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Sustainable collection center location selection in emerging economy for electronic waste with fuzzy Best-Worst and fuzzy TOPSIS

Muhittin Sagnak [a,*], Yalcin Berberoglu [b], İlker Memis [b], Ogulcan Yazgan [b]

[a] Department of Information Management, Izmir Kâtip Celebi University, Balatcik Kampusu, 35620 Cigli/Izmir, Turkey
[b] Yasar University, Universite Caddesi, No: 37-39, Bornova/Izmir, Turkey

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ABSTRACT

In emerging economies, electronic waste is an important problem, because it negatively affects the health of staff and people, and causes pollution. Moreover, the location of the collection center has a crucial role in sustainable supply chains. Therefore, in this study, a framework was proposed to identify the location of sustainable collection centers for e-waste. The criteria set includes 3 main criteria, and 23 sub-criteria, and 7 different location options. The main criteria cover economic, social, and environmental criteria, which are organized as the Triple-Bottom-Line dimensions. Alternatives are Manisa, Menemen, Gaziemir, Kemalpaşa, Torbalı, Çiğli, and Akhisar. Fuzzy Best-Worst Method (BWM) and Fuzzy TOPSIS methods are used to calculate the weights of criteria and rankings of the alternatives, respectively. Transportation cost was found as the most important criterion for sustainable collection center selection, followed by collection cost, storage/holding cost, land cost, greenhouse gas emissions, energy cost, tax, and investment cost, respectively. Among other alternatives, Çiğli was found as the best alternative for sustainable collection center, followed by Gaziemir, and Manisa. Managerial implications were presented based on the findings.

1. Introduction

Waste management is an important policy for countries (Managi et al., 2014; Ishimura et al., 2021). In waste management literature, one of the most important wastes is electronic waste (e-waste). Electronic waste (e-waste) became one of the greatest problems (Tsydenova and Bengtsson, 2011; Kiddee et al., 2013; Shittu et al., 2021). It receives a great deal of attention in connection with sustainability considerations including economic, social, and environmental aspects. In 2016, the amount of e-waste generated was nearly 45 million tons, 20 percent of which could be collected (Baldé et al., 2017). It is the greatest increasing form of waste (Tsydenova and Bengtsson, 2011; Fetanat et al., 2021; McMahon et al., 2021; Wang et al., 2021), which is also estimated to increase 75 million tons in 2030 (Mohammadi et al., 2021) with regards to environmental effects on the globe. Many useful substances are obtained from recycling of e-waste; however, the hazardous compounds must be processed before they are discarded (Kumar et al., 2017).

There are three types of economies contributing to sustainable development goals with different priorities. Starting countries consider and explore some policies for e-waste, emerging economies have policies and some activities in terms of collection of e-waste, and developed economies have both policies and considerable amount of regulated collection and treatment activities (Huisman et al., 2019a, 2019b).

E-waste is a serious problem especially for emerging economies (Ikhlayel, 2018) because of inadequate management systems and the absence of awareness (Kumar et al., 2017). Emerging economies are those who have policies about e-waste collection and treatment. The main objective of those is to implement, expand, and improve the maturity and efficiency of collection and treatment mechanisms. The important step to be taken is to propose a framework for basic collection and treatment standards and rules for e-waste management (Huisman et al., 2019a).

Many end-of-life items are discarded without classification, or thrown away because of the absence of safety standards in the reprocessing phase of effective waste classifying protocols (Garlapati, 2016). Also, emerging economies may be subject to threats to health resulting from contaminants in e-waste due to the absence of routine and efficient regulations (Frazzoli et al., 2010; Nguyen et al., 2021). There is a lack of sufficient and effective infrastructure for efficient reverse processes for e-waste in developing countries (Azevedo et al., 2017). Thus, end-of-life products

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* Corresponding author.
E-mail address: muhittin.sagnak@ikcu.edu.tr (M. Sagnak).

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are normally stored at house or disposed of directly in landfills (Kazancoglu et al., 2021).

Increasing world population and living standards lead to high consumption of products which requires more natural resources; however, natural resources are limited (Benjamin and Wagner, 2006; Akao and Managi, 2007). This situation creates the obligation of the existence of the reverse production systems (Higashida and Managi, 2014). Besides, political responsibility for the atmosphere has also contributed to sustainability strategies for product recovery. Germany introduced the concept of "life cycle of products responsibility" for industrial firms and became one of the first countries which have legislation on product recovery (Thierry, 1997). Since then, specific regulations have been introduced by several countries. For instance, the Waste Electrical and Electronic Equipment Directive of the European Union has entered into force to increase the recycling of WEEE (2003).

E-waste is stated as all electronic products, which came to its end-of-life and had not been turned to a value for the economy. Because of the materials used, The Basel Convention identifies e-waste as a harmful type of waste. However, the percentage of precious metals in e-waste is over 60%, which is approximately 30 times higher than pollutants (Widmer et al. 2005). It differs from other types of wastes because of its high economic value and negative environmental effects. Rapid changes in technology lead to dramatic increases in the total e-waste amount worldwide. The exact e-waste amount created in the world is undetermined, but studies show that the yearly-generated amount of e-waste is approximately 50–60 million tons. (Menikpura et al., 2014; Baldé et al., 2017). Numerous emerging economies encounter enormous rigors in e-waste management, which is locally-created or imported as used goods. In many emerging economies, especially lower-income countries, a substantial ratio of e-waste is disposed of in unrestrained landfill places. (Nnorom and Osibanjo, 2008; Ikhlayel, 2018). Turkey is one of the developing countries that have faced many problems in controlling e-waste. In Turkey, the proportion of recycled e-waste is about 6%, which is under the world average. (Baldé et al. 2017).

In an attempt to comprehend the severity of e-waste, it is important to establish a systematic framework to identify e-waste management applications in emerging countries. Within this perspective, reverse logistics activities may lead to e-waste collection management. Therefore, proper roadmaps are necessary to handle reverse logistics operations. Within this perspective, the first research question is established as:

RQ1: How can a framework and a guideline for managers and policymakers be developed for e-waste collection?

E-waste is processed and recycled without any categorization in emerging economies (Leader et al., 2018) when compared to developed countries, and hence the usable and desirable components and goods are either burned or destroyed (Needhidasan et al., 2014). For this reason, a comprehensive collection process, which is a vital aspect of reverse logistics, is required to manage economic, social, and environmental issues. Moreover, the location of the e-waste collection center has a crucial role, because if a proper collection center location cannot be specified, then subsequent transactions may suffer.

Within this perspective, this study aims to propose a novel framework for sustainable collection center location selection for e-waste. This study focuses to solve the sustainable collection center location problem by the association of circular economy (CE) and sustainability concepts. The criteria set includes 3 main criteria, and 23 sub-criteria, and 7 different location alternatives. The main criteria cover economic, social, and environmental criteria, which are organized as the Triple-Bottom-Line dimensions. Alternatives are Manisa, Menemen, Gaziemir, Kemalpaşa, Torbalı, Çig -li, and Akhisar. Each alternative was evaluated regarding each criterion to select the best possible one. The fuzzy BWM is utilized to figure out the weights for each criterion, and the fuzzy TOPSIS method is used to find the rankings of the alternatives. The main contribution of this study is to develop a framework e-waste collection center selection by the association of Ce and sustainability concepts. To the best of authors' knowledge, there is no study using the fuzzy BWM method for the e-waste collection center location problem.

In this regard, the second and third research questions of this study can be specified as;

RQ2: Which criteria set should be used for sustainable collection center selection for e-waste?

RQ3: Which solution methods can be used to calculate the weights of criteria, and rankings of the alternatives?

Following the introduction, Section 2 identifies the theoretical background. Section 3 describes the proposed framework, and Section 4 introduces the methodology. Section 5 discusses the case study and the results. Section 6 proposes the implications and discussions, and finally, Section 7 presents the conclusion and possible future research directions.

2. Theoretical background

The section highlights the research areas of the CE and sustainable supply chain management (SSCM). Firstly, the CE was identified briefly, then, SSCM was clarified, and finally, e-waste and e-waste collection center location was represented.

2.1. Circular economy

Pearce and Turner (1989) introduced the concept of CE, which explains economic and environmental concerns primarily in the literature, but the roots of it are based on industrial ecology and environmental economics which stress the benefits of recycling waste materials (Jacobsen 2006, Andersen 2007, Ghisellini et al., 2016). Industrial ecology supports the idea of minimization of resources, generation of less waste, and adoption of green technologies (Andersen, 1997; 1999). CE has benefits for society and the economy as a whole in terms of providing industrial ecology. While reducing the usage of natural resources, it ensures the abatement of harmful residual waste materials for the society and environment and the creation of value for the economy simultaneously.

Since the 1970s, a great amount of research has been undertaken on the idea of the CE focusing on industrial economics and specified certain features of the CE (Geissdoerfer et al., 2017). Ellen MacArthur Foundation (2015) determined the most famous definition of a CE as an economy that can restore itself by an effective design. Webster (2015) specified the fundamental aim of a CE as keeping the highest value of the components and products in the production system. A circular economy instead of a linear production system (take-make-dispose) can be defined as an industrial model that targets to redefine production processes with the idea of using scarce materials and energy repeatedly in the same or other production processes (Korhonen et al., 2018). Understanding the functions of the reverse production systems like recycling, repair, reuse, remanufacturing, refurbishment, and maintenance of the waste flows of materials is crucial to achieving the objectives of CE.

CE approach attempts to explain development by reflecting on potential benefits across society. It includes a progressive differentiation of economic operations from the use of energy, resources, and the nature of the disposal of waste. The circular model, driven by the use of renewable sources, is developing economic, social, and environmental benefits. The principles of CE are: (1) to avoid contamination and waste; (2) to keep goods and items in use; and (3) to preserve natural environments (Ellen MacArthur Foundation, 2015).

CE concept was established to create a more sustainable human society (Sehnem et al., 2019; Kurita and Managi, 2021). Organizations established sustainable activities based on circular economy-based manufacturing processes to provide sustainability by enhancing the circularity of products and natural resources (Kirchherr et al., 2017). There has been increasing attention from researchers and practitioners (Galeano and Rodríguez, 2021; Li and Wang, 2021). This is illustrated by more than 100 peer-reviewed publications published in 2016, in comparison to 30 in 2014 (Geissdoerfer et al., 2017). The CE concept promotes the use of green resources and technology and is introduced as an alternative to the "take, make and dispose" paradigm of the linear economy (Ness, 2008; Dey et al., 2020). In other words, CE is a healing mechanism in which waste pollution and contamination are reduced by reusing, refurbishing, remanufacturing, or recycling practices (Geissdoerfer et al., 2017). It seeks to protect natural resources for the benefit of humanity (Zucchella and Previtali, 2019).

2.2. Sustainable supply chains and a circular economy

Sustainability became a necessity in the policies and strategies of enterprises in consequence of the extinction of natural reserves, resources, and the importance of social issues (Luthra and Mangla, 2018). Stakeholders force organizations to integrate supply chain strategies with sustainability concept to provide interaction between material management and information to enhance the environmental, social, and economic performances (Luthra et al., 2018).

The content of SSCM consists of environmental, social, and economic benefits referring to the Triple Bottom Line approach (Carter and Rogers, 2008). It aims the reduction of resource usage, and negative environmental consequences, and minimization of waste (Sarkis et al., 2011).

SSCM includes circularity concerning closed-loop activities, reverse logistics, and recovery (De Angelis et al., 2018). Reverse logistics is the main pillar of the CE and covers the reverse flow of distribution, remanufacturing, reusing, repairing, recycling, and refurbishing activities (Kazancoglu et al., 2021). Moreover, the CE helps organizations improve environmental and economic sustainability through the integration of forward and reverse logistics, and waste management (Winkler, 2011). Also, the SSCM performance is directly associated with the adaptation capability of the organizations to the CE (Zeng et al., 2017). Furthermore, the CE not only provides the resource utilization and life cycle extension but also designs a sustainable production system in the supply chain; therefore, alignment of SSCM activities with CE practices is important (Genovese et al., 2017). Also, the key point of transformation from traditional to sustainable supply chains require the extension of a life cycle, which can only be achieved by the association of CE and sustainability (De Angelis et al., 2018), because these approaches are mutually supportive (Liu et al., 2018a). Within this perspective, the CE provides the integration of SSCM with an economic system aiming at long-term sustainability (Schrödl and Simkin, 2014).

From this point, this study targets a problem faced in the CE, location selection problem for e-waste collection center, in sustainable supply chains. This study aims to solve the sustainable location selection problem for the collection center by the association of CE and sustainability. Therefore, the criteria list includes criteria based on the Triple Bottom Line approach.

2.3. Sustainable E-waste collection center

E-waste became a very important problem especially for developing countries (Park et al., 2017). Some of the developed countries deliver their generated e-waste to the developing countries since recycling and reprocessing is cheaper and simpler in those (Garlapati, 2016). This creates an opportunity for developing countries to receive usable materials from the disposal of e-waste; however, e-waste cannot be adequately recycled and disposed of; therefore, labeled as the greatest cause of the damage (Heeks et al., 2015; Garlapati, 2016). As a consequence, disposal in unsafe standards and non-classification of electronic waste triggers a lot of harmful chemicals incident throughout disposal and recycling (Park et al., 2017), negatively affects the health of staff and people, and causes pollution (Kellenberg, 2012; Orlins and Guan, 2016; Boubellouta and Kusch-Brandt, 2021).

The e-waste collection is also a critical problem (Park et al., 2017). In emerging economies, e-waste must be deposited in consequence of the absence of sustainable collection and disposal systems, and sufficient recycling infrastructure. Most of the emerging economies are facing problems with e-waste management regarding the illegal collection and reprocessing (Ikhlayel, 2018).

Due to the rapid growth in the amount of e-waste, some regulatory legislation is needed to trigger the transformation process. Regulation on Control of Waste Electrical and Electronic Equipment (WEEE) is published in 2012 in Turkey to deliver information regarding e-waste regulations, the effects of generated waste, and potential initiatives based on extended producer responsibility (EPR) approach. EPR is a policy approach that gives the responsibility of taking back, properly recycling and dispose of the product to its producer after its end-of-life (EoL) to protect the environment from the hazardous substances in wastes based on the polluter pays principle (Kiddee et al., 2013; Li et al., 2013, 2015; Kunz et al., 2018). This legislation aims to coordinate legal and technological recommendations for reducing the volume of e-waste by way of repairing, reusing, recycling, refurbishing, or remanufacturing operations, keep the human health and environment safe, and minimize e-waste (Ozturk, 2015). However, despite of the low e-waste collection rate targets of the regulation, registered collection rates are below the targets. Collection of e-waste is still highly irregular and uncontrolled in Turkey, and a serious problem for human health and the environment. Most of the e-waste is collected by unauthorized persons or institutions, and recycled in primitive ways. Therefore, the collaboration of the stakeholders is a requirement to achieve a systematic collection and recycling system by applying EPR effectively.

In recent years, like other developing markets, Turkey has an e-waste problem, especially in the collection of e-waste. In Turkey, the proportion of recycled e-waste is about 6% that is under the world average (Baldé et al. 2017), which is caused by the absence of a sustainable collection mechanism. Therefore, this study attempts to propose a novel framework for the location of sustainable e-waste collection centers.

The fundamental thought behind the study is that collection is the first step of reverse production systems and reverse logistics systems. Selecting the right collection center provides many advantages regarding economic, environmental, and social aspects. Also, collecting is the first step of collection, sorting, and recycling activities; therefore, if a correct collection center cannot be found, subsequent transactions may suffer.

There are a few amounts of studies dealing with the selection of collection center locations for e-waste. Many studies were multi-criteria decision-making (MCDM) applications; however, some mathematical programming formulations such as mixed-integer linear programming (MILP), or dynamic programming models were also used.

Kannan et al. (2008) used the Analytic Hierarchy Process (AHP) and Fuzzy AHP to select the best location of a collection area in Reverse Logistics Supply Chain Model in India. Queiruga et al., (2008) evaluated different WEEE recycling location alternatives in Spain using PROMETHEE. Kim et al. (2009) used AHP to evaluate the potential of recycling of materials regarding economic and environmental criteria in South Korea. Wäger et al., (2011) used life-cycle assessment (LCA) and Material flow analysis (MFA) to identify the impacts of e-waste collection in Switzerland. Kaya (2012) evaluated the WEEE outsourcing management system in Turkey using Fuzzy AHP. Malik et al. (2015) utilized Graph Theory and Matrix Approach (GTMA) to evaluate e-waste collection center locations in India. An et al. (2015) evaluated the selection process of the effective portfolio for minimization of informal collection and irregular recycling problems of e-waste in China using interval AHP and interval VIKOR methods. Dias et al. (2017) made surveys with 134 Brazilian WEEE recycling companies to develop a systematic approach to WEEE procedures. Dias et al. (2018) analyzed the Australian e-waste recycling scheme using qualitative research. Kumar and Dixit (2019) used fuzzy AHP and VIKOR methods to evaluate the partners for e-waste recycling in India. Kazancoglu et al. (2021) used Grey Prediction Model to forecast the amount of future e-waste, and then propose a sustainable collection center framework to monitor e-waste in Turkey.

Shih (2001) utilized a MILP model for reverse network framework of electronics appliances in Taiwan. Achillas et al. (2012) used multi-objective linear programming to select e-waste equipment transportation media in Greece. Kilic et al. (2015) introduced a novel reverse network design for electronical waste in Turkey using the MILP model. Aras et al. (2015) worked on a MILP model to evaluate the optimal recycling locations in Turkey. Ayvaz et al. (2015) used stochastic programming to develop a reverse network framework for e-waste in Turkey. Coelho and Mateus (2017) introduced the capacitated plant location model using MILP in Brazil. Alegoz and Kaya (2017) used dynamic programming to provide optimization for collection center profits and dispatching fees in Turkey. Tian et al (2018) developed a minimum distance and maximum flow (MDMF) algorithm to identify the e-waste geographical transfers in China. Kusakci et al. (2019) worked on a fuzzy MILP model for optimizing reverse network design for end-of-life (EoL) vehicles in Turkey. Messmann et al. (2019) used the MILP model for WEEE reverse network design in Europe. de Aquino et al. (2021) used mathematical programming for locating the e-waste collection center to minimize transportation and opportunity costs.

Table 1 represents the related past studies.

3. Proposed framework

In this part, a novel framework is developed to present the flow of the study for sustainable collection center location selection. The criteria list includes 3 main criteria, and 23 sub-criteria, and 7 different location alternatives. The main criteria cover economic, social, and environmental criteria, which are organized as the Triple-Bottom-Line dimensions. Alternatives are Manisa, Menemen, Gaziemir, Kemalpaşa, Torbalı, Çiğli, and Akhisar. Each alternative was evaluated according to respective criteria to select the best possible one.

Based on a literature review, the proposed 23 criteria are validated with two academics, two industry, and one governmental expert. The academic experts include electronics engineering and environmental engineering professors. The industrial experts are from supply chain managers in the electronic industry. These mentioned experts have experience in this sector, more than 15 years. The governmental expert is selected from the Ministry of Commerce. The criteria list was discussed with these experts through interviews. After the validation stage, the fuzzy Best-Worst Method is applied to prioritize the respective criteria weights, whereas the fuzzy TOPSIS method is applied to rank the alternatives. The reason of hiring fuzzy logic is its capability to deal with the uncertainties and vagueness inherent in decision-making process (Zadeh, 1965). The reason to use fuzzy BWM is that it needs fewer comparisons than in Analytic Hierarchy Process or

Table 1
Related literature.

Author(s)	Objectives	Method
Shih, 2001	Developing a reverse network design for electronics appliances in Taiwan	MILP
Kannan et al., 2008	Finding the best location of a collection center for the tyre manufacturing industry under the Reverse Logistics concept in India.	AHP, fuzzy AHP
Queiruga et al., 2008	Evaluating different WEEE recycling location alternatives in Spain	PROMETHEE
Kim et al., 2009	Assessing the potential of recycling of materials regarding economic and environmental criteria in South Korea.	AHP
Wäger et al., 2011	Identifying the effects of electronical waste collection in Switzerland	MFA and LCA
Kaya, 2012	Evaluating the WEEE outsourcing management system in Turkey.	Fuzzy AHP
Achillas et al., 2012	Selecting e-waste equipment transportation media in Greece	Multiple-objective linear programming
Kilic et al., 2015	Introducing a novel reverse network design for electronical waste in Turkey	MILP
Malik et al., 2015	Evaluating e-waste collection center locations in India	GTMA
An et al., 2015	Evaluating the selection process of an effective portfolio for minimization of informal electronical waste recycling and collection problem in China	Interval AHP, interval VIKOR
Aras et al., 2015	Evaluating the optimal recycling locations in Turkey	MILP
Ayvaz et al., 2015	Developing a reverse network design for electronical waste in Turkey	Stochastic programming
Coelho and Mateus, 2017	Introducing a capacitated plant location model in Brazil	MILP
Alegoz and Kaya, 2017	Maximizing the profit of collection center and providing the optimization for dispatching fees in Turkey	Dynamic programming
Dias et al., 2017	Developing a systematic approach for WEEE procedures in Brazil	Survey
Tian et al., 2018	Identifying the electronical waste geographical transfers in China	Minimum distance and maximum flow (MDMF) algorithm
Dias et al., 2018	Examining the Australian electronical waste recycling scheme	Qualitative Research
Kusakci et al., 2019	Optimizing the reverse network design for EoL vehicles in Turkey	Fuzzy MILP
Messmann et al., 2019	Developing WEEE reverse network design in Europe	MILP
Kumar and Dixit, 2019	Evaluating the partners for e-waste recycling in India	Fuzzy AHP, VIKOR
Kazancoglu et al., 2021	Predicting the amount of future e-waste, and proposing a sustainable collection center framework to monitor e-waste in Turkey	Grey Prediction Model
de Aquino et al., 2021	Developing a model for locating the e-waste collection center	Mathematical Model

Analytic Network Process, because it is a vector-based method. Since there are fewer comparisons, the solution can be obtained in less time with less complexity. The reason to use fuzzy TOPSIS is its ability to rank a set of alternatives with respect to conflicting criteria.

The proposed framework is represented in Fig. 1.

Table 2 shows the criteria set. It shows the main criteria, and related sub-criteria, respectively.

In the next section, fuzzy set theory, fuzzy Best-Worst, and fuzzy TOPSIS techniques were introduced.

4. Methodology

Multi-criteria decision-making (MCDM) methods are some of the best methods in dealing with decision-making problems. These methods can be implemented in different areas such as engineering, supply chain management, logistics, production, healthcare, etc. Many researchers confirmed that MDCM methods are successful in solving complex multi-criteria problems. MCDM deals with selecting the best alternative among various potential alternatives according to various criteria or attributes.

4.1. Fuzzy sets theory

The decisions include uncertainties owing to the vagueness in decision-making process. In an attempt to deal with uncertainties, fuzzy set theory was introduced by Zadeh (1965). The theory helps decision-makers minimize subjectivity and vagueness.

A fuzzy set is called a group of objects with continuity of grades. Among options, in this paper, triangular fuzzy numbers indicated as l_{ij}, m_{ij}, u_{ij} were used.

4.2. Fuzzy Best-Worst method

For weighting the criteria, the most commonly used methods are AHP, and Analytic Network Process (ANP). There is also a comparatively newer method, Best Worst Method (BWM), which was introduced by Rezaei (2015). BWM determines the weights of deci-

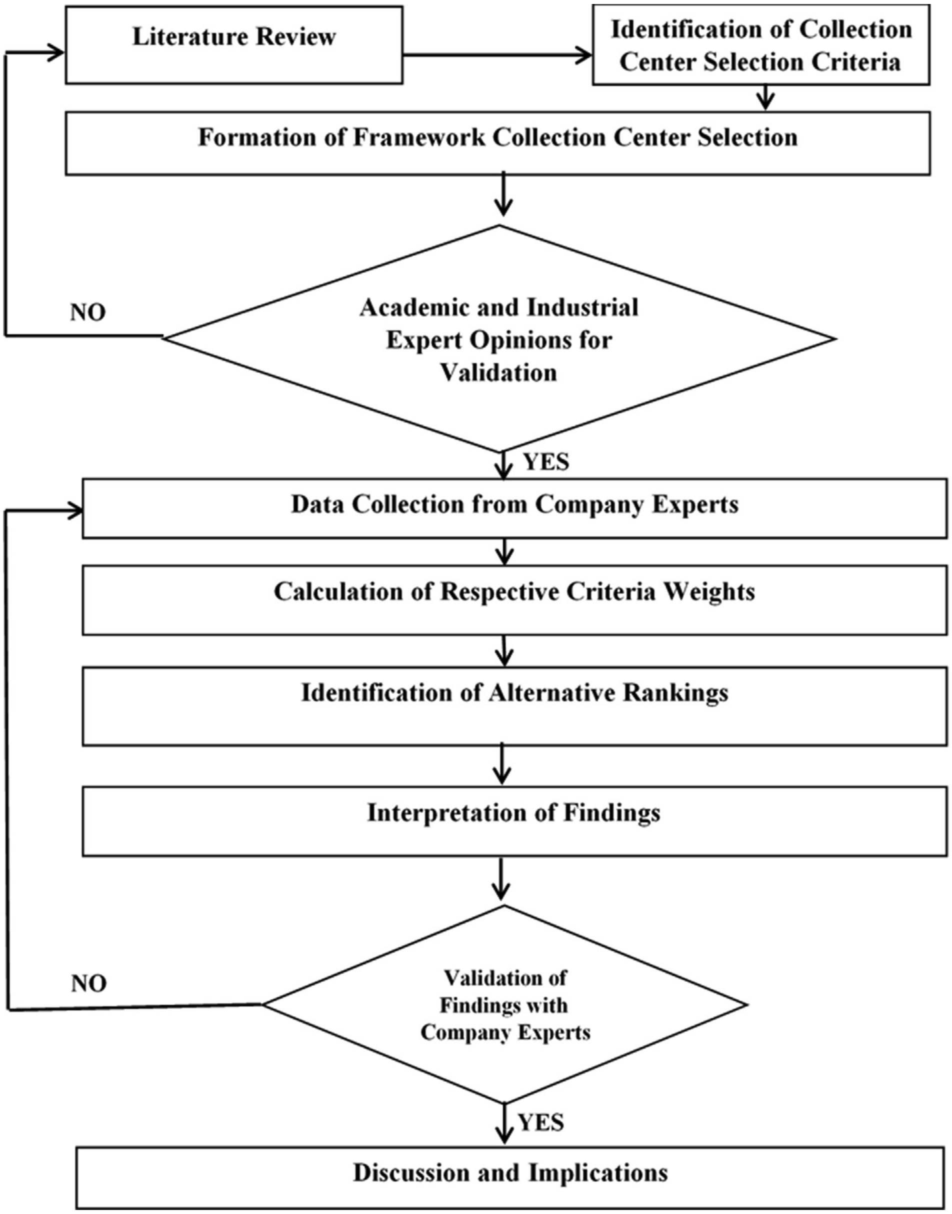

Fig. 1. The proposed framework.

Table 2
Criteria set.

Criteria	References
Economic	
Land Cost	Kannan et al., 2008; Queiruga et al., 2008; Ayvaz et al., 2015; Malik et al., 2015; Kumar et al., 2020
Storage/Holding Cost	Tagaras and Zikopoulos, 2008; Malik et al., 2015
Transportation Cost	Bloemhof-Ruwaard et al., 1996; Kannan et al., 2008; Achillas et al., 2012; Gołebiewski et al., 2013; Ayvaz et al., 2015; Coelho and Mateus, 2017; Kumar et al., 2020
Collection Cost	Sangwan, 2017; Kusakci et al., 2019
Energy Cost	Queiruga et al., 2008; Kumar et al., 2020
Tax	Kannan et al., 2008; Malik et al., 2015; Kumar et al., 2020
Personnel Cost	Kannan et al., 2008; Queiruga et al., 2008
Investment Cost	Temur et al., 2014; Coelho and Mateus, 2017; Sangwan, 2017; Kheybari et al., 2019
Operation Cost	Temur et al., 2014; Malik et al., 2015; Sangwan, 2017; Kheybari et al., 2019; Kumar et al., 2020
Social	
Generating Job Opportunities	Santibañez-Aguilar et al., 2014; Ozceylan et al., 2016; Kheybari et al., 2019; Kumar et al., 2020
Providing Industrial Development	Ozceylan et al., 2016; Kheybari et al., 2019
Work Safety	Kheybari et al., 2019
Government Support Degree	Santibañez-Aguilar et al., 2014; Essaadi et al., 2019; Kheybari et al., 2019; Zhang et al., 2019
Community Engagement	Liu et al., 2018b
Education and Qualification	Kheybari et al., 2019
Society Benefits	Kheybari et al., 2019; Kumar et al., 2020
Environmental	
Connection with City Centers	Kumar et al., 2020
Proximity to inhabited areas	Queiruga et al., 2008
Greenhouse Gas Emissions	Kannan et al., 2008; Agrawal et al., 2016; Kheybari et al., 2019; Kumar and Dixit, 2019
Pollution Prevention and Control	Chang and Chung, 2000; Agrawal et al., 2016; Kumar and Dixit, 2019
Effect on Protected Areas	Kheybari et al., 2019
Proximity to Suppliers	Kannan et al., 2008; Temur et al., 2014; Malik et al., 2015
Proximity to Customers	Kannan et al., 2008; Temur et al., 2014; Malik et al., 2015

sion criteria by comparing the most important criterion with others, and the other decision criteria with the least important criterion.

In this study, BWM is selected, because the method needs fewer comparisons than in AHP or ANP. After all, BWM is a vector-based MCDM method. Since there are fewer comparisons, the solution can be obtained in less time with less complexity. Moreover, the BWM method uses a mathematical model; therefore, it is more reliable compared to other methods. BWM has five steps to perform for weighting the decision criteria.

Step 1: Define a decision criterion set $\{c_1, c_2, \ldots, c_n\}$.

Step 2: Define the criteria that have the highest importance and the lowest importance and create a set for each. Criteria with the highest importance and the lowest importance can be represented as c_B and c_W, respectively.

Step 3: Compare the most important criterion with each other criterion. Since decision-makers use linguistic statements, these statements should be converted to fuzzy numbers. These fuzzy pairwise comparisons should be ranked between 1 and 9 for each judgment. These ranks are the force of the most important criterion over the other criteria. Applying this step will lead to the Best-to-Others vector. Best-to-Others vector can be expressed as $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn},)$. Since A_B is a fuzzy vector, a_{Bj} represents the fuzzy force of the most important criterion over criterion j. For example, $a_{BB} = (1, 1, 1)$.

Step 4: Compare each criterion with the least important criterion. Similarly, linguistic statements of decision-makers should be converted to fuzzy numbers and compare the decision criteria. The pairwise comparison should be ranked between 1 and 9, in which the values are a force of each criterion over the least important criterion. This step will lead to the Others-to-Worst vector, which can be expressed as $A_W = \left(a_{1W}, a_{2W}, \cdots, a_{nW}\right)^T$. Since A_W is a fuzzy vector, a_{iW} represents the fuzzy force of criterion *j*over the least important criterion. For example, $a_{WW} = (1, 1, 1)$.

Step 5: Calculate the optimal fuzzy weights $(w_1^*, w_2^*, \ldots, w_n^*)$. Each criteria's optimal fuzzy weights are $w_B/w_j = a_{Bj}$and $w_j/w_W = a_{jW}$ for each pair. These should determine the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all *j* and all *j* values should be written into minimization model.w_B, w_W and w_j are fuzzy triangular numbers. All variables should be 0, or greater than 0. Sum of the weights should be exactly 1. Following mathematical model will be created by using these constraints.

$$\text{Minimize } \max\left\{\left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right|\right\}$$

$$s.t.\begin{cases} \sum_{j=1}^{n} R\left(w_j\right) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ l_j^w \geq 0 \\ j = 1, 2, \cdots, n \end{cases}$$

$$w_B = \left(l_B^w, m_B^w, u_B^w\right), w_W = \left(l_W^w, m_W^w, u_W^w\right), w_j = \left(l_j^w, m_j^w, u_j^w\right)$$

Suppose that this model can be modified as the following constrained mathematical model;

Minimize ξ

$$s.t.\begin{cases} \sum_{j=1}^{n} R\left(w_j\right) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ \left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi \\ \left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi \\ l_j^w \geq 0 \\ j = 1, 2, \cdots, n \end{cases}$$

$$\xi = \left(l^\xi, m^\xi, u^\xi\right)$$

It can be supposed that $\xi^* = (k^*, k^*, k^*)$ and $k^* \leq l^\xi$ when $l^\xi \leq m^\xi \leq u^\xi$. Then, the mathematical model can be transformed into;

Minimize ξ

$$s.t.\begin{cases} \sum_{j=1}^{n} R(w_j) = 1 \\ l_j^w \leq m_j^w \leq u_j^w \\ \left| \frac{l_B^w, m_B^w, u_B^w}{\left(l_j^w, m_j^w, u_j^w\right)} - (l_{Bj}, m_{Bj}, u_{Bj}) \right| \leq (k^*, k^*, k^*) \\ \left| \frac{\left(l_j^w, m_j^w, u_j^w\right)}{\left(l_W^w, m_W^w, u_W^w\right)} - (l_{jW}, m_{jW}, u_{jW}) \right| \leq (k^*, k^*, k^*) \\ l_j^w \geq 0 \\ j = 1, 2, \cdots, n \end{cases}$$

By solving the mathematical model, optimal fuzzy weights (w_1^*, w_2^*, …, w_n^*) can be obtained.

4.3. Fuzzy TOPSIS

One of the most powerful decision-making methods is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking the various options. It was introduced by Hwang and Yoon (1981), and then developed by Yoon (1987), and Hwang et al. (1993). TOPSIS is a multidimensional decision-making method dealing with x-points in y-dimensional space.

The aim of TOPSIS method is to find the rankings of the different options. The best option was represented as a point that has the largest geometric distance to the negative ideal solution and has the smallest distance to the positive ideal solution. The steps of the fuzzy TOPSIS method are as follows:

Step 1: Define a valuation matrix be formed of x options, and y criteria, with the junction of each option and each criterion given as $x_{ij} = (l_{ij}, m_{ij}, u_{ij})$. The matrix, $(x_{ij})_{xxy}$. u_j^*occurs.

Step 2: Normalize the matrix $(x_{ij})_{xxy}$ to the form of $R = (r_{ij})_{xxy}$, using the normalization method;

For Benefit Criteria: $r_{ij} = \left(\frac{l_{ij}}{u_j^*}, \frac{m_{ij}}{u_j^*}, \frac{u_{ij}}{u_j^*}\right)$ and $u_j^* = \max(u_{ij})$

For Cost Criteria: $r_{ij} = \left(\frac{l_j^-}{l_{ij}}, \frac{l_j^-}{m_j^*}, \frac{l_j^-}{u_{ij}}\right)$ and $l_j^* = \min(l_{ij})$

Step 3: Compute the fuzzy weighted normalized decision matrix.

$$v_{ij} = r_{ij} * w_j^*$$

Step 4: Find fuzzy positive (A^*) and fuzzy negative (A^-) ideal solutions.

$$A^* = (v_1^*, v_2^*, \cdots, v_n^*), \text{where} v_j^* = \max\{v_{ij3}\}$$

$$A^- = (v_1^-, v_2^-, \cdots, v_n^-), \text{where} v_j^- = \min\{v_{ij1}\}$$

Step 5: Find the distances of each option from the Negative Ideal Solution (A^-), and Positive Ideal Solution (A^*).

$$d(x, y) = \sqrt{\frac{1}{3} * \left[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2\right]}$$

Distance from (A^*);
$d_i^* = \sum_{j=1}^{n} d_{ij}$, for all i = 1, 2, …, n
Distance from (A^-);
$d_i^- = \sum_{j=1}^{n} d_{ij}$, for all i = 1, 2, …, n
Step 6: Calculate the harmony to the worst condition.

$$C_i^* = \frac{d_i^-}{d_i^- + d_i^*}$$

Step 7: Rank the options.

However, there is a rank reversal problem that TOPSIS can cause. Rank reversal phenomenon is that the relative rankings of alternatives can be rearranged when an alternative is included or excluded. Total rank reversal, which states a complete change of ranking of the alternatives, even occurs with the inclusion or exclusion of an alternative from the process. To overcome this problem, some studies propose absolute normalization with the use of two fictional alternatives. One of the fictional alternatives should contain 0 for all its values, and the other fictional alternative should contain the maximum value in the decision matrix for all its values. By this method, rank reversal phenomenon can be overcome (García-Cascales and Lamata, 2012; de Farias Aires and Ferreira, 2019).

5. Case study

This paper considers the implementation, which was conducted in 10 companies from the electronics industry located in Izmir, Turkey. The main aim is to understand the selection process of sustainable collection center location for e-waste. The criteria set includes 3 main criteria, 23 respective sub-criteria, and 7 different location alternatives. The main criteria cover economic, social, and environmental criteria, which are organized as the Triple-Bottom-Line dimensions. Alternatives are Manisa, Menemen, Gaziemir, Kemalpaşa, Torbalı, Çiğli, and Akhisar. Each alternative was evaluated concerning each criterion to select the best one. The reasons to evaluate these alternatives are; 1) None of them are located in the city center, and 2) They all contain industrial zones.

In the data collection process, data were gathered through pairwise comparisons. These comparisons are conducted with the permission and approval of the Board of Directors. Large-scale

Table 3
Information about participants.

Experts	Position	Total Work Experience in Years	Experts	Position	Work Experiences (Year)
1	Supply Chain Manager	21	16	Supply Chain Vice Manager	10
2	Supply Chain Manager	18	17	Supply Chain Vice Manager	9
3	Supply Chain Manager	17	18	Supply Chain Vice Manager	12
4	Supply Chain Manager	18	19	Supply Chain Vice Manager	13
5	Supply Chain Manager	14	20	Supply Chain Vice Manager	11
6	Supply Chain Manager	16	21	Purchasing Manager	13
7	Supply Chain Manager	16	22	Purchasing Manager	14
8	Supply Chain Manager	17	23	Purchasing Manager	12
9	Supply Chain Manager	19	24	Purchasing Manager	19
10	Supply Chain Manager	17	25	Purchasing Manager	18
11	Supply Chain Vice Manager	12	26	Purchasing Manager	16
12	Supply Chain Vice Manager	14	27	Purchasing Manager	10
13	Supply Chain Vice Manager	13	28	Purchasing Manager	9
14	Supply Chain Vice Manager	11	29	Purchasing Manager	11
15	Supply Chain Vice Manager	11	30	Purchasing Manager	13

Table 4
The weights of main criteria.

Weights	L	M	U
Economic	0.405824	0.608736	0.608736
Social	0.12682	0.157821	0.202912
Environmental	0.202912	0.27055	0.304368

group decision-making has been adopted. Thirty authorities carried out pairwise comparisons. Table 3 presented information about participants in detail.

The proposed framework and criteria set are generic, and applicable to similar studies where sustainable collection center location selection is studied; however, the results are unique and shall not be generalized.

Before the calculations of weights for the main criteria, the best and worst criterion was selected as Economic, and Social, respectively. The fuzzy weights of the main criteria can be shown in Table 4. These weights were found by applying the step-by-step formation of Fuzzy BWM.

Moreover, before the calculations of weights for sub-criteria, the best and worst criterion was selected as Transportation Cost, and Operations Cost for Economic main criterion, Generating Job Opportunities, and Community Engagement for Social main criterion, and finally, Greenhouse Gas Emissions, and Effect on Protected Areas for Environmental main criterion, respectively. The fuzzy weights of the sub-criteria can be shown in Table 5. These weights were found by applying the step-by-step formation of Fuzzy BWM.

Table 5
The weights of sub-criteria.

Criteria	L	M	U
Land Cost	0.030546	0.069198	0.069198
Storage / Holding Cost	0.034287	0.077672	0.077672
Transportation Cost	0.055885	0.125741	0.125741
Collection Cost	0.035586	0.082198	0.083103
Energy Cost	0.029116	0.060978	0.061649
Tax	0.029116	0.060978	0.061649
Personnel Cost	0.028053	0.05762	0.05762
Investment Cost	0.029116	0.060978	0.061649
Operation Cost	0.021747	0.046132	0.047979
Generating Job Opportunities	0.02143	0.040002	0.051431
Providing Industrial Development	0.012532	0.022014	0.028304
Work Safety	0.012532	0.022014	0.028304
Government Support Degree	0.012027	0.021351	0.028865
Community Engagement	0.007189	0.011562	0.018193
Education and Qualification	0.013007	0.023553	0.030282
Society Benefits	0.0135	0.0252	0.0324
Connection with City Centers	0.017813	0.033161	0.037716
Proximity to inhabited areas	0.017813	0.033161	0.037716
Greenhouse Gas Emissions	0.03419	0.068381	0.076928
Pollution Prevention and Control	0.021539	0.043077	0.048462
Effect on Protected Areas	0.0119	0.020929	0.027082
Proximity to Suppliers	0.021539	0.043077	0.048462
Proximity to Customers	0.021539	0.043077	0.048462

According to Table 4, the most important main criterion for sustainable collection center selection was found as economic, followed by environmental, and social main criteria, respectively. Analysis of the results demonstrated that economic criteria have a total of most likely 60% importance weight. The remaining most likely 40% is affected by social, and environmental criteria.

According to Table 5, the most important criterion for sustainable collection center selection was found as transportation cost, followed by collection cost, storage/holding cost, land cost, greenhouse gas emissions, energy cost, tax, and investment cost, respectively. Analysis of the results demonstrated that among 23 sub-criteria, transportation cost, collection cost, storage/holding cost, land cost, energy cost, tax, and investment cost have a total most likely 53% importance weight.

Table 6 shows the rankings of different locations near Izmir.

According to Table 6, Çiğli is the best solution for a sustainable collection center, followed by Gaziemir, and Manisa. The reason why this result comes out is they are the closest industrial zones to the city center.

The findings were validated through in-depth interviews conducted with the same company experts who participated the data collection process. The findings were indicated in line with the expectations of these experts.

In the following part, discussions, and implications are given based on obtained results.

6. Discussions & implications

This study considers the e-waste collection center location problem in sustainable supply chains. Since the collection is the first step of reverse production and logistics systems, accurate collection center provides many advantages from the point of economic, social, and environmental aspects. In this respect, the e-waste collection center location problem is solved through the association of CE and sustainability. The findings of this study are further developed with managerial implications, supported by past studies.

The use of smart vehicles may decrease transportation cost, which is found as the most important criterion for a sustainable collection center location problem. This is in accordance with the contributions of Esmaeilian et al. (2018), who claimed that intelligent vehicle systems provide better monitoring and data transfer in e-waste collection.

Moreover, driverless cars enable organizations to reduce staff costs, ensure time optimization, and provide safe transportation in e-waste collection. This is parallel with the identifications of Hasan et al. (2020), who determined that driverless cars consider environmental concerns through innovative and safe transportation.

Furthermore, to provide a reduction in the number of traveled distance and trips, and, traffic jams, delays, and CO_2 emissions, smart routing may provide route optimization for e-waste collection. This is in line with the statements of Hrabec et al. (2019), who claimed that smart routing ensures routing optimiza-

Table 6
Alternative rankings.

Relative Closeness	d^*	d-	C^*	Rank
Manisa	0.129613	0.092537	0.416554	3
Menemen	0.138955	0.082602	0.372824	5
Gaziemir	0.083093	0.129173	0.608545	2
Kemalpaşa	0.130528	0.093008	0.416076	4
Torbalı	0.141702	0.069717	0.329756	7
Çiğli	0.08169	0.136876	0.626247	1
Akhisar	0.130105	0.076994	0.371776	6

tion for waste collection systems. Besides, radio frequency identification (RFID) and the global positioning system (GPS) may permit routing optimization through tracking transactions which are in line with the implications of Kazancoglu et al. (2021).

Also, collection costs may decrease through big data management. Smart planning enables sustainable solutions through decreasing collection costs for e-waste. This is parallel with the representations of Babar and Arif (2017), who recommended the use of smart planning through big data management to consider cost limitations.

The distance to the urban area and the development level of the districts affected the outcomes. As it can be seen in Table 6, Torbalı and Akhisar are found as the worst alternatives since they have the longest distance to the urban area. Most of the electronic wastes are kept by households in their houses or directly disposed of without being separated from other wastes. As a result of this situation, transportation and collection costs are increasing, which are two of the most important criteria.

The main reasons that Çiğli is the best alternative among all are the lowest land cost, investment cost, and staff cost. Gaziemir is the second-best alternative because it has the best connection with an urban area. Besides, the education and qualification of the staff in Gaziemir are the highest among all alternatives.

Finally, Gaziemir has tax advantages compared to other alternatives; this is because the tax levels are lower in the industrial free zone. However, since this tax advantage does not take precedence over other important criteria such as transportation, and collection costs, Gaziemir was not found as the best alternative. Transportation cost and distances, and collection cost play a greater role than tax levels in the decision-making process.

For policymakers perspectives, following implications can be developed.

The governments should force the Extended Producer Responsibility-related legislations to decrease the amount of electronic waste. Through this legislation, the organizations take the responsibility, fully or partially, of end-of-life products. Also, governmental incentives may be given to the electronics producer organizations to improve the design of the products according to the EPR considerations.

The governments and local bodies should develop a set of standards for supporting the e-waste collection mechanism. This is in line with the implications of Kumar et al. (2020), who stated that policy makers should propose the regulations based on the sustainable considerations.

The policy makers can also regulate the guidelines about collection center locations. The proposed framework can be used for both new collection center locations, and assessing the performance level of existing collection centers.

7. Conclusion

E-waste is a critical global problem in waste management and receives high attention in connection with sustainability considerations including environmental, social, and economic aspects (Baldé et al., 2017). It is, especially the collection of it, an increasingly serious issue in Turkey as other emerging economies over the years. Within this perspective, the main objective of this study is to develop a novel framework for sustainable collection center location selection for e-waste by the association of CE and sustainability concepts.

This study focuses on a problem, e-waste collection center location problem. The criteria set contains 3 main criteria, 23 sub-criteria, and 7 different sustainable collection center location alternatives. The main criteria include economic, social, and environmental criteria, which are organized as the Triple-Bottom-Line dimensions. Alternatives are Manisa, Menemen, Gaziemir, Kemalpaşa, Torbalı, Çiğli, and Akhisar. Each alternative was evaluated with regards to each criterion to select the best one.

The fuzzy Best-Worst Method is used to compute the weights for each criterion, and the fuzzy TOPSIS method is used to calculate the rankings of the different options. It has been the first time that Fuzzy BWM method is used for collection center decision-making process. The main contribution of this study is to develop a framework e-waste collection center selection by the association of Ce and sustainability concepts.

The most vital criterion for sustainable collection center selection was found as transportation cost, followed by collection cost, storage/holding cost, land cost, greenhouse gas emissions, energy cost, tax, and investment cost, respectively. Among other alternatives, Çiğli was found as the best alternative for sustainable collection center, followed by Gaziemir, and Manisa.

This study considers an implementation in Turkey, an emerging economy, which can be identified as the limitation of this study. The framework should be implemented in other emerging economies. Another limitation is that since the data collection process includes subjective judgments, the findings of this study is unique and specific; and therefore, cannot be generalized.

Further possible research may focus on the implementation of the proposed framework in other emerging economies. In addition, this study considers a collection center location selection in a small area. To form a bigger structure for e-waste collection center selection, the application can be made in a larger area. Moreover, future possible research may include the use of DEMATEL technique to investigate the causal relationship between the e-waste collection center selection criteria.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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