reflect the vagueness of the subjective assessment. To reflect the decision maker's knowledge and experience in the fuzzy assessment process, the triangular fuzzy numbers given in Figures 1 and 2 can be adjusted. For example, if the decision maker's knowledge or experience is excellent, good, or fair, the corresponding fuzzy assessment can be (4, 5, 6), (3, 5, 7), or (2, 5, 8), respectively (Chang, Yeh, & Wang, 2007).

Table 1
Value Fuzzification for Importance Pairwise Comparisons of Sustainability Criteria

Equally important	Moderately more important		Strongly more important		Very strongly more important		Extremely more important	
1	2	3	4	5	6	7	8	9
		a_1		a_2		a_3		

Table 2
Value Fuzzification for Performance Pairwise Comparisons of E-waste Products

As good as	Moderately better		Strongly better		Very strongly better		Extremely better	
1	2	3	4	5	6	7	8	9
		a_1		a_2		a_3		

In this paper, the fuzzy pairwise comparison process is conducted by the decision maker of an e-recycling company to assess: (a) the relative importance of each sustainability dimension with respect to the corporate sustainability performance of the e-recycling company, (b) the relative importance of each sustainability criterion under each sustainability dimension, and (c) the relative performance of each e-waste product with respect to each sustainability criterion.

Applying the fuzzy pairwise comparison process to all n alternatives (e.g., the sustainability criteria or e-waste products) produces a positive $n \times n$ fuzzy reciprocal matrix with all its elements $\tilde{a}_{ij} = 1/\tilde{a}_{ij}$, $(i = 1, 2, ..., n;\ j = 1, 2, ..., n)$. In solving the fuzzy positive reciprocal matrix, the geometric mean method is used to calculate the fuzzy weights for all the alternatives (Buckley, 1985). Given a fuzzy positive reciprocal matrix $R = \left[\tilde{a}_{ij}\right]$, the method first calculates the geometric mean of each row as:

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{a}_{ij} \right)^{1/n} \quad (2)$$

The fuzzy relative weights (importance or performance) $\tilde{w}_i$ for n alternatives are then computed as:

$$\tilde{w}_i = r_i / \sum_{j=1}^{n} r_j \quad (3)$$

The fuzzy pairwise comparisons with fuzzy ratios and Equations 2 and 3 are used by the e-recycling company to obtain: (a) the relative importance $\tilde{w}_p^D$ of the sustainability dimension D_p, (b) the relative importance $\tilde{w}_{pq}^C$ of sustainability criteria C_{pq} $(p = 1,2,3;\ q = 1,2,...,Q_p)$ under each sustainability dimension D_p, and (c) the relative performance $\tilde{w}_{pqk}^E (k = 1,2,..., K)$ of each e-waste product E_k with respect to each sustainability criterion C_{pq}. The arithmetic operations on fuzzy numbers are based on fuzzy arithmetic (Kaufmann & Gupta, 1991).

The Fuzzy TOPSIS Evaluation Model

With the relative importance $\tilde{w}_{pq}^C$ of sustainability criteria C_{pq} and the relative performance $\tilde{w}_{pqk}^E$ of each e-waste product E_k with respect to each sustainability criterion C_{pq}, p weighted fuzzy performance matrices $V_p = \left[\tilde{v}_{pqk} \right]$ can be constructed under each sustainability dimension, where

$$\tilde{v}_{pqk} = \tilde{w}_{pq}^C \, \tilde{w}_{pqk}^E, k = 1,2,..., K \quad (4)$$

In order to compare the weighted fuzzy performance value $\tilde{v}_{pqk}$ of e-waste products, the concept of α-cut is applied to defuzzify the corresponding triangular fuzzy number to a crisp value (i.e., a numerical value). By using α-cut on the fuzzy numbers $\tilde{v}_{pqk}$ in the weighted fuzzy performance matrices V_p, the interval performance matrices V_p^α are derived as given in Equation 5, where $0 \le \alpha \le 1$.

$$V_p^\alpha = \begin{bmatrix} \left[v_{p11l}^\alpha, v_{p11u}^\alpha \right] & \cdots & \left[v_{pQ_p1l}^\alpha, v_{pQ_p1u}^\alpha \right] \\ \vdots & & \vdots \\ \left[v_{p1kl}^\alpha, v_{p1ku}^\alpha \right] & \cdots & \left[v_{pQ_pkl}^\alpha, v_{pQ_pku}^\alpha \right] \end{bmatrix}, p = 1,2,3 \quad (5)$$

$\left[v_{pqkl}^\alpha, v_{pqku}^\alpha \right]$ is a value interval for each e-waste product with respect to each sustainability criterion. For a given α, v_{pqkl}^α and v_{pqku}^α are the average of the lower bounds and upper bounds of the crisp intervals respectively, obtained from all the α-cuts using the alpha values equal to or greater than the specified value of α.

The value of α represents the confidence degree of the decision maker in the fuzzy assessments (Yeh & Kuo, 2003). A larger α value indicates that the decision maker is more confident in choosing a crisp value interval to represent the corresponding fuzzy number, as the interval is smaller and has a higher possibility and lower uncertainty (Kao & Liu, 2003). In this case, a confident decision maker would not consider less possible values embedded in a fuzzy number.

To reflect the decision maker's attitude towards the fuzzy assessment results regarding the e-waste products under evaluation, an attitude index λ is used. As a result, a crisp value can be obtained by:

$$v_{pqk}^\lambda = \lambda v_{pqku}^\alpha + (1-\lambda) v_{pqkl}^\alpha,\ 0 \le \lambda \le 1 \quad (6)$$

In actual decision settings, $\lambda = 1$, 0.5, or 0 can be used to indicate the decision maker's optimistic, moderate, or pessimistic attitude, respectively, regarding fuzzy assessment results (Yeh & Kuo, 2003). A higher value of the crisp value interval would be obtained if the decision maker has a more optimistic attitude.

By applying Equation 6 to each value interval $\left[v^{\alpha}_{pqkl}, v^{\alpha}_{pqku}\right]$ in the interval performance matrices V^{α}_{p}, p crisp performance matrices $V^{\lambda}_{p\alpha} = \left[v^{\lambda}_{pqk}\right]$ are derived for each sustainability dimension D_p, where its element v^{λ}_{pqk} is the weighted performance value of each e-waste product E_k with respect to each sustainability criterion C_{pq}. To represent the best possible and the worst possible sustainability performances of the e-waste products under each sustainability dimension D_p, the positive ideal solution $A^{\lambda+}_{p}$ and the negative ideal solution $A^{\lambda-}_{p}$ are determined by:

$$A^{\lambda+}_{p} = (v^{+}_{p1k}, v^{+}_{p2k}, ..., v^{+}_{pqk}),\ A^{\lambda-}_{p} = (v^{-}_{p1k}, v^{-}_{p2k}, ..., v^{-}_{pqk}) \tag{7}$$

$$\text{where } v^{+}_{pqk} = \max\left\{v_{pq1}, v_{pq2}, ..., v_{pqK}\right\},\ v^{-}_{pqk} = \min\left\{v_{pq1}, v_{pq2}, ..., v_{pqK}\right\} \tag{8}$$

Based on the concept of TOPSIS, the distance between the alternatives can be measured by the Euclidean distance. The distances of each e-waste product from the positive ideal solution $A^{\lambda+}_{p}$ and from the negative ideal solution $A^{\lambda-}_{p}$ under each sustainability dimension D_p are then given respectively by:

$$s^{+}_{pk} = \sqrt{\sum_{q=1}^{Q_p} (v_{pqk} - v^{+}_{pqk})^2},\ s^{-}_{pk} = \sqrt{\sum_{q=1}^{Q_p} (v_{pqk} - v^{-}_{pqk})^2},\ p = 1, 2, 3 \tag{9}$$

A total sustainability performance score t_{pk} of each e-waste product under each sustainability dimension can then be obtained by:

$$t_{pk} = s^{-}_{pk} / (s^{+}_{pk} + s^{-}_{pk}) \tag{10}$$

The e-waste products E_k can then be ranked in terms of their total sustainability performance score t_{pk} under each sustainability dimension.

The Optimal Weighting Model

The optimal weighting model generates a set of optimal weights w^{o}_{p} for the three sustainability dimensions D_p by maximizing the overall corporate sustainability performance value contributed by the sustainability performance of all e-waste products of an e-recycling company. With the weighted performance value v^{λ}_{pqk} of each e-waste product E_k under each sustainability dimension D_p, the total performance value $V_p{}'$ of all the products under each sustainability dimension can be obtained by:

$$V_p{}' = \sum_{q=1}^{Q_p} \sum_{k=1}^{K} v^{\lambda}_{pqk} \tag{11}$$

The optimal weights w^{o}_{p} for each sustainability dimension D_p are then obtained by the following optimization model:

$$\text{Objective: } Max \sum_{p=1}^{3} w^{o}_{p} V_p{}' \tag{12}$$

$$\text{Subject to: } \sum_{p=1}^{3} w^{o}_{p} = 1 \tag{13}$$

$$w^{\alpha}_{pl} \le w^{o}_{p} \le w^{\alpha}_{pu},\ p = 1, 2, 3 \tag{14}$$

where, decision variable:

w_p^o = the optimal weights of sustainability dimension D_p;

parameters:

V_p' = the total performance value of all the products under each sustainability dimension D_p given by Equation 11;

w_{pl}^α = the lower bounds of the optimal weights for each sustainability dimension D_p;

w_{pu}^α = the upper bounds of the optimal weights for each sustainability dimension D_p.

The objective function (12) is to maximize the overall corporate sustainability performance value, which is represented by multiplying the optimal weights of the three sustainability dimensions by the total performance value of all the e-waste products under each sustainability dimension. Constraint (13) states that the optimal weights obtained for each sustainability dimension are to be normalized to sum to 1. Constraints (14) impose that the optimal weights generated must lie within the importance (weight) ranges assessed by the decision maker. Given the relative importance $\tilde{w}_p^D$ of the sustainability dimension D_p obtained from the fuzzy pairwise comparisons process and by Equations 2 and 3, a normalization procedure is applied as:

$$\tilde{w}_p' = \tilde{w}_p^D / \sum_{p=1}^{3} \tilde{w}_p^D \tag{15}$$

By using the concept of α-cut on the normalized fuzzy numbers, an interval importance matrix $W^D = \left[w_{pl}^\alpha, w_{pu}^\alpha \right]$ is derived, where $0 \le \alpha \le 1$. For a given α, w_{pl}^α and w_{pu}^α are the average of the lower bounds and upper bounds of the crisp intervals respectively, which reflect the subjective assessments of the decision maker about the weight ranges of the three sustainability dimensions. Solving model (12)-(14) will obtain the optimal weights w_p^o for the three sustainability dimensions D_p.

Evaluating the Overall Sustainability Performance of E-waste Products

The optimal weights w_p^o obtained from the optimal weighting model reflect the best sustainability interests and priorities of the e-recycling company. They can be incorporated in the evaluation of the overall sustainability performance score T_k of e-waste products E_k by applying the fuzzy TOPSIS evaluation model.

Given the weighted fuzzy performance matrices $V_p = \left[\tilde{v}_{pqk} \right]$ and the optimal weights vector $W^o = \left[w_p^o \right]$, p overall fuzzy performance matrices $Z_p = \left[\tilde{z}_{pqk} \right]$ are constructed, where the overall fuzzy performance value $\tilde{z}_{pqk}$ of each e-waste product E_k can be obtained by:

$$\tilde{z}_{pqk} = w_p^o \tilde{v}_{pqk}, \; p = 1,2,3 \tag{16}$$

By using α-cut on the fuzzy numbers $\tilde{z}_{pqk}$ in the overall fuzzy performance matrices Z_p, the interval overall performance matrices Z_p^α are derived, where $0 \le \alpha \le 1$. $\left[z_{pqkl}^\alpha, z_{pqku}^\alpha \right]$ is a value interval for each product with respect to each sustainability criterion. For a given α value, z_{pqkl}^α and z_{pqku}^α are the average of the lower bounds and upper bounds of the crisp intervals respectively. By using an attitude index λ to each value interval $\left[z_{pqkl}^\alpha, z_{pqku}^\alpha \right]$ in the interval overall performance matrices Z_p^α, p crisp performance matrices $Z_{p\alpha}^\lambda = \left[z_{pqk}^\lambda \right]$ are derived under each sustainability dimension D_p. The element z_{pqk}^λ is the overall performance value of each e-waste product E_k with respect to each sustainability criterion C_{pq} under each sustainability dimension.

To represent the best possible and the worst possible overall sustainability performances of the e-waste products for all three sustainability dimensions, the positive ideal solution $A^{\lambda+}$ and the negative ideal solution $A^{\lambda-}$ are determined respectively by:

$$A^{\lambda+} = (z_{11k}^{+}, z_{12k}^{+}, \ldots, z_{1Q_1k}^{+}, \ldots, z_{p1k}^{+}, z_{p2k}^{+}, \ldots, z_{pQ_pk}^{+})$$

$$A^{\lambda-} = (z_{11k}^{-}, z_{12k}^{-}, \ldots, z_{1Q_1k}^{-}, \ldots, z_{p1k}^{-}, z_{p2k}^{-}, \ldots, z_{pQ_pk}^{-}) \tag{17}$$

where $z_{pqk}^{+} = Max\left\{z_{pq1}, z_{pq2}, \ldots, z_{pqK}\right\}$, $v_{pqk}^{-} = Min\left\{z_{pq1}, z_{pq2}, \ldots, z_{pqK}\right\}$ (18)

The distances of each e-waste product from the positive ideal solution $A^{\lambda+}$ and from the negative ideal solution $A^{\lambda-}$ are given respectively by:

$$s_k^{+} = \sqrt{\sum_{p=1}^{3}\sum_{q=1}^{Q_p}(z_{pqk} - z_{pqk}^{+})^2}, \; \text{s}_k^{-} = \sqrt{\sum_{p=1}^{3}\sum_{q=1}^{Q_p}(z_{pqk} - z_{pqk}^{-})^2} \tag{19}$$

An overall sustainability performance score T_k of each e-waste product can be obtained by:

$$T_k = s_k^{-} / (s_k^{+} + s_k^{-}) \tag{20}$$

The e-waste products E_k can then be ranked in terms of their overall sustainability performance score T_k.

The solution procedure for evaluating the relative sustainability performance of e-waste products presented above is summarized below and illustrated in Figure 3.

Step 1: Conduct fuzzy pairwise comparison assessments for a set of sustainability criteria C_{pq} $(p = 1, 2, 3;$ $q = 1, 2, \ldots, Q_p)$, three sustainability dimensions D_p, and K e-waste products E_k $(k = 1, 2, \ldots, K)$.

Step 2: Solve the fuzzy positive reciprocal matrices derived from Step 1 by Equations 2 and 3 to obtain the relative importance $\tilde{w}_{pq}^{C}$ of the sustainability criteria, the relative importance $\tilde{w}_{p}^{D}$ of the three sustainability dimensions, and the relative performance $\tilde{w}_{pqk}^{E}$ of the e-waste products.

Step 3: Calculate the weighted fuzzy performance value $\tilde{v}_{pqk}$ of e-waste products with respect to each sustainability criterion C_{pq} by Equation 4.

Step 4: Specify a value for α-cut and for the attitude index λ on the fuzzy performance value $\tilde{v}_{pqk}$ to obtain the crisp weighted performance value v_{pqk}^{λ} for each e-waste product E_k with respect to each sustainability criterion C_{pq} by Equations 5 and 6.

Step 5: Obtain the total sustainability performance score t_{pk} of each e-waste product under each sustainability dimension by Equations 7 to 10.

Step 6: Set the weight ranges for the three sustainability dimensions according to the subjective assessments of the decision maker by Equation 15 and a value specified for α -cut.

Step 7: Generate a set of optimal weights for the three sustainability dimensions by applying Equation 11 and Model (12)-(14).

Step 8: Obtain an overall sustainability performance score T_k with respect to all three sustainability dimensions for each e-waste product E_k by Equations 16 to 20.

Step 9: Rank the e-waste products in terms of their overall sustainability performance score.

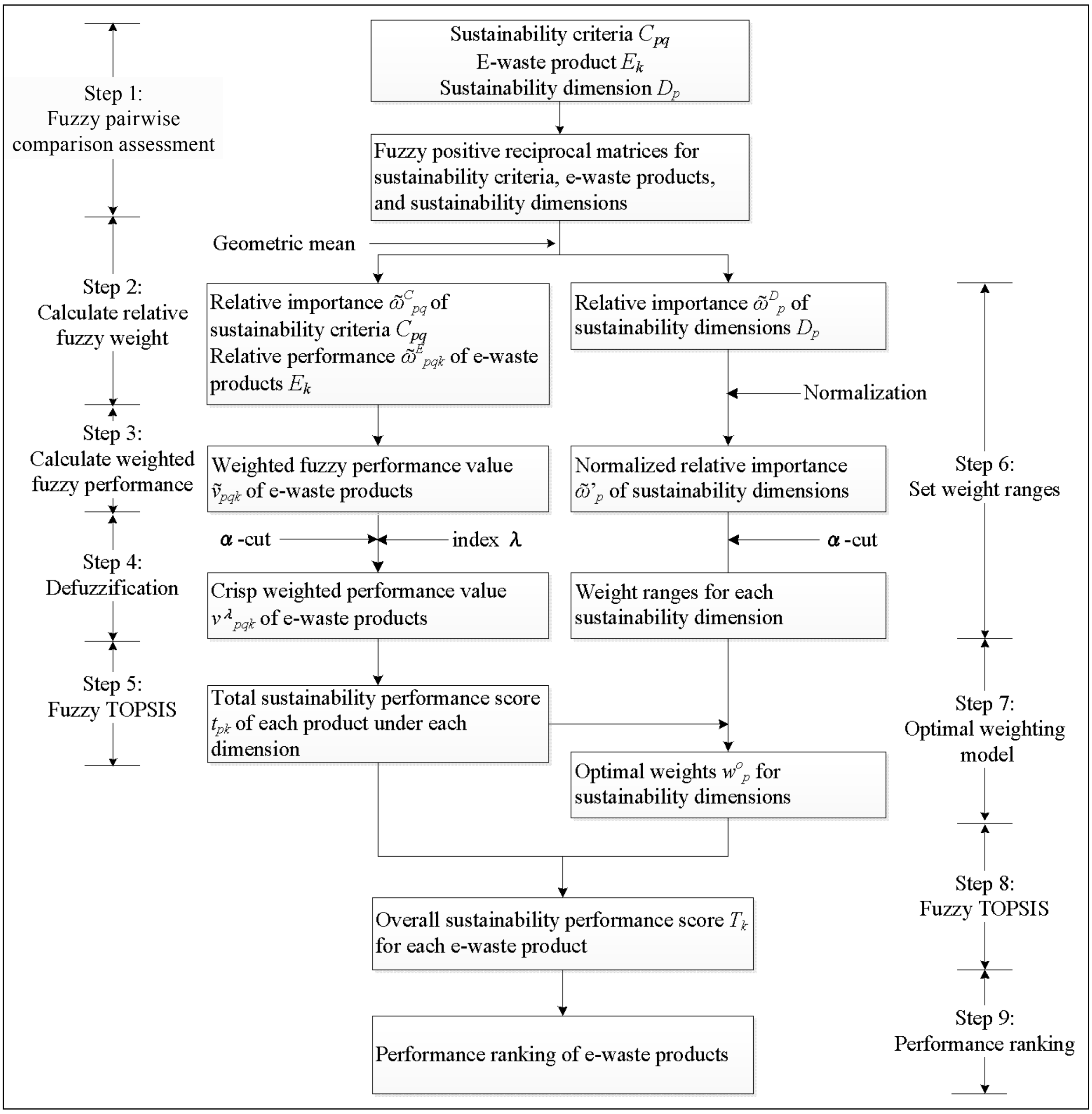

Figure 3. The sustainability performance evaluation procedure.

Empirical Study

To illustrate the sustainability performance evaluation approach presented above, we conduct an empirical study on a leading e-recycling company in Australia. The company provides a total service approach to e-waste recycling with innovative methods of disassembly and careful management of resulting waste streams. Its high-profile clients include government departments and global brand owners (e.g., Dell, Hewlett-Packard, International Business Machines–IBM, and Toshiba). With 20 years' experience in e-waste recycling solutions, the company has a high sustainability focus and is willing to achieve best practice recycling outcomes and maximize returns to both clients and the environment. To evaluate the performance of its e-waste products in achieving corporate sustainability, the company wishes to conduct the sustainability performance evaluation from the environmental, economic, and social dimensions. Six categories of e-waste products are identified by the company for the evaluation. Table 3 gives the details of these e-waste products. Figure 4 shows the framework of the evaluation approach conducted by the company.

Table 3
E-waste Products of the E-recycling Company

E-waste product category	Description
E_1 Computer	PC, notebook computer, CRT monitor, LCD monitor, PC keyboard, mouse, cables associated with PC system, modem, etc.
E_2 Communication equipment	Server, rack mount cabinet, hub, switch, router, modem/print server, assorted network gear, PABX controller unit, telephone handsets, uninterruptable power supply, etc.
E_3 Battery	Lead acid battery, lithium ion, lithium battery, NiCad battery (sealed/vented), NiMH battery, Alkaline battery, etc.
E_4 Mobile phone	Mobile phone handsets, batteries, chargers, accessories, etc.
E_5 Office electrical equipment	Desktop printer, enterprise printer, photocopier, fax machine, desktop scanner, desktop multifunction printer/scanner, etc.
E_6 Consumer electrical equipment	CRT television, plasma television, LCD television, VCR/DVD/set top box, Hi-Fi stereo, speakers, domestic vacuum cleaner, microwave oven, cordless phone, video camera, digital still camera, etc.

Note. Cathode Ray Tube (CRT), Liquid Crystal Display (LCD), Personal Computer (PC), Private Automatic Branch Exchange (PABX), Nickel Cadmium (NiCad), Nickel Metal Hydride (NiMH), Video Cassette Recorder (VCR), Digital Versatile Disc (DVD), High Fidelity (Hi-Fi).

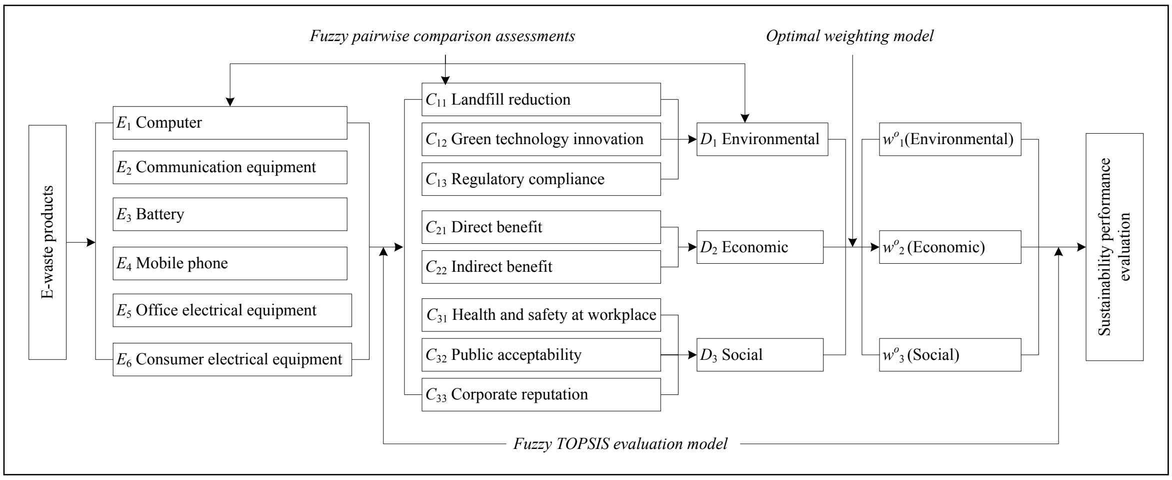

Figure 4. The framework of the sustainability performance evaluation approach.

As shown in Figure 4, the sustainability criteria are identified for each sustainability dimension:

- For the environmental dimension (D_1), the e-waste products are assessed by: (a) landfill reduction (C_{11}) –the possible reduced amount of trash/waste in the landfill, (b) green technology innovation (C_{12}) –the innovation rate of new technology for reducing environmental impacts, and (c) regulatory compliance (C_{13}) –the level of commitment to compliance with applicable environmental legislation and regulations.
- For the economic dimension (D_2), the e-waste products are assessed by: (a) direct benefit (C_{21}) –the profitability gained, and (b) indirect benefit (C_{22}) –the potential business opportunities/markets explored.
- For the social dimension (D_3), the e-waste products are assessed by: (a) health and safety in the workplace (C_{31}) –the reduced number of worker compensation claims, (b) public acceptability (C_{32}) –the general attitude/perception of the public towards the e-waste products of the company, and (c) corporate reputation (C_{33}) –the stakeholders' satisfaction level regarding the e-waste products of the company.

As the decision maker, the managing director of the company first conducts: (a) three assessments for the eight sustainability criteria under each of the three sustainability dimensions and (b) eight assessments for the six e-waste products with respect to each sustainability criterion by pairwise comparisons using the fuzzy linguistic terms and the rating scales defined in Figures 1 and 2, respectively. The assessment results are first examined using the consistency ratio developed by Saaty (1980). The consistency ratios of all the 11 assessments are less than 0.1, which meets the consistency requirement. By applying Equations 2 and 3 to the assessment results, the relative importance of the sustainability criteria and the relative performance of the e-waste products with respect to each sustainability criterion are obtained. Tables 4 and 5 show the results.

Table 4
Relative Importance of Sustainability Criteria

Sustainability criteria C_{pq}	Relative importance $\tilde{w}^{C}_{pq}$
C_{11} Landfill reduction	(0.432, 0.634, 0.895)
C_{12} Green technology innovation	(0.139, 0.174, 0.229)
C_{13} Regulatory compliance	(0.150, 0.192, 0.262)
C_{21} Direct benefit	(0.366, 0.667, 1.098)
C_{22} Indirect benefit	(0.211, 0.333, 0.634)
C_{31} Health and safety in the workplace	(0.255, 0.594, 1.190)
C_{32} Public acceptability	(0.118, 0.249, 0.632)
C_{33} Corporate reputation	(0.088, 0.157, 0.348)

Table 5
Relative Performance of E-waste Products on each Sustainability Criterion

E-waste product E_k		Relative performance $\tilde{w}^E_{pqk}$		Relative performance $\tilde{w}^E_{pqk}$
E_1	C_{11}	(0.036, 0.068, 0.182)	C_{12}	(0.190, 0.384, 0.693)
E_2		(0.064, 0.130, 0.280)		(0.043, 0.070, 0.125)
E_3		(0.090, 0.226, 0.518)		(0.080, 0.165, 0.375)
E_4		(0.146, 0.358, 0.761)		(0.143, 0.265, 0.499)
E_5		(0.069, 0.149, 0.359)		(0.047, 0.083, 0.158)
E_6		(0.038, 0.068, 0.154)		(0.023, 0.034, 0.055)
E_1	C_{13}	(0.033, 0.052, 0.099)	C_{21}	(0.192, 0.380, 0.667)
E_2		(0.196, 0.326, 0.526)		(0.074, 0.122, 0.219)
E_3		(0.074, 0.121, 0.211)		(0.026, 0.044, 0.077)
E_4		(0.043, 0.073, 0.146)		(0.019, 0.031, 0.056)
E_5		(0.175, 0.326, 0.556)		(0.087, 0.168, 0.365)
E_6		(0.065, 0.102, 0.167)		(0.141, 0.256, 0.471)
E_1	C_{22}	(0.196, 0.387, 0.715)	C_{31}	(0.029, 0.044, 0.080)
E_2		(0.027, 0.051, 0.109)		(0.100, 0.182, 0.349)
E_3		(0.023, 0.039, 0.075)		(0.235, 0.421, 0.704)
E_4		(0.116, 0.258, 0.538)		(0.145, 0.252, 0.439)
E_5		(0.079, 0.161, 0.338)		(0.034, 0.062, 0.124)
E_6		(0.053, 0.104, 0.253)		(0.026, 0.039, 0.064)
E_1	C_{32}	(0.061, 0.127, 0.261)	C_{33}	(0.273, 0.432, 0.675)
E_2		(0.063, 0.134, 0.279)		(0.073, 0.156, 0.298)
E_3		(0.095, 0.227, 0.493)		(0.042, 0.075, 0.143)
E_4		(0.194, 0.385, 0.731)		(0.023, 0.036, 0.062)
E_5		(0.039, 0.079, 0.200)		(0.143, 0.243, 0.405)
E_6		(0.025, 0.049, 0.132)		(0.033, 0.059, 0.123)

The weighted fuzzy performance value $\tilde{v}_{pqk}$ of e-waste products with respect to each sustainability criterion C_{pq} can be calculated by multiplying the relative importance $\tilde{w}^C_{pq}$ of the sustainability criteria and the relative performance of the e-waste products $\tilde{w}^E_{pqk}$. The company shows a medium confidence level in choosing the crisp value interval $\left[v^{\alpha}_{pqkl}, v^{\alpha}_{pqku}\right]$ for the obtained weighted fuzzy performance value $\tilde{v}_{pqk}$ and takes a moderate attitude on the fuzzy assessment results. In this case, by using $\alpha = 0.5$ and $\lambda = 0.5$ in Equations 5 and 6, the crisp weighted performance value v^{λ}_{pqk} of each product with respect to each sustainability criterion is obtained. Table 6 shows the results.

Table 6
Crisp Weighted Performance Value v_{pqk}^{λ} (λ = 0.5)

E-waste product E_k	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}
E_1	0.066	0.080	0.013	0.327	0.188	0.039	0.059	0.099
E_2	0.111	0.015	0.073	0.107	0.027	0.164	0.063	0.040
E_3	0.197	0.039	0.028	0.038	0.020	0.349	0.109	0.019
E_4	0.300	0.057	0.018	0.027	0.134	0.214	0.169	0.009
E_5	0.135	0.018	0.074	0.164	0.085	0.057	0.043	0.057
E_6	0.060	0.007	0.023	0.228	0.060	0.032	0.028	0.016

The fuzzy TOPSIS evaluation model is solved based on the crisp weighted performance value v_{pqk}^{λ}. The positive ideal solution (or the e-waste product with the best relative performance) and the negative ideal solution (or the e-waste product with the worst relative performance) of all e-waste products with respect to each sustainability criterion under each sustainability dimension are calculated by using Equations 7 and 8. Table 7 shows the results.

Table 7
Performance Score of E-waste Products on each Sustainability Dimension

Sustainability dimension D_p	Environmental (D_1)	Economic (D_2)	Social (D_3)
Positive ideal solution $A_p^{\lambda+}$	(0.300, 0.080, 0.074)	(0.327, 0.188)	(0.349, 0.169, 0.099)
Negative ideal solution $A_p^{\lambda-}$	(0.060, 0.007, 0.013)	(0.027, 0.020)	(0.032, 0.028, 0.009)
E-waste product E_k	Total sustainability performance score t_{pk}		
E_1	0.232	1.000	0.225
E_2	0.284	0.228	0.387
E_3	0.542	0.031	0.767
E_4	0.801	0.274	0.587
E_5	0.357	0.439	0.151
E_6	0.039	0.558	0.020

To obtain the optimal weights w_p^o for each sustainability dimension D_p, the company assesses the relative importance $\tilde{w}_p^D$ of the three sustainability dimensions by pairwise comparisons with the fuzzy linguistic terms and the rating scale defined in Figure 1. As shown in Table 8, a set of relative importance $\tilde{w}_p^D$ (or subjective fuzzy weights) of the three sustainability dimensions is obtained by solving Equations 2 and 3. With a medium confidence level in choosing a crisp value interval for the sustainability dimension weights (i.e., α = 0.5), the subjective weight ranges $\left[w_{pl}^{\alpha}, w_{pu}^{\alpha}\right]$ are calculated and act as the constraints for the optimal weighting model (12)-(14). In addition, as the company has more interest in the economic aspect of sustainability, specific constraints $w_2^o \geq w_1^o$ and $w_2^o \geq w_3^o$ are incorporated into the model. By solving Equation 11 and the optimization model (12)-(14), the optimal weights of the three sustainability dimensions are obtained and shown in the last row of Table 8. The optimal weights are objectively generated and clearly reflect the best sustainability interests and priorities of the company.

Table 8
Optimal Weights of Sustainability Dimensions

Sustainability dimension D_p	Environmental (D_1)	Economic (D_2)	Social (D_3)
Subjective fuzzy weight $\tilde{w}_p^D$	(0.291, 0.327, 0.371)	(0.291, 0.413, 0.535)	(0.201, 0.260, 0.371)
Normalized fuzzy weight $\tilde{w}_p'$	(0.227, 0.327, 0.475)	(0.227, 0.413, 0.684)	(0.158, 0.260, 0.475)
Weight range (α = 0.5)	[0.277, 0.401]	[0.320, 0.548]	[0.209, 0.367]
Optimal weight w_p^o	0.28	0.37	0.35

The evaluation of the overall sustainability performance score T_k of the six e-waste products is then conducted by incorporating the optimal weights in the evaluation model. By solving Equations 16 to 20, the evaluation results are shown in Table 9. Based on the relative ranking of the six e-waste products, computer (E_1) is the company's most important e-waste product with its best overall sustainability performance, while the least important e-waste product is communication equipment (E_2).

Table 9
Overall Sustainability Performance of E-waste Products

Sustainability dimension D_p	Environmental (D_1)			Economic (D_2)		Social (D_3)		
Sustainability criteria C_{pq}	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}
Positive ideal solution $A^{\lambda+}$	0.084	0.022	0.021	0.121	0.070	0.122	0.059	0.035
Negative ideal solution $A^{\lambda-}$	0.017	0.002	0.004	0.010	0.007	0.011	0.010	0.003
E-waste product E_k	Overall sustainability performance score T_k						Ranking	
E_1	0.499						1	
E_2	0.307						6	
E_3	0.477						2	
E_4	0.473						3	
E_5	0.315						5	
E_6	0.327						4	

The evaluation results shown in Table 7 are obtained without considering the relative importance (weight) of the three sustainability dimensions. Hypothetically, if the company wished to use equal weights for the three sustainability dimensions, the overall sustainability performance scores of the six e-waste products and their rankings can be calculated based on the evaluation results in Table 7. As shown in Table 10, a comparison of relative performance rankings of the six e-waste products can then be made between the use of the optimal weights and the use of the equal weights for the three sustainability dimensions. The differences between the two sets of rankings show that the relative performance of the six e-waste products will largely be affected by the sustainability interests and priorities of the company.

Table 10
Ranking Comparison of E-waste Products using Optimal Weights and Equal Weights

Sustainability dimension D_p	D_1	D_2	D_3	D_1	D_2	D_3
Relative weight	Optimal weight			Equal weight		
	0.28	0.37	0.35	0.33	0.33	0.33
E-waste product E_k	Overall sustainability performance score		Ranking	Overall sustainability performance score		Ranking
E_1	0.499		1	0.472		2
E_2	0.307		6	0.468		3
E_3	0.477		2	0.324		6
E_4	0.473		3	0.617		1
E_5	0.315		5	0.445		4
E_6	0.327		4	0.361		5

With $\alpha = 0.5$ and $\lambda = 0.5$, the crisp overall performance values z_{pqk}^{λ} of e-waste products E_k with respect to each sustainability criterion C_{pq} under each sustainability dimension are obtained. The settings used for α and λ show that the company has a moderate preference for the fuzzy assessment results. $\alpha = 0.5$ implies that the company has a medium confidence level in choosing a crisp value interval for the overall fuzzy performance value of each e-waste product. $\lambda = 0.5$ indicates that the company has a moderate attitude towards the fuzzy assessment results; that is, the company weights all the values derived from fuzzy assessments equally. Table 11 shows the results of this analysis.

Table 11
Crisp Overall Performance Value z_{pqk}^{λ} ($\lambda = 0.5$)

E-waste product E_k	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{31}	C_{32}	C_{33}
E_1	0.019	0.022	0.004	0.121	0.070	0.014	0.021	0.035
E_2	0.031	0.004	0.020	0.040	0.010	0.058	0.022	0.014
E_3	0.055	0.011	0.008	0.014	0.007	0.122	0.038	0.007
E_4	0.084	0.016	0.005	0.010	0.050	0.075	0.059	0.003
E_5	0.038	0.005	0.021	0.061	0.031	0.020	0.015	0.020
E_6	0.017	0.002	0.006	0.084	0.022	0.011	0.010	0.006

The results of the sustainability performance evaluation would help the company identify the e-waste products to be improved or those that require most focus in order to best enhance their corporate sustainability performance. For example, the relative sustainability performance of computer (E_1) and consumer electrical equipment (E_6) can be improved by reducing the recycling trash to landfills and incinerators or increasing the health and safety in the workplace. More green technology innovation may help improve the relative sustainability performance of communication equipment (E_2), office electrical equipment (E_5), and consumer electrical equipment (E_6). As regards the regulatory compliance, the company should pay more attention to the computer (E_1) and mobile phone (E_4) products, especially in terms of deciding to outsource them to the downstream partners in other countries. For the economic dimension, it is clear that computer (E_1) has the best performance regarding gaining both direct and indirect benefits. This e-waste product also earns the most reputation for the company.

The evaluation results also provide the e-recycling company with useful insights to manage its recycling activities of specific e-waste products in terms of their relative contribution to its corporate sustainability. The company can put its management focus on certain e-waste products to meet the specific environmental, economic, and/or social requirements of its recycling activities. For example, to have higher economic benefits, the company can become more involved in the recycling of computers or consumer electrical equipment. To become a better environmental performer, the company can focus more on the recycling of mobile phones or batteries. To be more socially responsible, the company can increase its recycling activities in relation to batteries or mobile phones.

Conclusions

E-waste products have significant environmental and social impacts in addition to their huge economic benefits. Aware of the increasing importance of e-waste issues, e-recycling companies often make achieving corporate sustainability (including environmental, economic, and social dimensions) part of their business vision. To help an e-recycling company achieve corporate sustainability, we have presented a new structured approach for the company to evaluate the relative recycling sustainability performance of its e-waste products.

This approach objectively determines a set of optimal weights for the environmental, economic, and social dimensions of corporate sustainability in order to reflect the best sustainability interests of the e-recycling company, while taking into account the subjective assessments of its decision maker based on the current business practice and concerns of the company. When its best sustainability interests are incorporated in the evaluation, the e-recycling company can examine how its e-waste products will best contribute to its corporate sustainability as a whole and to the environmental, economic, and social dimensions individually.

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