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Sustainable planning of e-waste recycling activities using fuzzy multicriteria decision making

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ABSTRACT

This paper develops a new approach to sustainable planning of e-waste recycling activities for meeting the best sustainability interests of an e-recycling company. A fuzzy multicriteria decision making algorithm is developed to evaluate alternative recycling activities of an e-waste recycling job in terms of their corporate sustainability performance on identified sustainability criteria under the environmental, economic, and social dimensions. A series of optimal weighting models are developed to determine the optimal weights for the three sustainability dimensions and their associated criteria. In consideration of an e-recycling company's subjective sustainability preferences, the optimal weights reflect the best corporate sustainability performance of the e-waste products processed by the company under its current operational settings. The approach represents an original contribution to the methodological development of weighting the three corporate sustainability dimensions for planning decisions. In practice, it provides e-recycling companies with a proactive mechanism for incorporating the concept of corporate sustainability into their regular planning decisions. An empirical study on a leading e-recycling company is conducted to illustrate how the approach works.

1. Introduction

End-of-life electrical and electronic equipment, also known as e-waste, has been recognized as secondary sources of various valuable materials and metals such as gold, silver, and platinum (Oguchi et al., 2011). E-waste has also been identified as one of the largest known sources of pollutants in municipal waste, due to its hazardous content (Oguchi et al., 2012). The advancing technology and shortened product life cycle make e-waste one of the fastest growing waste streams, creating significant risks to human health and the environment. The negative impacts of e-waste on the environment and humans will increase if the e-waste is sent to landfill without proper recycling.

E-recycling companies strive to provide high standard recycle and disposal services and solutions to e-waste products, thus making a substantial contribution to the management of e-waste. As a sound business proposition and ecologic solution, e-waste recycling jobs are performed to help the economic growth of the e-recycling companies, as well as the elimination of environmental and health hazards. For a given e-waste recycling job, the e-recycling companies often require making planning decisions for selecting from its available job routes. This is because an e-waste recycling job can often be completed by a number of available job routes, each involving a sequence of different recycling activities. In the current practice, the e-recycling companies make such planning decisions based on their experiences. This rule-of-thumb approach cannot always ensure that the e-waste recycling jobs are carried out in an economically viable, environmentally friendly, and socially responsible manner that will maximize their corporate sustainability. To achieve this, a structured approach is required to evaluate the recycling activities of available job routes in terms of their contribution to the corporate sustainability.

The corporate sustainability of a company is achieved by delivering environmental, economic, and social benefits simultaneously, which are the generally accepted triple bottom-line of sustainable development (Elkington, 1997). In order to achieve economic benefits and meet the requirements of environmental management and corporate social responsibility (Commission of the European Communities, 2002), e-recycling companies should consider the economic, environmental, and social dimensions of their corporate sustainability simultaneously when planning the recycling activities for their e-waste recycling jobs. The available job routes of a given e-waste recycling job often contribute differently to the three dimensions of the corporate sustainability. The

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selection from the available job routes based on their corporate sustainability performance is thus affected by the relative importance (weight) of the three sustainability dimensions. However, there is no universally accepted approach for determining the relative weights of the three sustainability dimensions. The trade-offs between the three sustainability dimensions are often dealt with subjectively by the decision maker. If the decision maker has no reason to prefer one dimension to another, equal weights are often used due to the principle of insufficient reason (Starr and Greenwood, 1977).

The use of subjective or equal weights does not necessarily guarantee that the selected job route and the associated recycling activities for a given job would best contribute to the corporate sustainability under the current operational settings. To ensure the selected recycling activities meet the best sustainability interests of an e-recycling company, it is desirable to objectively determine a set of optimal weights for the three sustainability dimensions, while considering the subjective sustainability preferences of the company. These optimal weights can then be used for the sustainable planning of the recycling activities that will have the best corporate sustainability performance.

To address the e-waste recycling planning issues mentioned above, we develop a novel sustainable planning approach for meeting the best sustainability interests of an e-recycling company. The approach uses a fuzzy multicriteria decision making (MCDM) method and a series of optimal weighting models to evaluate and select alternative recycling activities for e-waste recycling jobs of an e-recycling company. It represents an original contribution to the methodological development of weighting the three dimensions of the corporate sustainability for planning decisions. In practice, the approach addresses the need for incorporating sustainability into the strategic and operational planning of a company (Hannon and Callaghan, 2011). In this regard, it contributes to the recycling planning practice of e-recycling companies by providing them with a proactive mechanism for incorporating the concept of corporate sustainability into their regular recycling planning decisions.

In subsequent sections, we first formulate the sustainable planning problem in a typical e-recycling company. We then present the sustainable planning approach together with the key methods developed. Finally, we use an empirical study to demonstrate the effectiveness of the approach.

2. The sustainable planning problem

We conduct an empirical study on a leading e-recycling company in Australia as an example to formulate the sustainable planning problem of e-waste recycling activities. The company provides e-waste recycling solutions with innovative methods and careful management of resulting waste streams. With a high sustainability focus, the company strives to achieve best practice recycling outcomes and maximize returns to both clients and the environment.

The process of performing e-waste recycling jobs involves a series of recycling activities conducted at a group of process units (Chancerel and Rotter, 2009). Table 1 shows the company's four main process units U_p and their regularly performed recycling activities r_{pq} ($p = 1, 2, \ldots, P$; $q = 1, 2, \ldots, Q_p$).

For a given e-waste recycling job, a number of job routes, each consisting of a series of different recycling activities, are often available for performing the job. The job routes available for completing a specific e-waste recycling job vary depending on the characteristics of the e-waste product and the current operational capacity of the company. For example, an e-waste recycling job for the company is to process a batch of 200 end-of-life personal computers from a contract client in the capital city. Fig. 1 shows the eight available job routes together with their corresponding recycling activities r_{pq} for performing this job.

To select from a set of available job routes often involves the selection among a set of *planning alternatives*, which can either be individual recycling activities or sub-routes (i.e. a series of activities) at certain process units. For instance, at the collection and transportation unit (U_1), the selection among the eight job routes involves the selection between two alternative recycling activities, one-cost service (r_{11}) and collection points (r_{14}). At the other three process units (U_2, U_3 and U_4), there are four available sub-routes which represent the company's two main streams of operation: offshore processing and onshore processing. Two offshore processing alternatives are outsourcing e-waste to overseas partners for recycling (i.e. r_{24} and r_{43} in Routes 1 and 5) and exporting to developing countries for reuse (i.e. r_{24} and r_{44} in Routes 2 and 6). Two onshore processing alternatives are refining treatment of e-waste and resale in markets (i.e. r_{25}, r_{31}, r_{32}, r_{33} and r_{41} in Routes 3 and 7) and remanufacturing e-waste into green products and resale in markets (i.e. r_{25}, r_{31}, r_{32}, r_{36} and r_{41} in Routes 4 and 8).

The eight available job routes shown in Fig. 1 will contribute differently to the corporate sustainability of the company, as they involve different recycling activities. Clearly, it is desirable for the company to select a job route that will have the best corporate sustainability performance. To this end, the corporate sustainability performance of each available job route is to be evaluated with respect to a set of *sustainability criteria* C_{ij} ($i = 1, 2, 3$; $j = 1, 2, \ldots, g_i$) identified under the three *sustainability dimensions* C_i ($i = 1, 2, 3$), namely the economic, environmental, and social dimensions respectively.

The sustainability criteria under each sustainability dimension are commonly used as a measure of sustainability performance. However, the criteria or indicators used in the literature for measuring sustainability are not yet standardized (Čuček et al., 2012a). As such, different sets of sustainability criteria have been proposed for specific contexts using different methods. For example, Labuschagne et al. (2005) propose a multi-level sustainability criteria framework to assess the sustainability of operations in a manufacturing sector. Gallego (2006) uses economic, social and environmental indicators to measure companies' sustainable development from different sectors. Chang et al. (2011) evaluate the corporate sustainability performance by incorporating the sustainability criteria into the data envelopment analysis. Skouloudis and Evangelinos (2009) and Lozano and Huisingh (2011) examine the sustainability criteria through the analysis of the company's sustainability reports. Sobhani et al. (2012) use annual reports and corporate websites to examine the economic, environmental and social dimensions of corporate sustainability for the banking industry. Fonseca et al. (2012) examine the predominant GRI-based reporting approach for assessing the sustainability of mining companies. Searcy and Elkhawas (2012) investigate how Canadian companies use the Dow Jones Sustainability Index for their corporate sustainability performance. Čuček et al. (2012a) give an overview of economic, social and environmental footprints as defined indicators to measure sustainability. Čuček et al. (2012b) use total footprints as sustainable criteria to evaluate the performance of a regional biomass and bioenergy supply chain using a multicriteria optimization approach. Mulliner et al. (2013) consider a range of economic, environmental and social criteria for assessing housing affordability and sustainability using MCDM. Herva and Roca (2013) give a comprehensive review of how multicriteria analysis methods are used for sustainability evaluation with respect to a set of economic, environmental and social criteria.

With no commonly agreed set of sustainability criteria available, a company often identifies these criteria by considering its sustainability concerns and interests under its current business

Table 1
Recycling process units and recycling activities of the e-recycling company.

U_p	Recycling process unit	r_{pq}	Recycling activity
U_1	Collection and transportation	r_{11}	One-cost service
		r_{12}	Provision of certified bins
		r_{13}	Separate collections
		r_{14}	Collection points
		r_{15}	Recycling by post
		r_{16}	Regional coverage
U_2	Sorting and dismantling	r_{21}	Identifying and testing for reuse, resale, or recycle for valuable materials
		r_{22}	Multiple pass destructive wipe of data
		r_{23}	Physical destruction of data
		r_{24}	Secure chain of custody arrangements
		r_{25}	Dismantling and sorting into components
U_3	Treatment	r_{31}	Removing critical components
		r_{32}	Mechanical processing (including shredder, magnetic separation, eddy current separation, density separation)
		r_{33}	Refining treatment of metals, plastics and glass
		r_{34}	Cathode Ray Tube (CRT) recycling
		r_{35}	Innovative reuse of CRT monitors
		r_{36}	Recovering plastics and remanufacturing into green products
		r_{37}	Recovering parts for reuse
		r_{38}	Testing and refurbishing items
		r_{39}	Packaging redesign in view of safe and easy disposal
U_4	Disposal/Marketing/Outsourcing	r_{41}	Resale in secondary markets
		r_{42}	Employee buyback program
		r_{43}	Exporting to overseas downstream partners
		r_{44}	Exporting to developing countries for reuse
		r_{45}	Incineration of wastes

objectives and operational practices. Table 2 shows the sustainability criteria identified by the e-recycling company under each sustainability dimension. These criteria are assessable and manageable by the company for evaluating the sustainability performance of the available planning alternatives.

For a given e-waste recycling job, the sustainable planning problem is to select from a set of available job routes so that the execution of the job will have the best overall contribution to all the sustainability criteria given in Table 2, thus meeting the best sustainability interests of the company. To address this important e-waste recycling planning problem, we develop a novel sustainable planning approach.

3. The sustainable planning approach

Fig. 2 shows the key data and methods of the sustainable planning approach. For a given e-waste recycling job, a set of available job routes can be identified under the current operational settings, from which the planning alternatives can be determined at the corresponding process units. For each set of planning alternatives, a fuzzy pairwise comparison method is used to subjectively assess their relative performance ratings with respect to the sustainability criteria under each dimension, shown in Table 2.

For each planning alternative, a fuzzy MCDM algorithm is used to obtain its *dimension sustainability score* under each dimension, relative to other alternatives. This is done by aggregating its relative performance rating with the optimal weights of the corresponding criteria. The algorithm is then used again to aggregate its three dimension sustainability scores with the optimal weights of the three dimensions for obtaining its *corporate sustainability score*, relative to other alternatives. With the use of the fuzzy MCDM algorithm, the corporate sustainability score obtained for each planning alternative is a relative concept (Chang and Yeh, 2004). It is in accordance with the notion of corporate sustainability that incorporates three sustainability dimensions of measures, shown in Table 2. The planning decision of selecting from the available job routes can thus be made based on the corporate sustainability score of each planning alternative.

Used with the fuzzy MCDM algorithm, the optimal weights for the sustainability criteria and for the sustainability dimensions are generated by a series of optimal weighting models. These models maximize the overall sustainability performance of all e-waste products processed by the company. We present the key methods in the following sections.

4. Fuzzy pairwise comparison assessments

A pairwise comparison process, as implemented in the analytic hierarchy process (AHP) (Saaty, 1980), is commonly used to facilitate comparative assessments where the performance of each alternative is compared with that of other alternatives on each evaluation criterion with relative measurement (Yeh and Chang, 2009). In AHP, a 1–9 ratio scale is used to compare two alternatives for indicating the strength of their relative importance or performance. In the sustainable planning approach, we use the 1–9 ratio scale in pairwise comparison as it has proven to be an effective measurement scale for reflecting the qualitative information of a decision problem and for enabling the unknown weights to be approximated (Vreeker et al., 2002).

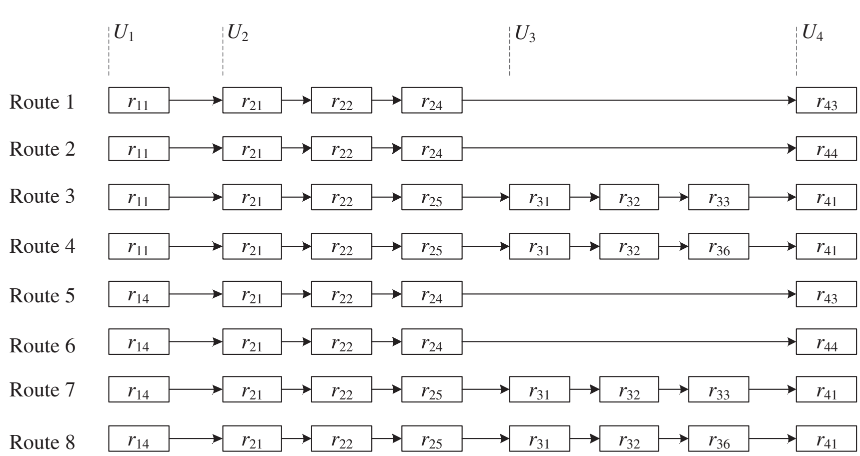

Fig. 1. Available job routes for an e-waste recycling job.

Table 2
Sustainability criteria under each sustainability dimension.

C_i	Sustainability dimension	C_{ij}	Sustainability criteria	Description
C_1	Economic	C_{11}	Direct benefit	The profit gained
		C_{12}	Indirect benefit	The potential business opportunities/markets explored
C_2	Environmental	C_{21}	Landfill reduction	The possible reduced amount of trash/waste in the landfill
		C_{22}	Green technology innovation	The innovation rate of new technology for reducing environmental impacts
		C_{23}	Regulatory compliance	The level of commitment and resources required to compliance with applicable environmental legislation and regulations
C_3	Social	C_{31}	Health and safety at workplace	The number of reduced workers compensation claimed
		C_{32}	Public acceptability	The general attitude/ perception of the public towards the e-recycling service of the company
		C33	Corporate reputation	The stakeholder's satisfaction level on e-recycling service of the company

To reflect the inherent subjectiveness and vagueness involved in the pairwise comparison process, the concept of fuzzy numbers is often used (Chen and Hwang, 1992). Modelling using fuzzy numbers has proven to be an effective way for formulating decision problems where the information available is subjective and imprecise (Zimmermann, 1996). In the sustainable planning approach, we use a triangular fuzzy number to represent the ratio value given in pairwise comparisons. Representing fuzzy numbers in a triangular form of the membership function is used most often in practical applications (Klir and Yuan, 1995). With their simplicity in both concept and computation, triangular fuzzy numbers constitute an immediate solution to the optimization problems in fuzzy modelling (Pedrycz, 1994).

A triangular fuzzy number $\tilde{a} = (a_1, a_2, a_3)$ is a convex fuzzy set (Zadeh, 1965) with its membership function defined as

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

where a_2 is the most possible value of a linguistic term, and a_1 and a_3 are the lower and upper bounds used to reflect the fuzziness of the assessment. To achieve the greatest flexibility, the decision maker needs to specify only the most possible value in pairwise comparisons and the value will be fuzzified to a corresponding triangular fuzzy number.

This fuzzy representation is similar in essence to the use of a set of linguistic terms, but it provides nine possible fuzzy numbers instead of five for the five terms given in Table 3 (Chang et al., 2007). Table 3 illustrates how the five linguistic terms are characterized by nine possible triangular fuzzy numbers and how a triangular fuzzy number is generated to represent the fuzzy assessment from a numeric ratio value assessed by the decision maker. Take a given ratio value 5 ("Strongly better") for instance, the fuzzy assessment represented as a triangular fuzzy number is (3, 5, 7). This implies that the assessment is "about 5" for reflecting 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 Table 3 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).

The fuzzy pairwise comparison assessments for all N alternatives produce a positive $N \times N$ fuzzy positive reciprocal matrix with all its elements $\tilde{a}_{xy} = 1/\tilde{a}_{xy}$ ($x = 1, 2, \ldots, N$; $y = 1, 2, \ldots, N$). Solving the

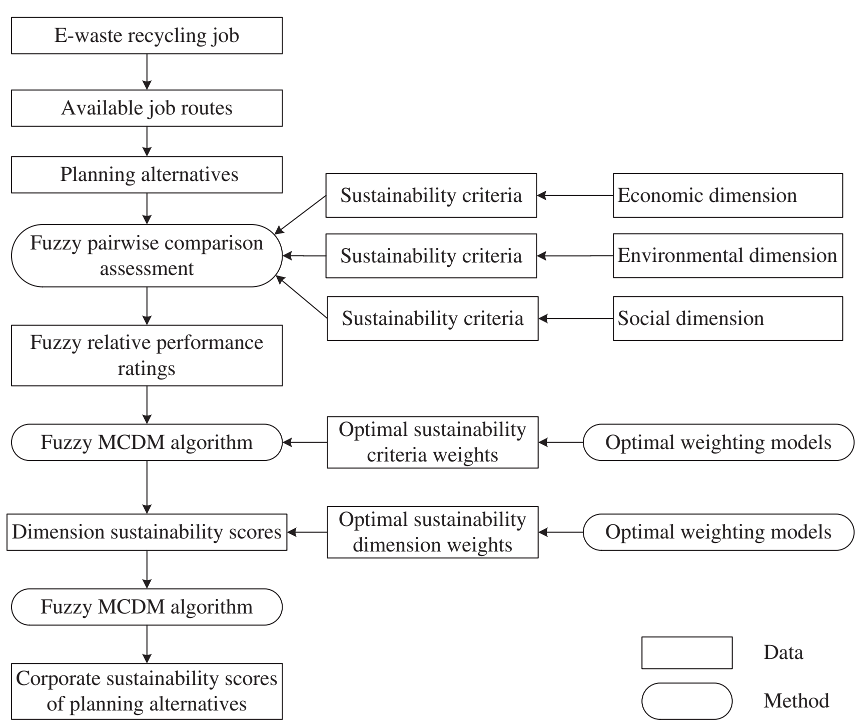

Fig. 2. The sustainable planning approach.

Table 3
Value fuzzification of pairwise comparison assessments on relative performance of alternatives.

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		

fuzzy positive reciprocal matrix will generate the relative fuzzy performance ratings (or fuzzy weights) for all the alternatives. To guarantee a unique solution, we use the geometric mean method (Buckley, 1985). Given a fuzzy positive reciprocal matrix $M = [\tilde{a}_{xy}]$, the method first calculates the geometric mean of each row as

$$\tilde{G}_x = \left(\prod_{y=1}^{N} \tilde{a}_{xy}\right)^{\frac{1}{N}} \tag{2}$$

The relative fuzzy performance ratings for N alternatives (or relative fuzzy weights for N criteria) $\tilde{R}_x$ are then computed as

$$\tilde{R}_x = \frac{G_x}{\sum_{y=1}^{N} G_y} \tag{3}$$

With the use of triangular fuzzy numbers, the arithmetic operations on fuzzy numbers are based on fuzzy arithmetic (Kaufmann and Gupta, 1991).

5. The fuzzy MCDM algorithm

The development of the fuzzy MCDM algorithm is based on the concept of the degree of optimality rooted in an alternative where multiple criteria characterize the notion of the best (Hwang and Yoon, 1981). This concept has been implemented by a widely used MCDM method called the technique for order preference by similarity to ideal solution (TOPSIS) (Hwang and Yoon, 1981). As suggested by the concept, the most preferred alternative should not only have the shortest distance from the positive ideal alternative, but have the longest distance from the negative ideal alternative.

According to the concept, the overall preference value of an alternative is determined by its distance to the positive ideal solution and to the negative ideal solution. This distance is thus interrelated with the criteria weights and should be incorporated in the distance measurement (Zeleny, 1982). To deal with this issue, the fuzzy MCDM algorithm developed uses the optimal criteria weights and the optimal dimension weights, as shown in Fig. 3 and discussed in Section 6, to weight the distance between the alternative and the positive/negative ideal alternative.

To obtain the dimension sustainability score and the corporate sustainability score for each alternative X_y (e.g. planning alternatives A_n or e-waste products P_m), the algorithm works as follows:

Step 1: Compute the relative degree of optimality for the performance of each alternative X_y with respect to each criterion C_{ij}.

The Hamming distances between the fuzzy performance rating $\tilde{a}_{yij}$ and a fuzzy positive ideal performance $M^{ij}_{\max}$ and a fuzzy negative ideal performance $M^{ij}_{\min}$ are first calculated by

$$h^{+}_{yij} = H\left(\tilde{a}_{yij}, M^{ij}_{\max}\right), h^{-}_{yij} = H\left(\tilde{a}_{yij}, M^{ij}_{\min}\right). \tag{4}$$

The fuzzy positive ideal performance $M^{ij}_{\max}$ and the fuzzy negative ideal performance $M^{ij}_{\min}$ represent the best possible performance and the worst possible performance of the alternative X_y with respect to each criterion C_{ij}, whose membership functions are defined as

$$\mu M^{ij}_{\max}(x_{yij}) = \begin{cases} x_{yij}, & \text{if } 0 \le x \le 1 \\ 0, & \text{otherwise} \end{cases},$$
$$\mu M^{ij}_{\min}(x_{yij}) = \begin{cases} 1 - x_{yij}, & \text{if } 0 \le x \le 1 \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

The Hamming distance between two fuzzy numbers $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ is calculated as (Klir and Yuan, 1995)

$$\mathrm{H}\left(\tilde{a}, \tilde{b}\right) = |a_1 - b_1| + |a_2 - b_2| + |a_3 - b_3|. \tag{6}$$

For each criterion C_{ij}, h^{+}_{yij} and h^{-}_{yij} in Eq. (4) represent the closeness of alternative X_y's fuzzy performance rating $\tilde{a}_{yij}$ to the fuzzy positive ideal performance and the fuzzy negative ideal performance, respectively. The degree of optimality of alternative X_y, relative to other alternatives, with respect to each criterion C_{ij} is thus obtained by

$$z_{yij} = \frac{h^{-}_{yij}}{h^{-}_{yij} + h^{+}_{yij}}. \tag{7}$$

Step 2: Determine the positive ideal solution X^{+}_{y} and the negative ideal solution X^{-}_{y} for representing the best possible and the worst possible results of the alternatives respectively.

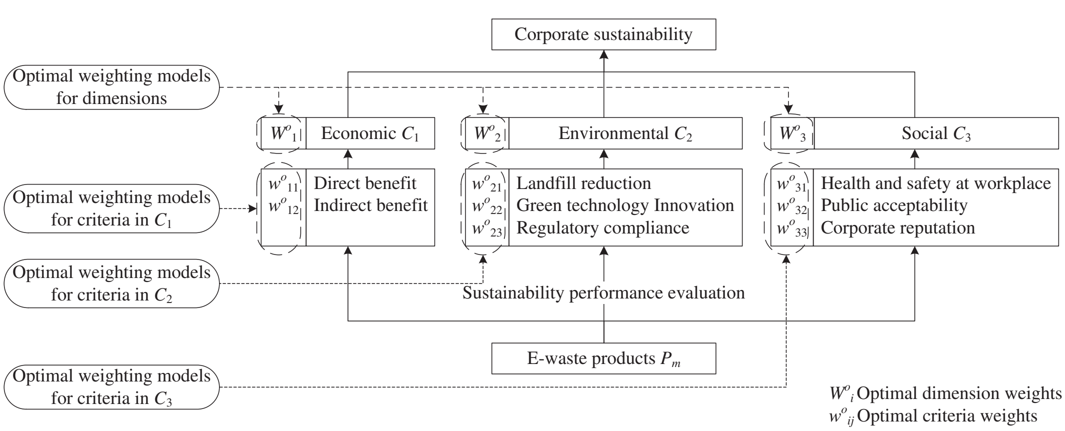

Fig. 3. Optimal weighting of sustainability criteria and dimensions.

The positive and negative ideal solutions consist of the degrees of optimality of the best possible and worst possible alternatives which have the highest and lowest performance ratings on all criteria C_{ij}. Thus, they are given as

$$X_y^+ = \left(z_{11}^+, z_{12}^+, \ldots, z_{ij}^+\right), \quad X_y^- = \left(z_{11}^-, z_{12}^-, \ldots, z_{ij}^-\right) \tag{8}$$

Step 3: Obtain the dimension sustainability score t_{yi} for each alternative X_y under each dimension C_i.

The weighted Euclidean distances between z_{yij} and z_{ij}^+, and between z_{yij} and z_{ij}^- under each dimension are first calculated by

$$d_{yi}^+ = \sqrt{\sum_{j=1}^{g_i} w_{ij}^o \left(d_{yij}^+\right)^2}, \quad d_{yi}^- = \sqrt{\sum_{j=1}^{g_i} w_{ij}^o \left(d_{yij}^-\right)^2}, \tag{9}$$

$$\text{where} \quad d_{yij}^+ = z_{ij}^+ - z_{yij}, \quad d_{yij}^- = z_{yij} - z_{ij}^-. \tag{10}$$

In Eq. (9), w_{ij}^o are the optimal weights for criteria C_{ij}, which are determined by the optimal weighing models to be presented in Section 6.2. The dimension sustainability score t_{yi} of each alternative X_y, relative to other alternatives, is then obtained by

$$t_{yi} = \frac{d_{yi}^-}{d_{yi}^- + d_{yi}^+}. \tag{11}$$

Step 4: Obtain the corporate sustainability score T_y for each alternative X_y for representing its overall contribution to the corporate sustainability performance of the company.

The weighted Euclidean distances between z_{yij} and z_{ij}^+, and between z_{yij} and z_{ij}^- for all the three dimensions are first calculated by

$$\begin{aligned} d_y^+ &= \sqrt{\sum_{i=1}^{3} W_i^o \sum_{j=1}^{g_i} w_{ij}^o \left(d_{yij}^+\right)^2}, \\ d_y^- &= \sqrt{\sum_{i=1}^{3} W_i^o \sum_{j=1}^{g_i} w_{ij}^o \left(d_{yij}^-\right)^2}, \end{aligned} \tag{12}$$

$$\text{where} \quad d_{yij}^+ = z_{ij}^+ - z_{yij}, \quad d_{yij}^- = z_{yij} - z_{ij}^-. \tag{13}$$

In Eq. (12), W_i^o are the optimal dimension weights for the three dimensions C_i, which are determined by the optimal weighing models to be presented in Section 6.3. The corporate sustainability score T_y of the alternative X_y, relative to other alternatives, is then obtained by

$$T_y = \frac{d_y^-}{d_y^- + d_y^+}. \tag{14}$$

The larger the corporate sustainability score, the higher the sustainability contribution of the alternative.

6. The optimal weighting models

As shown in Fig. 3, four sets of optimal weighting models are developed to determine the optimal criteria weights w_{ij}^o for the sustainability criteria C_{ij} and the optimal dimension weights W_i^o for the sustainability dimensions C_i. The development of these models is based on the notion that the optimal weights should reflect the best possible operational condition of the e-recycling company where the e-waste products processed as a whole will have the best overall corporate sustainability performance in terms of the three sustainability dimensions and their associated criteria. As such, the model development begins with the evaluation of the best possible sustainability performance of the e-waste products with respect to each criterion under the company's current operational settings.

6.1. The sustainability performance evaluation of e-waste products

In assessing the best possible performance rating of the e-waste products on qualitative sustainability criteria (as shown in Table 2 and Fig. 3), subjective judgements are to be made based on the company's current operational practice and capacity. To reflect the inherent subjectiveness and vagueness involved, the fuzzy assessment process is used.

To facilitate the subjective assessments using fuzzy numbers, linguistic terms defined in Table 4 are used for assessing the degree to which each e-waste product can best satisfy each sustainability criterion. These linguistic terms are characterized by triangular fuzzy numbers for representing their approximate value range between 0 and 10, denoted as $\tilde{a} = (a_1, a_2, a_3)$, where $0 \le a_1 \le a_2 \le a_3 \le 10$. The intervals of the membership functions used in Table 4 are suggested in Chen and Hwang (1992) for a linguistic variable with a set of five linguistic terms and a value range between 0 and 10.

Using the linguistic terms given in Table 4, the best possible fuzzy performance rating $\tilde{a}_{m\,ij}$ of each e-waste product P_m with respect to each criterion C_{ij} can be assessed. With a given set of criteria weights and dimension weights, the dimension sustainability score t_{mi} of each e-waste product P_m under each dimension C_i and the corporate sustainability score T_m for all three dimensions can be obtained respectively by applying the fuzzy MCDM algorithm given in Eqs. (4)–(14).

6.2. The optimal weighting models for sustainability criteria under each dimension

An e-waste product will normally have different performances on different sustainability criteria under each dimension. For each e-waste product, there exists a set of best criteria weights that will maximize the dimension sustainability score of the product under each dimension. The following model determines this set of best criteria weights for each e-waste product P_m under each dimension C_i by considering the preferred criteria weight ranges given by the company.

Objective:

$$\text{Maximize} \quad t_{mi}(w_{mij}) \tag{15}$$

Subject to:

$$\sum_{j=1}^{g_i} w_{mij} = 1 \tag{16}$$

$$w_{ijl}^{\alpha} \le w_{mij} \le w_{iju}^{\alpha}, \; i = 1, 2, 3. \tag{17}$$

where

Decision variable:

w_{mij} = the best criteria weights of criteria C_{ij}.

Parameters:

w_{ijl}^{α} = the lower bound of the criteria weights for each criterion C_{ij}.

w_{iju}^{α} = the upper bound of the criteria weights for each criterion C_{ij}.

Table 4
Linguistic terms used for assessing sustainability performance of e-waste products.

Linguistic term	Very low (VL)	Low (L)	Mediate (M)	High (H)	Very high (VH)
Membership function	(0, 0, 2.5)	(0, 2.5, 5)	(2.5, 5, 7.5)	(5, 7.5, 10)	(7.5, 10, 10)

The objective function (15) is to maximize the dimension sustainability score $t_{mi}(w_{mij})$ of product P_m, which is obtained by Eqs. (4)–(11) using the to-be-determined best criteria weights w_{mij}. Constraints (16) state that the best criteria weights obtained for the criteria under each dimension are to be normalized to sum to 1. Constraints (17) impose that the best criteria weights generated must lie within the criteria weight ranges specified by the company using the fuzzy pairwise comparison assessment.

The use of Constraints (17) is to ensure that the criteria weights generated by optimal weighting models for recycling activity planning are acceptable to the company. As such, these specified weight ranges are used as constraints for all the optimal weighting models. These weight ranges are specified by the company using the fuzzy pairwise comparison technique.

Based on its business objectives, the company assesses the relative importance of the criteria C_{ij} under each dimension. This assessment process is the same as the fuzzy pairwise comparison process presented in Section 4, but use the linguistic terms defined in Table 5 instead of Table 3. With a fuzzy positive reciprocal matrix produced by the assessment, the fuzzy criteria weights $\tilde{w}_{ij}$ are obtained by Eqs. (2) and (3). These subjective fuzzy weights represent the company's preferences in weighting the criteria; however, they do not necessarily reflect the best possible operational condition of the company. To ensure its acceptance and effectiveness, the optimal weighting model considers the company's preferences on criteria weights as its constraints. To achieve this, we use the concept of α-cut to derive the lower and upper bounds of the company's preferred criteria weights.

By using α-cut on the fuzzy criteria weights $\tilde{w}_{ij}$, a value interval $[w^{\alpha}_{ijl}, w^{\alpha}_{iju}]$ for each criterion can be obtained. For a given α, w^{α}_{ijl} is the average of the lower bounds, while w^{α}_{iju} is the average of the upper bounds of the crisp intervals, resulted from all the α-cuts using the alpha values equal to or greater than the specified value of α. The value interval $[w^{\alpha}_{ijl}, w^{\alpha}_{iju}]$ for each criterion bounds the weight range as Constraints (17). The value of α represents the confidence degree of the decision maker in the fuzzy assessments (Yeh and 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 and Liu, 2003). In this case, a confident decision maker would not consider less possible values embedded in a fuzzy number.

Model (15)–(17) will give each e-waste product a different set of the best criteria weights. From the perspective of the company, the best sustainability contribution of all e-waste products for the criteria under each dimension should ideally be considered as a whole. In other words, the company requires a set of optimal criteria weights that will meet the company's best interests on each dimension in consideration of all e-waste products. As such, the total differences between the best dimension sustainability score of individual e-waste products and their optimal dimension sustainability score under each dimension generated by the optimal criteria weights should be minimized. These differences should be measured by taking their square, as positive and negative differences are equally undesirable. The optimal criteria weights w^{o}_{ij} for the criteria C_{ij} under each dimension C_i can thus be obtained by applying the following optimization model:

Objective:

$$\text{Minmize} \quad \sum_{m=1}^{M}\left[t^{*}_{mi}(w_{mij}) - t_{mi}\left(w^{o}_{ij}\right)\right]^2 \tag{18}$$

Subject to:

$$\sum_{j=1}^{g_i} w^{o}_{ij} = 1 \tag{19}$$

$$w^{\alpha}_{ijl} \le w^{o}_{ij} \le w^{\alpha}_{iju}, \quad i = 1,2,3. \tag{20}$$

where

Decision variable:
w^{o}_{ij} = the optimal criteria weights of criteria C_{ij}.
Parameters:
$t^{*}_{mi}(w_{mij})$ = the best dimension sustainability score of each e-waste product P_m under each dimension C_i generated by Model (15)–(17).
w^{α}_{ijl} = the lower bound of the criteria weights for each criterion C_{ij}.
w^{α}_{iju} = the upper bound of the criteria weights for each criterion C_{ij}.

The objective function (18) is to minimize the sum of the squared differences between individual e-waste products' best dimension sustainability score and their optimal dimension sustainability score under each dimension C_i. The optimal dimension sustainability score $t_{mi}(w^{o}_{ij})$ of each e-waste product P_m under each dimension C_i is generated by Eqs. (4)–(11) using the optimal criteria weights w^{o}_{ij}. Constraints (19) state that the optimal criteria weights obtained for the criteria under each dimension are to be normalized to sum to 1. Constraints (20) impose that the optimal criteria weights generated must lie within the criteria weight ranges specified by the company using the fuzzy pairwise comparison assessment.

6.3. The optimal weighting model for sustainability dimensions

Different e-waste products will contribute differently to the corporate sustainability, due to their different performances on each sustainability dimension. With the same notion and logic as Model (15)–(17), the following model determines the best dimension weights (W_{mi}) for each e-waste product P_m by maximizing its corporate sustainability score $T_m(W_{mi})$:

Table 5
Value fuzzification of pairwise comparison assessments on criteria weights.

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 6
E-waste products of the company.

E-waste product P_m		Description
P_1	Computer	Personal computer, notebook computer, CRT monitor, LCD monitor, PC keyboard, mouse, cables associated with PC system, modem, etc.
P_2	Communication equipment	Server, rack mount cabinet, hub, switch, router, modem/print server, assorted network gear, PABX controller unit, telephone handsets, uninterruptible power supply, etc.
P_3	Battery	Lead acid battery, lithium ion, lithium battery, NiCad battery (sealed/vented), NiMH battery, Alkaline battery, etc.
P_4	Mobile phone	Mobile phone handsets, batteries, chargers, accessories, etc.
P_5	Office electrical equipment	Desktop printer, enterprise printer, photocopier, fax machine, desktop scanner, desktop multifunction printer/scanner, etc.
P_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.

Objective:

$$\text{Maximize} \quad T_m(W_{mi}) \tag{21}$$

Subject to:

$$\sum_{i=1}^{3} W_{mi} = 1 \tag{22}$$

$$W_{il}^{\alpha} \le W_{mi} \le W_{iu}^{\alpha}, \quad i = 1,2,3. \tag{23}$$

The corporate sustainability score $T_m(W_{mi})$ is obtained by Eqs. (4)–(14) using the best dimension weights W_{mi} to be determined by Model (21)–(23).

Similar to Model (18)–(20), the following model determines the optimal dimension weights (W_i^o) by considering the best dimension weights (W_{mi}) of all e-waste products:

Objective:

$$\text{Minimize} \quad \sum_{m=1}^{M} \left[T_m^*(W_{mi}) - T_m\left(W_i^o\right)\right]^2 \tag{24}$$

Subject to:

$$\sum_{i=1}^{3} W_i^o = 1 \tag{25}$$

$$W_{il}^{\alpha} \le W_i^o \le W_{iu}^{\alpha}, \quad i = 1,2,3. \tag{26}$$

$T_m^*(W_{mi})$ is the best corporate sustainability score of each e-waste product generated by Model (21)–(23). The corporate sustainability score $T_m(W_i^o)$ of each e-waste product is obtained by Eqs. (4)–(14) using the optimal dimension weights W_i^o to be determined by Model (24)–(26).

Table 8
Optimal weights for sustainability criteria.

Sustainability dimension C_i	Sustainability criteria C_{ij}	Fuzzy criteria weight $\tilde{w}_{ij}$	Criteria weight range $[w_{ijl}^{\alpha}, w_{iju}^{\alpha}]$	Optimal criteria weight w_{ij}^o
C_1	C_{11}	(0.366, 0.667, 1.098)	[0.516, 0.882]	0.516
	C_{12}	(0.211, 0.333, 0.634)	[0.272, 0.484]	0.484
C_2	C_{21}	(0.432, 0.634, 0.895)	[0.533, 0.764]	0.600
	C_{22}	(0.139, 0.174, 0.229)	[0.157, 0.202]	0.199
	C_{23}	(0.150, 0.192, 0.262)	[0.171, 0.277]	0.201
C_3	C_{31}	(0.356, 0.594, 0.949)	[0.475, 0.772]	0.589
	C_{32}	(0.141, 0.249, 0.431)	[0.195, 0.340]	0.195
	C_{33}	(0.098, 0.157, 0.299)	[0.128, 0.228]	0.216

The optimal criteria weights obtained by Model (18)–(20) and the optimal dimension weights obtained by Model (24)–(26) reflect the best sustainability preference and interests of the company in processing its e-waste products under the current operational settings. They can be used with Eqs. (2)–(14) to obtain the best possible corporate sustainability score for each planning alternative of a new e-waste recycling job. Based on this optimal scoring result, planning decisions of selecting from available job routes can be made to ensure that the selected recycling activities will have the maximum performance (contribution) to the corporate sustainability of the company. Appendix A summarizes the equations used in the sustainable planning approach.

7. An empirical study on sustainable planning of an e-waste recycling job

7.1. Implementation of the sustainable planning approach

To implement the sustainable planning approach for e-waste recycling jobs in an e-recycling company, the company first determines the optimal weights for the three sustainability dimensions and for their associated criteria, based on its current business objectives and operational settings. This involves the following steps:

Step W1: Assess the best possible sustainability performance of e-waste products P_m with respect to criteria C_{ij} under each dimension C_i using fuzzy assessments with the linguistic terms given in Table 4.
Step W2: Specify the preferred weights for the criteria C_{ij} and for the dimensions C_i using fuzzy pairwise comparisons with the linguistic terms given in Table 5.
Step W3: Obtain the fuzzy criteria weights $\tilde{w}_{ij}$ of criteria C_{ij} and the fuzzy dimension weights $\tilde{W}_i$ of dimensions C_i by solving the fuzzy positive reciprocal matrices derived from Step W2 by Eqs. (2) and (3).

Table 7
Performance assessment results of the six e-waste products.

E-waste product P_m	Fuzzy assessment and the best dimension sustainability score											The best corporate sustainability score
	Economic C_1			Environmental C_2				Social C_3				
	C_{11}	C_{12}	t_{m1}^*	C_{21}	C_{22}	C_{23}	t_{m2}^*	C_{31}	C_{32}	C_{33}	t_{m3}^*	T_m^*
P_1	H	H	0.800	H	H	M	0.723	M	H	VH	0.640	0.744
P_2	H	M	0.701	M	M	M	0.502	H	M	M	0.680	0.601
P_3	H	M	0.701	H	H	M	0.723	M	H	H	0.629	0.674
P_4	M	M	0.500	H	H	H	0.771	H	H	M	0.680	0.650
P_5	H	H	0.800	M	M	M	0.502	M	H	H	0.629	0.660
P_6	M	M	0.500	M	M	M	0.502	M	M	M	0.502	0.500

Table 9
Optimal weights for sustainability dimensions.

Sustainability dimension	Fuzzy dimension weight $\tilde{W}_i$	Dimension weight range $[W_{il}^{\alpha}, W_{iu}^{\alpha}]$	Optimal dimension weight W_i^o
C_1	(0.330, 0.443, 0.589)	[0.386, 0.516]	0.463
C_2	(0.262, 0.387, 0.535)	[0.324, 0.461]	0.387
C_3	(0.114, 0.169, 0.294)	[0.142, 0.232]	0.150

Table 10
Planning alternatives of the e-waste recycling job.

Process unit U_p	Alternative A_n	Recycling activity involved r_{pq}	Job route involved
U_1	A_1	r_{11}	1, 2, 3, 4
	A_2	r_{14}	5, 6, 7, 8
U_2, U_3 and U_4	A_3	$r_{21}\rightarrow r_{22}\rightarrow r_{24}\rightarrow r_{43}$	1, 5
	A_4	$r_{21}\rightarrow r_{22}\rightarrow r_{24}\rightarrow r_{44}$	2, 6
	A_5	$r_{21}\rightarrow r_{22}\rightarrow r_{25}\rightarrow r_{31}\rightarrow r_{32}\rightarrow r_{33}\rightarrow r_{41}$	3, 7
	A_6	$r_{21}\rightarrow r_{22}\rightarrow r_{25}\rightarrow r_{31}\rightarrow r_{32}\rightarrow r_{36}\rightarrow r_{41}$	4, 8

Step W4: Determine the preferred or acceptable weight range $[w_{ijl}^{\alpha}, w_{iju}^{\alpha}]$ for each criterion and the weight range $[W_{il}^{\alpha}, W_{iu}^{\alpha}]$ for each dimension by using α-cut on the fuzzy weights obtained at Step W3.

Step W5: Obtain the optimal criteria weights w_{ij}^o and the optimal dimension weights W_i^o by solving Models (15)–(17), (18)–(20), (21)–(23) and (24)–(26), using the weight ranges obtained at Step W4 as constraints.

With the optimal criteria weights and the optimal dimension weights, the following steps help the company select from available job routes and associated recycling activities for a new e-waste recycling job that will have the best corporate sustainability performance:

Step S1: Specify the available job routes and identify the corresponding sets of planning alternatives A_n for a new e-waste recycling job.

Step S2: Assess the relative performance ratings of the alternatives within each set with respect to criteria C_{ij} under each dimension C_i using fuzzy pairwise comparisons with the linguistic terms given in Table 3.

Step S3: Obtain the corporate sustainability score T_n for each alternative A_n using Eqs. (2)–(14) by incorporating the optimal criteria weights w_{ij}^o and the optimal dimension weights W_i^o obtained at Step W5.

Step S4: Select the recycling job route with its corresponding planning alternatives having the highest relative corporate sustainability score.

The sustainable planning approach and its implementation steps described above can be easily implemented using computers. In its actual application to the company described in Section 2, the industrial decision maker has no problem in making assessments as required by Steps W1, W2, S1 and S2. The assessments made at Steps W1 and W2 for obtaining the optimal weights are required only when the operational settings of the company change. The assessments made at Steps S1 and S2 for obtaining the corporate sustainability score are required for each new e-waste recycling job individually. As the required amount of data processing is not great, a solution can be obtained in a short amount of computer time, normally within minutes.

7.2. Sustainable planning of an e-waste recycling job

To illustrate the sustainable planning approach, we use the e-waste recycling job presented in Section 2 as an example. With its six main e-waste products shown in Table 6, the company first conducts Steps W1–W5 to obtain the optimal weights for the three sustainability dimensions C_i and their associated criteria C_{ij} shown in Table 2.

Table 7 shows the best possible performance ratings of the six e-waste products with respect to the eight criteria C_{ij} assessed at Step W1. The preferred fuzzy criteria weights and the preferred fuzzy dimension weights are specified by Steps W2 and W3. The company determines the acceptable weight range for each criterion and for each dimension by specifying an α-cut level of 0.5 at Step W4. Tables 8 and 9 show the results.

The best dimension sustainability score t_{mi}^* of each product P_m under each dimension C_i is computed by solving the optimal weighting models (15)–(17) at Step W5. Table 7 shows the result. The optimal criteria weights w_{ij}^o under each dimension are then obtained by solving Model (18)–(20). By solving Model (21)–(23), the best total corporate sustainability score T_m^* of each e-waste product is obtained and shown in the last column of Table 7. The optimal dimension weights W_i^o are then obtained by solving Model (24)–(26). The last column of Tables 8 and 9 shows the result. The optimal dimension weights shown in Table 9 do reflect the company's current sustainability interests and priorities, which require its recycling jobs having the highest economic sustainability, followed by the environmental and social sustainability.

It is noteworthy that the company's sustainability interests and priorities will change as its operational settings or business objectives change over time. For example, if the company would like the environmental or social sustainability to have more significant influence on future decisions, the company can specify a higher preferred weight for the environmental or social dimension at Step W2.

With the optimal criteria weights and the optimal dimension weights given in Table 9, the company then conducts Steps S1 to S4

Table 11
Relative fuzzy performance ratings of planning alternatives A_1 and A_2.

Alternative A_n	Relative fuzzy performance rating $\tilde{w}_n$		
Economic C_1	C_{11}	C_{12}	
A_1	(0.522, 0.750, 1.045)	(0.366, 0.333, 0.634)	
A_2	(0.185, 0.250, 0.369)	(0.366, 0.667, 1.098)	
Environmental C_2	C_{21}	C_{22}	C_{23}
A_1	(0.500, 0.500, 0.500)	(0.211, 0.333, 0.634)	(0.185, 0.250, 0.369)
A_2	(0.500, 0.500, 0.500)	(0.366, 0.667, 1.098)	(0.522, 0.750, 1.045)
Social C_3	C_{31}	C_{32}	C_{33}
A_1	(0.138, 0.167, 0.208)	(0.221, 0.333, 0.634)	(0.185, 0.250, 0.369)
A_2	(0.678, 0.833, 1.017)	(0.366, 0.667, 1.098)	(0.522, 0.750, 1.045)

Table 12
Relative fuzzy performance ratings of planning alternatives A_3, A_4, A_5, and A_6.

Alternative A_n	Relative fuzzy performance rating $\tilde{w}_n$		
Economic C_1	C_{11}	C_{12}	
A_3	(0.191, 0.426, 0.841)	(0.076, 0.109, 0.170)	
A_4	(0.114, 0.246, 0.500)	(0.076, 0.109, 0.170)	
A_5	(0.093, 0.192, 0.452)	(0.173, 0.297, 0.533)	
A_6	(0.071, 0.136, 0.343)	(0.278, 0.484, 0.784)	
Environmental C_2	C_{21}	C_{22}	C_{23}
A_3	(0.069, 0.083, 0.104)	(0.081, 0.104, 0.142)	(0.084, 0.120, 0.185)
A_4	(0.069, 0.083, 0.104)	(0.085, 0.110, 0.152)	(0.135, 0.187, 0.290)
A_5	(0.339, 0.417, 0.509)	(0.254, 0.354, 0.476)	(0.160, 0.247, 0.410)
A_6	(0.339, 0.417, 0.509)	(0.334, 0.432, 0.557)	(0.233, 0.446, 0.750)
Social C_3	C_{31}	C_{32}	C_{33}
A_3	(0.336, 0.524, 0.789)	(0.084, 0.120, 0.185)	(0.060, 0.099, 0.191)
A_4	(0.163, 0.262, 0.420)	(0.135, 0.187, 0.290)	(0.128, 0.219, 0.394)
A_5	(0.077, 0.107, 0.160)	(0.160, 0.247, 0.410)	(0.152, 0.243, 0.424)
A_6	(0.077, 0.107, 0.160)	(0.233, 0.446, 0.750)	(0.221, 0.439, 0.776)

Table 13
Corporate sustainability scores of planning alternatives.

Alternative A_n	Recycling activity involved r_{pq}	Job route involved	Sustainability score T_n	Ranking
A_1	r_{11}	1, 2, 3, 4	0.484	2
A_2	$\mathbf{r_{14}}$	5, 6, 7, **8**	0.530	1
A_3	$r_{21} \rightarrow r_{22} \rightarrow r_{24} \rightarrow r_{43}$	1, 5	0.398	3
A_4	$r_{21} \rightarrow r_{22} \rightarrow r_{24} \rightarrow r_{44}$	2, 6	0.374	4
A_5	$r_{21} \rightarrow r_{22} \rightarrow r_{25} \rightarrow r_{31} \rightarrow r_{32} \rightarrow r_{33} \rightarrow r_{41}$	3, 7	0.410	2
A_6	$\mathbf{r_{21} \rightarrow r_{22} \rightarrow r_{25} \rightarrow r_{31} \rightarrow r_{32} \rightarrow r_{36} \rightarrow r_{41}}$	4, **8**	0.438	1

to select from the eight available job routes for the e-waste recycling job shown in Fig. 1.

Table 10 shows the two sets of planning alternatives identified at Step S1. At the collection and transportation unit (U_1), one-cost service (r_{11}) and collection points (r_{14}) are the two planning alternatives (A_1 and A_2), each being required by four job routes. After identifying, testing and wiping data for the end-of-life computers (r_{21} and r_{22}), the company can choose between two main streams of operation: offshore processing and onshore processing. This forms four planning alternatives (A_3, A_4, A_5 and A_6) to be processed at the process units U_2, U_3 and U_4. Specifically, for offshore processing alternatives (A_3 and A_4) involving job routes 1, 2, 5, and 6, the company outsources this computer recycling job with a safe chain of custody arrangements (r_{24}) before exporting to overseas downstream partners for recycling (r_{43}) or to developing countries for reuse (r_{44}). For onshore processing alternatives (A_5 and A_6) involving job routes 3, 4, 7 and 8, the company performs in-house recycling processes and resells valuable metals and recovered items in markets (r_{41}). In this case, the end-of-life computers are dismantled and sorted (r_{25}) with all critical components removed (r_{31}) before entering the mechanical processing (r_{32}) phase. A typical mechanical processing phase involves such activities as shredders, magnetic separation, eddy current separation, and density separation. For end-of-life computers, this phase produces metal fractions (such as steel, copper and gold) and residual fractions (such as plastics, glass and wood). As one of the most important flow of materials, plastics need to be recycled, reused or disposed. The company identifies two alternatives (A_5 and A_6) to deal with plastics, which are refining treats (r_{33}) and green recovery method (r_{36}).

The relative performance ratings of the alternatives (A_1 and A_2) and the alternatives (A_3, A_4, A_5 and A_6) are assessed by Step S2. Tables 11 and 12 show the results. The consistency ratio of all the pairwise assessments is less than 0.1, thus meeting the consistency requirement. After conducting Step S3 using the data in Tables 8, 9, 11 and 12, the corporate sustainability score of each alternative, relative to its comparable alternatives, is obtained. As shown in Table 13, alternatives A_2 and A_6 have respectively the highest corporate sustainability performance, compared to other alternatives. This suggests that job route 8 is the choice as it involves both alternatives A_2 and A_6. In Table 13, the selected job route 8 and its recycling activities are indicated in bold.

8. Conclusions

E-recycling companies require performing their e-waste recycling jobs in an economically viable, environmentally friendly, and socially responsible manner to ensure their sustainable development. Although many concepts, frameworks and tools are available to address the sustainability issue, the question of how to integrate sustainability into the operational decisions of a company persists (Hannon and Callaghan, 2011). To fill this important gap in sustainability research, we have presented a new structured approach for incorporating the concept of corporate sustainability into e-recycling companies' regular planning decisions for their e-waste recycling jobs. In its methodological significance, the approach develops a series of optimal weighting models for addressing the important issue of weighting the three dimensions of the corporate sustainability, together with their associated criteria. The concept used for developing optimal weighting models is applicable to other decision problems where the weighting of the sustainability criteria plays an important role. In its practical significance, the approach provides e-recycling companies with a proactive mechanism to ensure that their recycling activities are selected and planned in the best possible way for achieving their corporate sustainability.

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Appendix A

Description and purpose of the equations used in the sustainable planning approach.

Equation number	Description	Purpose
Eq. (1)	Membership functions of a triangular fuzzy number	To facilitate the value fuzzification in the fuzzy assessment process
Eqs. (2) and (3)	The geometric mean method	To obtain the fuzzy criteria weights $\tilde{w}_{ij}$ and the fuzzy dimension weights $\tilde{W}_i$
Eq. (4)	Hamming distance between the fuzzy performance rating and the fuzzy positive/negative ideal performance	To compute the degree of optimality z_{yij} for the performance of each alternative, relative to other alternatives, with respect to each criterion
Eq. (5)	Membership functions of the fuzzy positive/negative ideal performance	
Eq. (6)	Hamming distance between two fuzzy numbers	
Eq. (7)	The relative degree of optimality of an alternative with respect to a criterion	
Eq. (8)	The positive and negative ideal solutions	To identify the alternatives with the best/worst possible degree of optimality
Eqs. (9) and (10)	Weighted Euclidean distance calculation under each dimension	To calculate the dimension sustainability score t_{yi} of each alternative, relative to other alternatives
Eq. (11)	The relative dimension sustainability score	
Eqs. (12)–(14)	Weighted Euclidean distance calculation under all the three dimensions	To calculate the corporate sustainability score T_y of each alternative, relative to other alternatives
Eq. (15)	The objective function of Model (15)–(17)	To obtain the best criteria weights w_{mij} of the sustainability criteria under each dimension
Eq. (16)	Criteria weight normalization under each dimension	
Eq. (17)	Specified value ranges for the best criteria weights as constraints	
Eq. (18)	The objective function of Model (18)–(20)	To obtain the optimal criteria weights w^o_{ij} of the sustainability criteria under each dimension
Eq. (19)	Criteria weight normalization under each dimension	
Eq. (20)	Specified value ranges for the optimal criteria weights as constraints	
Eq. (21)	The objective function of Model (21)–(23)	To obtain the best dimension weights W_{mi} of the three sustainability dimensions
Eq. (22)	Dimension weight normalization	
Eq. (23)	Specified value ranges for the best dimension weights as constraints	
Eq. (24)	The objective function of Model (24)–(26)	To obtain the optimal dimension weights W^o_i of the three sustainability dimensions
Eq. (25)	Dimension weight normalization	
Eq. (26)	Specified value ranges for the optimal dimension weights as constraints	

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