Technology in Society 71 (2022) 102100

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

IoT based sustainable smart waste management system evaluation using MCDM model under interval-valued q-rung orthopair fuzzy environment

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ARTICLE INFO

Keywords:
Waste management
IoT
Uncertainty
MCDM

ABSTRACT

Waste management has a crucial role for human health and well-being. The novel waste collection technologies, information and communications technologies (ICTs) and Internet of Things (IoT) play important roles in the field of municipal waste management considering sustainability aspects such as economic, social and environmental. Considering future development and the sustainability of the environment, selecting the most appropriate smart technology to manage waste collection may have long-term impacts. This paper aims to evaluate the smart waste collection systems based on IoT with respect to uncertain parameters by applying modified Entropy measure and Multi-Criteria Decision Making (MCDM) method for the local municipal in Istanbul. To deal with uncertainty and vagueness associated with the decision-making process Interval-valued q-rung orthopair fuzzy sets (IVq-ROFSs) is employed in the process. As a result, the waste collection system developed using RFID, GIS and GPRS is selected as the most appropriate smart waste collection system based on IoT for municipal. To validate results and prove robustness of the proposed method in the decision making, Sensitivity and Comparative analysis are conducted at the end of the study.

1. Introduction

Waste management plays important role with the rapid population growth and industrialization due to increasing product consumption [1, 2]. Waste management consists of the collection, processing, transportation and disposal of wastes and it is important for both public health, aesthetic and environmental protection. However, traditional waste collection methods have become inefficient and costly due to the increase in the amount of waste considering population growth and urbanization. In the traditional waste management system, waste collection trucks and drivers collect waste by following a predefined route [3,4]. Thus, while trucks move to half-filled containers by collecting garbage without knowing filling level of garbage in the containers, the full containers can wait for the next collection period. This situation causes loss of time in the system, increases fuel consumption and excessive use of resources. Not detecting a fire or displacement in the containers are also other disadvantages of traditional waste collection. Further, air pollution due to the emission of dangerous gases and greenhouse gas CO2 (carbon dioxide) from the exhausts of collection vehicles is increasing day by day [5].

In order to make the current system better and prevent the drawbacks mentioned above, the technological innovations and advances have been implemented to collect the waste regularly and reduce effect of the wastes for the environment and air [5]. Therefore, smart waste management has come to the fore all over the world to increase operational efficiency with the developments in technology and different methods have been proposed for the waste management [2,6]. While sustainable and smart waste management systems support policy-appropriate treatment technologies, optimal waste and resource recovery methods help to achieve sustainable development goals. This system aims to provide maximum benefit for the society with minimum unprocessed material and low energy consumption with minimum damage to the environment [1,7].

Thus, the efficient waste management requires to identify the desires and needs of the public in detail [8]. Several solutions are proposed in the literature, most of these are based on the use of RFID technology and cloud-computing [9]. The use of Information and Communication Technology (ICT) and the Internet of Things (IoT) propose a new paradigm to develop the global waste management system effectively and efficiently in developed countries. The ICT-IoT integration involves the use of local sensing, data integration, analytics of things, and cognitive action in the area for the waste management [8,10]. In addition, instead of old and inefficient garbage collection systems, smart waste collection systems such as IoT, sensors and data transfer technologies have been

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https://doi.org/10.1016/j.techsoc.2022.102100
Received 26 December 2021; Received in revised form 13 July 2022; Accepted 18 August 2022
Available online 25 August 2022

used. IoT is effective in waste management system. The technology provides to show the level of garbage container at any time and optimizes waste collection route for trucks in turn reduce fuel consumption. It also allows waste collectors to plan their daily/weekly pick up scheduling [9]. The overall architecture of the IoT-based waste management is shown in Fig. 1.

To apply the necessary measures in accordance with the guidelines, effective waste management system requires a variety of waste management scenarios with conflicting objectives or unexpected results [12]. Given the potential crucial consequences, the selection of sustainable smart waste collection technology can be a challenging task and takes account of multiple conflicting criteria. Since technology investments will be used for a long time, it is important to consider the weights of the evaluation criteria for such investments. The aim of this study is to select a sustainable and smart waste management system based on today's technology considering ICTs and IoT across the country considering better and sustainable cities.

Due to increasing urbanization and industrialization with population, waste has become an increasingly large national problem in Turkey. In waste management, Turkey is faced with a series of challenges related to garbage collection, transportation, processing (composting, recycling). To control the amount of waste, regulations and action plans have been established by the Ministry of Environment and Urbanization with respect to EU directives [13].

In this study, the smart waste collection systems based on IoT are to be evaluated for one of the municipal in Istanbul. The problem has been handled as a multidimensional problem, since the selected smart waste collection system based on IoT must be environmentally efficient, economically affordable, compatible with modern city design and socially acceptable to public for a sustainable waste management. To address the related issues, the smart waste collection systems based on IoT must be evaluated using Multi Criteria Decision Making (MCDM) tools by comprising both qualitative and quantitative aspects such as human resources, operational and financial issues which can be conflict and ambiguous in uncertain and complex environments. Thus, since ICT and IoT systems bring more economic, social, and environmental benefits for waste management [14,15], the proposed MCDM method has optimally affected the economic, social, and environmental aspects for the selection of suitable smart waste collection system based on IoT technology.

As an effective decision making method COmbinative Distance-based ASsessment (CODAS) method proposed by Ghorabaee et al. [16] is extended and presented to handle decision making problem under uncertainty. To cope with the multiple uncertainties in the input data and help decision makers (DMs) express their ambiguous thoughts more clearly, Interval-valued q-rung orthopair fuzzy sets (IVq-ROFS) [17] is used, since IVq-ROFS ensure more reliable information in comparison to other efficient fuzzy extensions such as intuitionistic fuzzy set (IFS) proposed by Atanassov [18] and Pythagorean fuzzy set (PFS) proposed by Yager and Abbasov [19]. Since the weights of criteria also play a key role in MCDM process, the modified entropy measure of IVq-ROFSs is developed to obtain the weight vector of criteria. As a result, the proposed approach presents a reliable, flexible and easy-to-use tool to support critical long-term strategic decision making problems for public. In addition, modified Entropy and CODAS on the basis of IVq-ROFSs is the first study introduced for decision making problems in the waste management.

The main motivations and contributions of this study are summarized as follows:

- ➢ The proposed hybrid MCDM model integrates modified entropy and CODAS method under IVq-ROFSs suggests a useful, practical and flexible tool to simplify the decision-making process in solving real-life MCDM problems.
- ➢ The modified entropy and CODAS method are extended first within the context of IVq-ROFSs to handle complex and uncertain MCDM problems effectively.
- ➢ IVq-ROFSs deal with a wider range of uncertain and fuzziness of evaluation information inherent in real-world decision-making problems, and expand the evaluation freedom degree of DMs, simultaneously.
- ➢ The weight vector of criteria is computed by modified entropy weighting method to determine criteria weights objectively.
- ➢ To reveal the effectiveness and practicality of the proposed approach, a case study evaluates the smart waste collection systems based on IoT from comprehensive perspectives by incorporating economic, social, environmental and technical criteria is conducted.
- ➢ The consequences of the case study reveal that the introduced approach is highly reliable, and consistent with the existing models in the literature.

The structure of the paper is organized as: Section 2 includes literature review on MCDM approaches for waste management. Section 3 describes proposed methodology with some preliminaries. To show effectiveness and applicability of the constructed framework, Section 4 consists of a case study conducted one of the municipal in Istanbul to evaluate IoT based sustainable smart waste management system. To discuss results of the proposed framework, the Sensitivity and

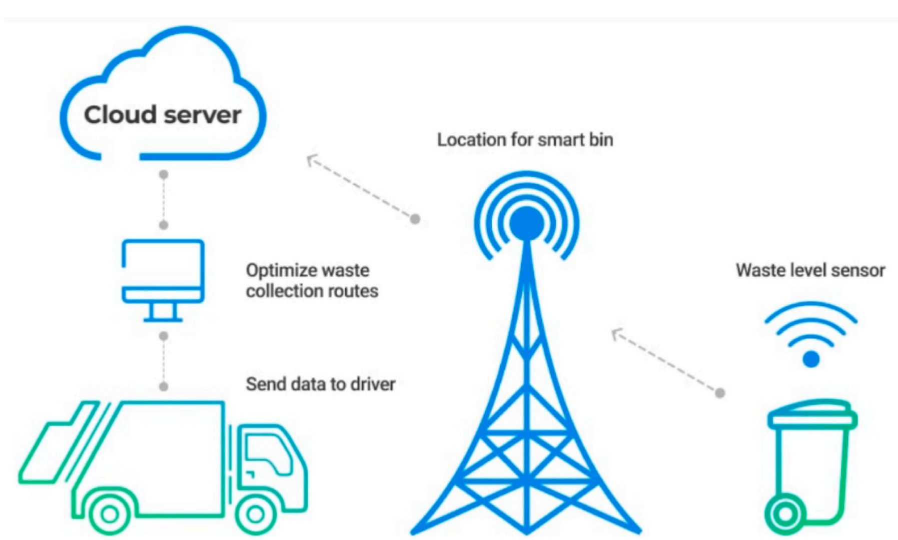


Fig. 1. Architecture of IoT-based waste management system [11].

Comparative analyses are performed in Section 5. Lastly, conclusions and contributions are presented in Section 6.

2. Literature review

Selection of waste collection technology is a major challenge in the field of municipal solid waste management and requires strategic decision making process. This decision has long-term benefits such as environmental and economic developments as well as social impacts. MCDM helps DMs in evaluating existing or potential alternatives by considering multiple conflicting criteria at the same time. For that reason, MCDM methods are considered as the most effective and comprehensive decision support frameworks for strategic decision making problems in many fields such as technology management [[20–23]], renewable energy [[24–26]], transportation [[27–29]], supply chain [[30–32]] and waste management [33,34] etc.

MCDM methods used in waste management have not only produced successful results in addressing the uncertainty of data and but also DMs can have evaluated attributes easily by linguistically [35]. Once the literature is reviewed, it has been shown that various techniques such as fuzzy logic is employed to overcome uncertainty in strategic decision making problems and different fuzzy extensions such as intuitionistic fuzzy sets (IFS) pythagorean fuzzy sets (PFS) and interval valued PFS proposed by Peng and Yang [36] etc. are employed efficiently in solving decision making problems. In existing literature some MCDM methods implemented in waste management were summarized as in the following.

Milutinovic et al. [37] performed MCDM method based on Analytic Hierarchy Process (AHP) to the select a waste management scenario with energy and resource recovery. The best suitable scenario was selected as recycling inorganic and composting organic waste. Jovanovic et al. [38] applied a process to obtain the best municipal waste management system for the city of Kragujevac (Republic of Serbia) by applying the simple additive weighting (SAW) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods. Once the six waste treatment variants were evaluated, 4 KG strategy was selected as the best municipal waste management system. To burn municipal solid waste, Shahnazari et al. [34] used traditional AHP and TOPSIS methods to select the best thermochemical technology considering the technical, economic, and environmental criteria. The results of both AHP and TOPSIS methods are similar and the plasma method was selected as a suitable thermochemical technology. Mir et al. [35] suggested VIKOR and TOPSIS methods to select from cases such as recycling, anaerobic digestion, and landfill. As a result joining recycling, anaerobic digestion, and landfill were obtained as the most sustainable alternatives for electricity generation. Liu et al. [39] proposed the combination of fuzzy logic and Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Multi-Objective Optimization on the basis of Ratio Analysis plus full multiplicative form (MULTIMOORA) to assess waste treatment alternatives for healthcare waste management. The steam sterilization was selected as the best technology where energy generation from municipal solid waste management was one of the objectives. Arıkan et al. [40] suggested an extended decision-making method to expose a waste disposal technology selection in Istanbul, Turkey, considering numerous criteria rely on sustainability goals and environmental development. Ordered storing was selected as the best option among all alternatives. Soltani et al. [41] used AHP and Analytic Network Process (ANP) widely used for sustainable solid waste management considering multiple stakeholders. Abba et al. [42] considered environmental, social and economic impacts as sustainable municipal solid waste management factors for Johor-Bahru, Malaysia by performing the AHP to evaluate four disposal plan alternatives. Incineration and recycling were selected to landfilling and composting disposal options. Coban et al. [43] used the TOPSIS, the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) I and the PROMETHEE II for the solid waste disposal scenario evaluation. They proposed the prominence of recycling and landfill technologies for developing countries.

The papers summarized above have deficiency due to lack of reflecting uncertain data and information in real-world problems.

However, Shi et al. [44] proposed a combined decision-making context based on the cloud model and the MABAC method for assessing the best health care waste treatment. Cloud model used to overcome uncertain linguistic assessments of DMs. Steam sterilization was selected as the best alternative for handling and safe disposal of health care wastes. Furthermore, Belhadi et al. [45] proposed a new risk-based performance evaluation method based on the life-cycle assessments and life-cycle costs (LCA–LCC), AHP, and VIKOR method in an interval-valued fuzzy (IVF) for assessing the e-waste management development strategies in e-waste recycling company in China. The results showed useful new insights in managing the improvement strategies and their potential risks as a whole and individually. Ugurlu and Kahraman [46] suggested a fuzzy VIKOR method for the assessment of the most desirable hazardous waste treatment methodology and thermal treatment methodologies (combustion) was selected as the suitable alternative in Istanbul.

In a smart city, on the other hand, instead of old and inefficient garbage collection systems, smart waste collection systems based on ICT such as IoT, sensors and data transfer technologies have been used to design a smart management system for municipal waste management. Technologies such as IoT or blockchain have become important parts of sustainable and intelligent waste management systems and implemented in smart cities [[8,47–50]]. Zhang et al. [51] identified obstacles for smart waste management in China related to Circular Economy using DEMATEL with respect to triangular fuzzy environment. Sharma et al. [49] proposed DEMATEL with fuzzy Matriced'Impacts Croisés Multiplication Appliquéan Classement (MICMAC) and interpretative structural modeling (ISM) to show the efficiency of Indian waste management against obstacles of IoT adoption. Topaloglu et al. [3] introduced a type-2 fuzzy multiple criteria methodology to assess and rate alternative waste collection systems for a real case study from Eskisehir, Turkey. Torkayesh et al. [52] suggested a MCDM model based on type-2 neutrosophic numbers (T2NNs) to recognize criteria donating to failure in the implementation of IoT and blockchain in smart medical waste management systems in Istanbul, Turkey. Results prove that training for different shareholders, market acceptance, transparency, and professional workers are the focal criteria that cause failure in the implementation of smart technologies.

Due to the limited number of studies for the evaluation of smart waste collection systems, this study introduces a new perspective to evaluate the smart waste collection systems based on IoT for municipal waste collection systems considering economic, social and environmental factors. According to the author' knowledge, there is no study applying modified Entropy and CODAS integration based on IVq-ROFs for decision making problems in waste management. Since as in mentioned above papers in most MCDM methods, the weight of criteria are determined based on subjective evaluation of DMs which may cause some errors or mistakes [47], in this study to compute weight of criteria objectively entropy measure is modified for IVq-ROFSs and applied.

Therefore, one of the main difference between the current study and previous ones is that in this study modified entropy based on IVq-ROFs is used to determine relative weights of criteria to avoid DMs' subjective judgments in determining weights of criteria. In addition, IVq-ROFSs are also more effective in handling complex and uncertain information and IVq-ROFSs provide more flexible way for DMs in expressing their opinions during MCDM process.

3. Methodology

In this section, some definitions and operational laws for IVq-ROFs and weighting method based on entropy of q-rung orthopair fuzzy sets are given. Then two-phase modified Entropy and CODAS method based

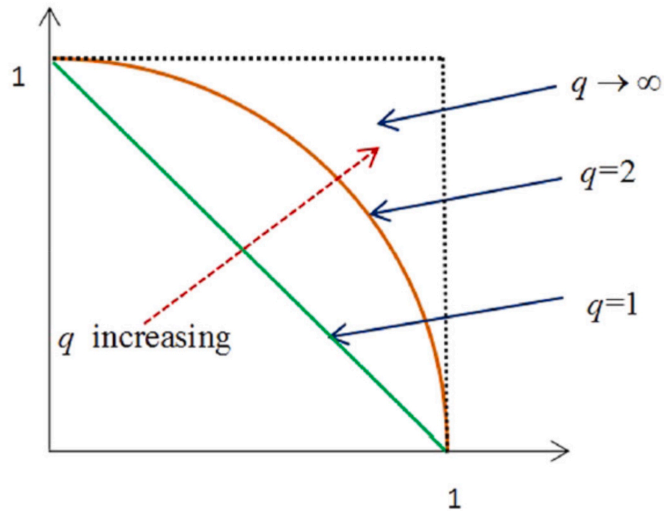


Fig. 2. Comparison of spaces of IFNs, PFNs, and q-ROFNs [54].

$$\widetilde{\pi}_{\widetilde{P}}(x) = [\pi_{\widetilde{P}}^{L}(x), \pi_{\widetilde{P}}^{U}(x)\ ] = \left[\sqrt[q]{1-(\widetilde{\mu}_{\widetilde{P}}^{L}(x))^{q}+(\widetilde{\nu}_{\widetilde{P}}^{L}(x)},\ \sqrt[q]{1-(\widetilde{\mu}_{\widetilde{P}}^{U}(x))^{q}+(\widetilde{\nu}_{\widetilde{P}}^{U}(x)}\right] \tag{6}$$

on IVq-ROFSs method is formulated and explained.

3.1. Interval-valued q-rung orthopair fuzzy sets

q-rung orthopair fuzzy set (q-ROFS) proposed by Yager [53] are expressed using the degree of membership and non-membership. q-ROFSs provide that the sum of the qth power of the membership and non-membership degrees must provide at most equal to one. q-ROFSs are the generalization of IFSs and PFSs. The representation of Intuitionistic Fuzzy Numbers (IFNs), Pythagorean fuzzy numbers (PFNs), and q-rung orthopair fuzzy numbers (q-ROFNs) are illustrated with their corresponding constraint conditions in Fig. 2.

Definition 1. (Yager [53]): A q-ROFS $\widetilde{Q}$ in a finite universe of discourse X is expressed and defined by Equation (1).

$$\widetilde{Q} = \{\ ((x,\ \mu_{\widetilde{Q}}(x), \nu_{\widetilde{Q}}(x))|x\ \varepsilon X)\} \tag{1}$$

where the function $\mu_{\widetilde{Q}}: X\to[0,1]$ and $\nu_{\widetilde{Q}}: X\to[0,1]$ are the degree of membership and non-membership, respectively. q-ROFS must provide the form of:

$$0 \le (\mu_{\widetilde{Q}}(x))^{q} + (\nu_{\widetilde{Q}}(x))^{q} \le 1 \quad (q\ \ \ge 1) \tag{2}$$

Accordingly, sum of the qth power of the membership degree and the qth power of the degrees of non-membership is equal or less than 1 (See Fig. 2).

The degree of indeterminacy is shown as:

$$\pi_{\widetilde{Q}}(x) = \sqrt[q]{1- \le \mu_{\widetilde{Q}}(x)^{q} + \nu_{\widetilde{Q}}(x)^{q}} \tag{3}$$

However, to handle vague and imprecise information better the degree of membership and non-membership are expressed in intervals than single valued. For this reason, to capture the imprecise and qualitative information better Joshi et al. [17] developed IVq-ROFS concept to express membership function and non-membership function values in intervals.

Definition 2. (Liu et al. [55]): Let X be a non-empty and finite set, a IVq-ROFS $\widetilde{P}$ on X is defined as:

$$\widetilde{P} = \{|x,\ (\widetilde{\mu}_{\widetilde{P}}(x), \widetilde{\nu}_{\widetilde{P}}(x)|x\varepsilon X\} \tag{4}$$

where the function $\widetilde{\mu}_{\widetilde{P}}(x) = [(\widetilde{\mu}_{\widetilde{P}}^{L}(x),\ \widetilde{\mu}_{\widetilde{P}}^{U}(x)] : X\to[0,1]$ and $\widetilde{\nu}_{\widetilde{P}}(x) = [(\widetilde{\nu}_{\widetilde{P}}^{L}(x),\ \widetilde{\nu}_{\widetilde{P}}^{U}(x)] : X\to[0,1]$ are intervals considering the membership and non-membership degrees of the element $x \in X$ belong to the set $\widetilde{P}$, respectively. In this situation IVq-ROFS must provide Equation (5).

$$(\widetilde{\mu}_{\widetilde{P}}^{U}(x))^{q} + (\widetilde{\nu}_{\widetilde{P}}^{U}(x))^{q} \le 1,\ q \ge 1 \tag{5}$$

Indeterminacy degree is defined as:

Definition 3. (Liu et al. [55]): For a Interval-valued q-rung orthopair fuzzy number

(IVq-ROFN) $\widetilde{p} = [\mu^{L}, \mu^{U}],\ [\nu^{L}, \nu^{U}]$, the score function $s(\widetilde{p})$ and the accuracy function $H(\widetilde{p})$ of $\widetilde{p}$ are computed using Equations (7) and (8):

$$s\left(\widetilde{p}\right) = \frac{1}{4}\left[1+\mu^{L}\right)\left(\mu^{L}\right)^{q} - \nu^{L}\right)\left(\nu^{L}\right)^{q}\right) + 1 + \left(\mu^{U}\right)^{q} - \left(\nu^{U}\right)^{q}\right)\right],\ s(\widetilde{p}) \in [0,1] \tag{7}$$

$$H\left(\widetilde{p}\right) = \frac{((\mu^{L})^{q} + (\nu^{L})^{q} + (\mu^{U})^{q} - (\nu^{U})^{q}}{2}\ ,H(\widetilde{p}) \in [0,1] \tag{8}$$

If.

$\widetilde{p}_1 = ([\mu_1^L, \mu_1^U], [\nu_1^L, \nu_1^U])$ *and* $\widetilde{p}_2 = ([\mu_2^L, \mu_2^U], [\nu_2^L, \nu_2^U])$ are two IVq-ROFNs, the score function and accuracy function of $\widetilde{p}_1$ and $\widetilde{p}_2$ are shown in the following: $s(\widetilde{p}_1) = \frac{1}{4}[1+\mu_1^L)(\mu_1^L)^q - \nu_1^L)(\nu_1^L)^q) + 1 + (\mu_1^U)^q - (\nu_1^U)^q)]$ and $s(\widetilde{p}_2) = \frac{1}{4}[1+\mu_2^L)(\mu_2^L)^q - \nu_2^L)(\nu_2^L)^q) + 1 + (\mu_2^U)^q - (\nu_2^U)^q)]$ $H(\widetilde{p}_1) = \frac{[((\mu_1^L)^q + (\nu_1^L)^q) + (\mu_1^U)^q - (\nu_1^U)^q)]}{2}$ and $H(\widetilde{p}_2) = \frac{[((\mu_2^L)^q + (\nu_2^L)^q) + (\mu_2^U)^q - (\nu_2^U)^q)]}{2}$ respectively.

If $s(\widetilde{p}_1) > s(\widetilde{p}_2)$ then $\widetilde{p}_1$ is bigger than $\widetilde{p}_2$ $(\widetilde{p}_1 > \widetilde{p}_2)$

If $s(\widetilde{p}_1) = s(\widetilde{p}_2)$ and $H(\widetilde{p}_1) = H(\widetilde{p}_2)$ then $\widetilde{p}_1$ is equal to $\widetilde{p}_2$ $(\widetilde{p}_1 = \widetilde{p}_2)$.

If $s(\widetilde{p}_1) = s(\widetilde{p}_2)$ and $H(\widetilde{p}_1) > H(\widetilde{p}_2)$ then $\widetilde{p}_1$ is bigger than $\widetilde{p}_2$ $(\widetilde{p}_1 > \widetilde{p}_2)$.

Definition 4. (Wang and Zhou [56]): Some mathematic operations considering IVq-ROFSs are expressed by:

$\widetilde{p}_1 = ([\mu_1^L, \mu_1^U], [v_1^L, v_1^U])$ and $\widetilde{p}_2 = ([\mu_2^L, \mu_2^U], [v_2^L, v_2^U])$ and $\widetilde{p} = [\mu^L, \mu^U]$, $[v^L, v^U]$

$$\widetilde{p}_1 \oplus \widetilde{p}_2 = \left[\sqrt[q]{(\mu_1^L)^q + (\mu_2^L)^q - (\mu_1^L)^q(\mu_2^L)^q}, \sqrt[q]{(\mu_1^U)^q + (\mu_2^U)^q - (\mu_1^U)^q(\mu_2^U)^q}\right], \left[v_1^L v_2^L,\ v_1^U v_2^U\right] \tag{9}$$

$$\widetilde{p}_1 \otimes \widetilde{p}_2 = \left[\left[\mu_1^L \mu_2^L, \mu_1^U \mu_2^U\right], \sqrt[q]{(v_1^L)^q + (v_2^L)^q - (v_1^L)^q(v_2^L)^q}, \sqrt[q]{(v_1^U)^q + (v_2^U)^q - (v_1^U)^q(v_2^U)^q}\right]$$

$$\lambda\widetilde{p} = \left(\left[\sqrt[q]{1 - \left((1-(\mu^L)^q)^\lambda\right.}, \sqrt[q]{1 - \left((1-(\mu^U)^q)^\lambda\right.}\right], \left[(v^L)^\lambda, (v^U)^\lambda\right]\right), \lambda > 0; \tag{11}$$

$$(\widetilde{p})^\lambda = \left(\left[(\mu^L)^\lambda, (\mu^U)^\lambda\right], \left[\sqrt[q]{1-(1-(v^L)^q\Big)^\lambda}\right], \left[\sqrt[q]{1-(1-(v^U)^q\Big)^\lambda}\right]\right), \lambda > 0 \tag{12}$$

Definition 5. (Ju et al. [57]): Interval-valued q-rung orthopair fuzzy weighted geometric (IVq-ROFWG) operator:

Suppose $\widetilde{b}_i = [\mu_i^L, \mu_i^U], [v_i^L, v_i^U]$ (i = 1,2, …,n) is a collection of the interval-valued q-rung orthopair fuzzy numbers (IVq-ROFNs) then Interval-valued q-rung orthopair fuzzy weighted geometric (IVq-ROFWG) operator is shown in the following:

$$\text{IVq} - \text{ROFWG}\left(\widetilde{b}_1, \widetilde{b}_2, \dots, \widetilde{b}_n\right) = \left(\left[\prod_{i=1}^n (\mu_i^L)^{w_i}, \prod_{i=1}^n (\mu_i^U)^{w_i}\right]\left[\sqrt[q]{1 - \prod_{i=1}^n (1-v_i^L)^{w_i}}, \sqrt[q]{1 - \prod_{i=1}^n (1-v_i^U)^{w_i}}\right]\right. \tag{13}$$

where $w_j = (w_1, w_2, \dots, w_n)^T$ thereby satisfying $w_j \in [0,1]$ and $\sum_{j=1}^n w_j = 1$.

Definition 6. (Liu et al. [55]): Let $\widetilde{p}_1 = ([\mu_1^L, \mu_1^U], [v_1^L, v_1^U])$ and $\widetilde{p}_2 = ([\mu_2^L, \mu_2^U], [v_2^L, v_2^U])$ be two IVq-ROFNs, then Minkowski distance $d(\widetilde{p}_1, \widetilde{p}_2)$ between them is defined as:

$$d(\widetilde{p}_1, \widetilde{p}_2) = \left(\frac{1}{4}|\mu_1^L - \mu_2^L|^p + \frac{1}{4}|\mu_1^U - \mu_2^U|^p + \frac{1}{4}|v_1^L - v_2^L|^p + \frac{1}{4}|v_1^U - v_2^U|^p\right)^{1/p}, p \geq 1 \tag{14}$$

when p = 1, $d(\widetilde{p}_1, \widetilde{p}_2) = \frac{1}{4}|\mu_1^L - \mu_2^L|^p + \frac{1}{4}|\mu_1^U - \mu_2^U|^p + \frac{1}{4}|v_1^L \ -v_2^L|^p + \frac{1}{4}|v_1^U - v_2^U|^p$ is the hamming distance.

When p = 2, $d(\widetilde{p}_1, \widetilde{p}_2) = \left(\frac{1}{4}|\mu_1^L - \mu_2^L|^2 + \frac{1}{4}|\mu_1^U - \mu_2^U|^2 + \frac{1}{4}|v_1^L - v_2^L|^2 + \frac{1}{4}|v_1^U - v_2^U|^2\right)^{1/2}$ is the Euclidian distance. When $p \to \infty$ $d(\widetilde{p}_1, \widetilde{p}_2) = \frac{1}{4}|\mu_1^L - \mu_2^L| + \frac{1}{4}|\mu_1^U - \mu_2^U| + \frac{1}{4}|v_1^L - v_2^L| + \frac{1}{4}|v_1^U - v_2^U|$ is the Chebyshev distance.

3.2. Entropy of q-rung orthopair fuzzy sets

Definition 7. (Wang and Lee [58]): The entropy method is applied to predict quantity of information. It can be used to compute the relative weight of information. In 1947, Shannon and Weaver [59] applied entropy method to calculate ambiguity of a component by performing information probability function as in the following:

$$H(p(x)) = -k\sum_{k=1}^{q} p(x) ln p(x) \tag{15}$$

where H represents the level of entropy and k is the constant level.

The greater value of entropy refers to smaller weight of information in MCDM process. De Luca and Termini [60] express non-probabilistic entropy of fuzzy set.

Let the degree of fuzziness of fuzzy set $\widetilde{A}$ (x) and membership degree $\mu_{\widetilde{A}}$ (x) to change the Shannon's probability function $p(x_k)$ by

$$H(\widetilde{A}(x)) = -k\sum_{k=1}^{q} \mu_{\widetilde{A}}(x_k) ln \mu_{\widetilde{A}}(x_k) \tag{16}$$

where k is the normalized value which equals to $1/\ lnq$.

Definition 8. (Liang et al. [61]): introduced both entropy and cross-entropy methods for q-ROFNs and then apply them to establish the fuzzy procedures.

Let p = (μ, v) be a q-ROFN, the entropy of α shown as $E(p)$ can be expressed as in the following:

$$E(p) = \frac{1}{\sqrt{2}-1}\left\{sin\frac{\pi}{4}(1 + \mu^q - v^q) + sin\frac{\pi}{4}(1 - \mu^q - v^q + 1) - 1\right\} \tag{17}$$

By considering the results from Liang et al. [62], it can be denoted the following propositions:

Definition 9. An entropy for the *q*-ROFN p = (μ, v) is a real-valued function E(p): p→ [0, 1], need the following axiomatic requirements:

1) $E(p) = 0$, if and only $p = P(0,1)$ or $p = P(1,0)$;
2) $E(p) = 1$ if and only if $\mu = v$;
3) Given two q-ROFNs $p_1 = (\mu_1, v_1)$ and $p_2 = (\mu_2, v_2)$, $E(p_1) \leq E(p_2)$, when we have $\mu_1 \leq \mu_2 \leq v_2 \leq v_1$ or $\mu_1 \geq \mu_2 \geq v_2 \geq v_1$;
4) $E(p) = E(\overline{p})$

Definition 10. (Liu et al. [62]): Entropy value for a group *q*-ROFNs are determined as:

$$\text{q}^-\text{ROFE} = \frac{1}{n}\sum_{i=1}^{n}[1 - (\mu^q(x_i) + v^q(x_i))|\mu^q(x_i) - v^q(x_i)|]\ i = 1, 2, \dots n \tag{18}$$

Table 1
Linguistic expressions and correspondence IVq-ROFNs to evaluate alternatives with respect to criteria [63].

Linguistic Expression	μ^L	μ^U	v^L	v^U
Extremely High (EH)	0.90	0.90	0.10	0.10
Very High (VH)	0.75	0.85	0.05	0.15
High (H)	0.60	0.75	0.10	0.20
Medium High (MH)	0.45	0.60	0.15	0.25
Medium (M)	0.50	0.50	0.50	0.50
Medium Low (ML)	0.35	0.45	0.40	0.55
Low (L)	0.25	0.35	0.50	0.60
Very Low (VL)	0.15	0.20	0.60	0.75
Extremely Low (EL)	0.10	0.10	0.90	0.90

3.3. The proposed approach: modified entropy and CODAS method based on IVq-ROFSs

As a new approach, modified Entropy and CODAS method under IVq-ROF environment is introduced in this section. The proposed approach is applied to select the smart waste collection system based on IoT for one of the municipal in Istanbul. The proposed approach is presented step-by-step as in the following:

Step 1. Construct a group of DMs and determine criteria and alternatives for MCDM problem to attain main goal. To express their opinions DMs group shown with (DM_1, DM_2 … DM_k) is formed. Their judgments for alternative options with respect to criteria are constructed as decision matrix using IVq-ROF linguistic expressions and corresponding IVq-ROFNs according to Table 1. Thus, decision matrix $\widetilde{X} = [\widetilde{x}^k_{ij}]_{mxn}$ has m alternatives (A_1, A_2 … A_m) and n evaluation criteria (C_1, C_2 … C_n) through a linguistic term expressed by DMs using IVq-ROFNs.

$$\widetilde{X}_K = \left[\widetilde{x}^k_{ij}\right]_{mxn} = \begin{bmatrix} \widetilde{x}^k_{11} & \widetilde{x}^k_{12} & \cdots & \widetilde{x}^k_{1m} \\ \vdots & & \ddots & \vdots \\ \widetilde{x}^k_{n1} & \widetilde{x}^k_{n2} & \cdots & \widetilde{x}^k_{mn} \end{bmatrix} \tag{18}$$

where $\widetilde{x}^k_{ij}$ shows the performance value of ith alternative with regard to jth criterion for each k^{th} DM and

$$\widetilde{x}^k_{ij} = \left[\mu^L_{ijk}, \mu^U_{ijk}\right], \left[v^L_{ijk}, v^U_{ijk}\right].$$

Then, since the weights of criteria play a key role in a decision making problem, the modified entropy measure of IVq-ROFNs is developed to calculate relative weight of criteria.

The weights of criteria are calculated based on modified IVq-ROF Entropy method as follows:

Step 2. Calculate the expected membership EV (μ_J) and non-membership EV (μ_J) values of an IVq-ROFNs. Assume $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_n)$ be the optimism degrees of DMs, expected membership EV (μ_J) and non-membership EV (μ_J) values of an IVq-ROFNs using degree of optimism (λ) are computed as follows:

$$\text{EV}\ (\ \mu_J) \ = (1-\lambda)\ \mu^L + \ \lambda\mu^U \tag{19}$$

$$\text{EV}\ (\ v_J) = (1-\lambda)\ v^L + \ \lambda v^U \tag{20}$$

Step 3. Aggregate IVq-ROF decision matrices. Once the individual decision matrices are aggregated using Equation (13), modified IVq-ROF Entropy method is developed to determine criteria weights. Aggregated IVq-ROF decision matrix $\widetilde{X} = [\widetilde{x}_{ij}]_{mxn}$ where $\widetilde{x}_{ij} = [\mu^L_{ij}, \mu^U_{ij}], [v^L_{ijk}, v^U_{ij}]$ is constructed.

Step 4. Compute weights of criteria. Let $W = (w_1, w_2, \ldots.., w_n)$ where $\sum_{j=1}^{n} w_j = 1$ be the relative weight vector of evaluation criteria and $(w_j)_{1xn}$ shows the IVq-ROF weight of j^{th} criterion. Based on the entropy measure theory, the entropy measure of each criterion $E(w_j)$ is calculated using the following equation:

$$E\left(w_j\right) = \sum_{i=1}^{n}\left[1 - \left(\mu^q\left(x_{ij}\right) + v^q\left(x_{ij}\right)\right)\left|\mu^q\left(x_{ij}\right) - v^q\left(x_{ij}\right)\right|\right] i = 1, 2, \ldots n \tag{21}$$

The normalized criteria weight for jth criterion can be computed as follows:

$$w_j = \frac{E\left(w_j\right)}{\sum_{j=1}^{n} E\left(w_j\right)} \tag{22}$$

The alternative options are evaluated using IVq-ROF CODAS method as follows:

Step 5. Normalize the aggregated IVq-ROF decision matrix considering the type of each criterion. Judgment information for alternatives considering the cost criteria is transformed into the judgment information concerning the benefit and cost criteria as in the following (Equation (23)):

$$\widetilde{N} = \left[\widetilde{n}_{ij}\right]_{nxm} = \left\{ \begin{array}{l} \left(\left[v^L_{ij}, v^U_{ij}\right], \left[\mu^L_{ij}, \mu^U_{ij}\right]\right) \textit{ if } C_j \textit{ is the cost type} \\ \left(\left[\mu^L_{ij}, \mu^U_{ij}\right], \left[v^L_{ij}, v^U_{ij}\right]\right) \textit{if } C_j \textit{ is the benefit type} \end{array} \right\} \tag{23}$$

where $\widetilde{n}_{ij}$ represents the normalized IVq-ROF decision matrix.

Step 6. Form the weighted normalized IVq-ROF decision matrix. The weighted normalized IVq-ROF decision matrix is established by using Equations 24 and 25.

$$\widetilde{S} = \left[\widetilde{s}_{ij}\right]_{\text{mxn}} \tag{24}$$

$$\widetilde{s}_{ij} = w_j \otimes \widetilde{n}_{ij} \tag{25}$$

Step 7. Determine the negative ideal solution. The negative ideal solution is determined for the weighted normalized IVq-ROF decision matrix as in the following.

$$\widetilde{NS} = \left[\widetilde{n}_{sj}^{\ -}\right]_{1xm} \tag{26}$$

$$\widetilde{n}_{sj}^{\ -} = \left[\begin{array}{cc} \min\mu^L_{ij}, & \min\mu^U_{ij} \\ i & i \end{array}\right], \left[\begin{array}{cc} \max v^L_{ij}, & \max v^U_{ij} \\ i & i \end{array}\right] j\epsilon J,\ i = 1, 2, \ldots, m \tag{27}$$

Step 8. Compute the IVq-ROF weighted Euclidean (ED) and IVq-ROF weighted Hamming (HD) distances. The most appropriate alternative is selected using the distances from the negative ideal solution. The distances are obtained as follows:

$$ED_i = \sum_{j=1}^{m} d_E\left(\widetilde{s}_{ij}, \widetilde{n}_{sj}^{\ -}\right) \tag{28}$$

$$HD_i = \sum_{j=1}^{m} d_H\left(\widetilde{s}_{ij}, \widetilde{n}_{sj}^{\ -}\right) \tag{29}$$

$$ED_i = \sum_{j=1}^{m} \sqrt{\left(\frac{1}{4}\left|\mu^L_{sij} - \mu^L_{n_{sj}^-}\right|^2 + \frac{1}{4}\left|\mu^U_{sij} - \mu^U_{n_{sj}^-}\right|^2 + \frac{1}{4}\left|v^L_{sij} - v^L_{n_{sj}^-}\right|^2 + \frac{1}{4}\left|v^U_{sij} - v^U_{n_{sj}^-}\right|^2\right.} \tag{30}$$

$$HD_i = \frac{1}{4}\sum\left|\mu^L_{sij} - \mu^L_{n_{sj}^-}\right| + \left|\mu^U_{sij} - \mu^U_{n_{sj}^-}\right| + \left|v^L_{sij} - v^L_{n_{sj}^-}\right| + \left|v^U_{sij} - v^U_{n_{sj}^-}\right| \tag{31}$$

Step 9. Obtain the relative assessment matrix (RA). Considering ED and HD values for each alternative option, the RA matrix is built using Equations 32–34

$$RA = [p_{it}]_{nxn} \tag{32}$$

$$p_{it} = (ED_i - ED_t) + \partial(ED_i - ED_t)^*(HD_i - HD_t) \tag{33}$$

$$\partial(x) = \left\{ \begin{array}{l} 1|x| \geq \rho \\ 0|x| < \rho \end{array} \right. \tag{34}$$

where $\partial \in \{1,2, \ldots,n\}$, the threshold value ($\rho$) of ∂ function can be determined by DMs. In this study, ρ value is taken between 0.01 and

0.05 by DM.

Step 10. Calculate the assessment score (*AS*) for each alternative option. Assessment score of each alternative can be calculated as shown in Equation (35).

$$AS_i = \sum_{t=1}^{n} p_{it} \tag{35}$$

Step 11. Alternative options are arranged in the decreasing values of assessment scores (AS). As a result, the most suitable alternative is obtained considering the highest AS.

4. Case study: evaluation of IoT based sustainable smart waste management system in Istanbul

To validate the applicability and effectiveness of the proposed model, the proposed model is applied to select the most appropriate smart waste collection system based on IoT for local municipal in Istanbul.

4.1. Problem definiton

Turkey's waste problem is a serious threat for the sustainability of the country's economy, society and environment. Waste collection requires a comprehensive and systematic process to provide economical, social and environmental benefits [64]. Considering production and consumption activities in Turkey, the collection of wastes produced as a result of increased consumption has become more important issue because it threatens human and environmental health. In order to prevent/reduce waste generation and protect the environment and natural resources with public health, the Ministry of Environment and Urbanization in Turkey implements waste regulations and action plans comply with European Union (EU) waste management policies [13,65].

According to the results of the 2018 Municipal Waste Statistics Survey applied to all municipalities, it was determined that 1395 out of 1399 municipalities provided waste services. Municipalities in Istanbul providing waste services collected 32 million 209 thousand tons waste in 2018. In three big cities in Turkey, the average daily amount of waste per person collected was 1.28 kg for Istanbul, 1.18 kg for Ankara and 1.36 kg for İzmir, respectively. The amount of municipal waste collected by years and the rate of landfill for municipals in Istanbul are shown in Fig. 3.

However, 65%–80% of the cost for the waste management system consists of the collection and transportation of waste. The operating cost of waste collection and transportation in Istanbul is approximately 220 million dollars for per year. It would be beneficial for local municipalities to draw up a waste map of the area they are responsible and determine an optimum way, since daily waste collection services encounter a serious financial burden for local governments in Istanbul. Therefore, having information about how much and what type of waste is generated in which area is crucial for the government. The constructed system should help local municipalities in developing the most appropriate collection period and method considering the time and cost aspects. As a result, If the municipalities do the necessary work on the waste management system, they can reduce the waste collection and transportation costs by half. Thus, savings in cost is by only $100 million per year in Istanbul and around $460 million in Turkey. They also contribute to the reduction of significant greenhouse gas emissions [67].

Waste collection using garbage containers is the most widely waste collection method, but this causes health problems and high operating cost. Therefore, technological innovations, such as infrared sensors, metal detectors, odor receptors that make waste monitoring fast and less free, have made significant contributions to waste management [68].

New solutions for waste collection with the development and application of smart city technologies and platforms have been developed in the world. The use of ICT and IoT propose a new generation approaches to manage the global waste management system effectively and efficiently [48]. With the application of IoT, digitalization and ICT in waste management, waste management becomes reliable, transparent, efficient and sustainable [49].

However, the wrong choice of waste disposal technologies has long-term negative effects on environmental development and economic growth. As different technologies for waste collection systems have disadvantages and advantages, several economic, social and environmental aspects need to be considered in the selection process of the most appropriate technology [69].

4.2. Smart waste collection alternatives and evaluation criteria

In this study, a smart system solution for the smart waste collection system based on IoT has been investigated for the efficient and affordable waste collection of a local municipality in Istanbul. The aim of the selected waste collection technology is to minimize waste management problems by maturing the waste management system with existing technologies for the long-term planning of the municipalities. Accordingly, municipal administrators evaluate four different smart waste collection system based on IoT, along with their pros and cons, in terms of economy, social, environmental, and technological aspects of the systems. Four different alternatives and related evaluation criteria determined concerning of sustainability of waste management systems are as follows:

RFID, GIS and GPRS integration of waste management system (A1). As a web based solution for real-time monitoring and management

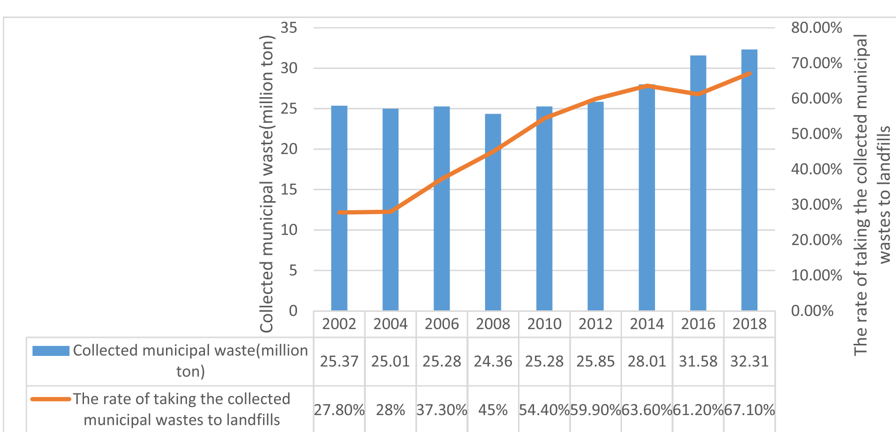


Fig. 3. The amount of municipal waste collected by years and the rate of landfill [66].

of waste, it incorporates RFIDs, GPS, GSM & GIS technologies. Sensors placed on containers report the real-time occupancy rate of the containers on the streets. Depending on the filling level of the waste containers, an optimized path is selected for the waste collection truck, which reduces the fuel cost based on GIS. With RFID sensors attached to vehicles and containers, the instant location of the waste truck can be tracked by GPS. With the developed software, it is possible to determine when the containers should be collected depending on the occupancy rate, how many trucks should work to collect these containers, and most importantly, which routes these trucks should follow on a daily basis due to the accurate tracking of a waste containers serial number and location.

The solar-powered waste compactor system (A2). This system consist of a smart device that reads the filling level of a container in real-time, triggering automatic compaction of waste, effectively increasing the capacity of the container by up to 5–8 times. The compactor system is powered by a battery charged and the solar panel. The mentioned IoT-based solar waste management system provides an efficient and cost-effective solution. This system also provides real-time remote monitoring.

***Underground Waste Container system (A3)*:** Underground waste containers are placed vertically under the ground in narrow areas and ensure that all wastes are collected by preventing the spread of odor, water bacteria, disease and similar undesirable consequences. Visual pollution is also completely eliminated by applying this sytem in the streets. With the sensors placed in waste containers, a significant part of which are placed underground, the amount of waste are noticed from the vehicle or from the center and the routes of the trucks are determined.

Mobile Application for the waste collection (A4): A mobile application is developed to support citizens to completely join in the waste management cycle. This system provides a smart application which includes smart monitoring and efficient collection of waste to collect wastes in the streets easier especially in narrow streets where it is difficult to put the waste containers. It is compatible with Android and IOS mobile operating systems. The waste trucks are integrated with the smart application for the collection of wastes in the streets. SMS based notification are sent to the residents of the neighborhood when the truck comes closer to the street. Thus, citizens unload their garbage in real-time. Environmental pollution is prevented due to reduced duration of the waste on the ground. Citizens can also check the status of trucks online via the mobile application.

Once the alternative solutions are determined, the evaluation criteria for the smart waste collection system based on IoT are determined as:

Providing interaction network between community, government and industry (C1): It is expected from the IoT based system to provide suggestion boxes where citizens can report their requests or complaints, a municipal feedback website, and a portal for interaction discussions between municipal and citizens.

Providing high productivity considering waste collection process cost (C2): IoT based system for waste management must provide material and labor productivity with low cost resource consumption considering more efficient use of resources and minimizing unnecessary expenses.

Affordable investment cost of IoT based waste management service (C3): Costs are the main problem of the IoT implementation due to high cost of smart devices and setting up for imparting information to the workers [[49,70,71]]. The selected IoT technology for waste management must provide services that are cost-effective and affordable.

Operational cost and extended payback period (C4): The selected IoT technology for waste management must provide minimum service cost per month, low maintenance and operation cost. The high cost of professionals, maintenance and training costs to inform employees require to perform these applications.

Security and privacy (C5): Data leakage may arise due to security and privacy issues. IoT technology systems may encounter several attacks like cross-site scripting, or having side channels that lead towards susceptibilities [70]. The risk is greater with mobility and the interactions among system components [49,72].

Environmental protection and hazardous reduction activities (C6): Smart applications for waste management must improve community's living capacity and provide safety and health for citizens in the area.

Aesthetics (C7): This criterion is related to the visual and physical aspects of the environment. IoT based technology system for waste management provides such aspects [3].

Sustainability (C8): Some sustainable aspects such as the environmental, economic, and social attributes must meet by smart waste technology based on IoT. Thus, IoT technology system includes appropriate sensors, GPS, mobile application, cloud system used in waste management and it must guarantee the environmental, economic, and social sustainability [3].

Standardization (C9): Smart waste technology requires standardization for communication and information exchange between the environment, smart objects and other systems. Standards such as identification, communication, and privacy are essential activities in successful implementation of IoT [[49,73,74]].

Ease of operation (C10): Ease of operation is critical for sustainable and reliable operation of IoT technology system since too much operational complexity might stimulate a higher rate of human error, cause increased maintenance costs and potentially longer failure downtimes.

Amount of wastes collected (C11): Maximum amount of waste collected by IoT technology system is related with the number and capacity of containers and monitoring real-time filling level of containers.

4.3. Problem solution and results

To select the most appropriate smart waste collection system based on IoT for local municipal in Istanbul, modified Entropy and CODAS under IVq-ROF environment first time is introduced and the application steps are carried out as follows:

Step 1. Construct a group of DMs and determine criteria and alternatives for the best appropriate IoT based waste management system. Once the alternatives and sustainable related criteria are determined by five DMs consist of two managers from environmental protection and control directorate in the municipality, two managers running smart city projects in the municipality and university academician who is working in smart waste management, decision matrix is created for each DM to select the most appropriate IoT-based waste management system. Decision matrices have *four* IoT based waste management system alternatives ($A_1, A_2 \dots A_m$) and *11* evaluation criteria determined as above ($C_1, C_2 \dots C_n$) are constructed through a linguistic terms expressed by DMs using IVq-ROFNs as in Table 1. The decision matrix for alternative IoT based waste management systems with respect to criteria is given in Table 2.

The relative weight vector for the evaluation criteria are determined using modified IVq-ROF-Entropy method as follows:

Step 2. Calculate expected membership and non-membership values for IVq-ROFNs. Expected membership and non-membership values for IVq-ROFNs using degree of optimism (0.5) are calculated using Equations 19 and 20.

Step 3. Establish the aggregated decision matrix. The individual decision matrices created by DMs are collected in one decision matrix using IVq-ROFWG given in Equation (13). Thus Aggregated IVq-ROF decision matrix for IoT based waste management system alternative evaluation with respect to criteria is constructed as in Table 3.

Step 4. Compute the weights of criteria. By applying entropy measure theory, the entropy measure of each criterion is calculated using equation (21). Then, the criteria weights are obtained using Equation (22).

Four IoT based waste management system alternatives with respect to evaluation criteria determined are evaluated as follows:

Table 2
Decision matrix for IoT based waste management system alternatives with respect to criteria.

DM	Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
DM1	A1	MG	G	G	MG	MG	MG	MG	G	MG	G	VG
	A2	MG	G	G	MG	G	M	MG	MG	MG	G	G
	A3	G	MG	M	G	G	MG	VG	MG	MG	M	MG
	A4	M	M	M	MG	MG	M	G	M	MG	M	M
DM2	A1	MG	G	G	G	G	G	MG	G	G	G	G
	A2	MG	VG	MG	MG	MG	G	MG	G	G	VG	G
	A3	G	MG	MG	VG	G	G	G	VG	MG	G	VG
	A4	VG	G	M	MG	M	MG	MG	G	M	MG	M
DM3	A1	MG	VG	G	VG	VG	G	VG	VG	G	G	VG
	A2	MG	G	MG	G	G	G	G	VG	MG	G	VG
	A3	G	MG	MG	VG	MG	M	G	MG	G	VG	G
	A4	G	MG	M	G	MG	M	MG	MG	MG	VG	MG
DM4	A1	G	G	G	MG	MG	G	G	G	MG	M	G
	A2	G	G	G	MG	M	G	G	MG	MG	MG	MG
	A3	MG	MG	MG	MG	MP	MG	G	MG	MG	MG	M
	A4	MG	M	MP	MP	MP	M	MG	MP	M	MG	MP
DM5	A1	MG	MG	MG	MG	MG	M	M	G	MG	MG	G
	A2	M	M	MG	MG	MG	M	MG	MG	MG	MG	G
	A3	M	M	M	MG	MG	M	MG	M	MG	MG	MG
	A4	MG	M	MP	M	M	M	M	MP	M	G	M

Table 3
Aggregated decision matrix.

	A1				A2				A3				A4			
Crit.	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U
C1	0.477	0.627	0.144	0.243	0.487	0.605	0.364	0.370	0.546	0.661	0.364	0.368	0.539	0.649	0.364	0.369
C2	0.592	0.735	0.116	0.209	0.605	0.709	0.363	0.366	0.460	0.579	0.364	0.372	0.508	0.562	0.452	0.453
C3	0.566	0.717	0.118	0.214	0.505	0.656	0.138	0.235	0.469	0.558	0.417	0.421	0.434	0.479	0.470	0.522
C4	0.528	0.673	0.137	0.232	0.477	0.627	0.144	0.243	0.585	0.721	0.127	0.217	0.463	0.571	0.385	0.443
C5	0.528	0.673	0.137	0.232	0.516	0.633	0.364	0.369	0.480	0.619	0.291	0.404	0.446	0.527	0.430	0.471
C6	0.546	0.661	0.364	0.368	0.558	0.638	0.417	0.418	0.497	0.583	0.417	0.420	0.490	0.519	0.479	0.479
C7	0.539	0.649	0.364	0.369	0.505	0.656	0.138	0.235	0.592	0.735	0.116	0.209	0.487	0.605	0.364	0.370
C8	0.627	0.769	0.096	0.193	0.528	0.673	0.137	0.232	0.509	0.620	0.364	0.370	0.440	0.539	0.401	0.485
C9	0.505	0.656	0.138	0.235	0.477	0.627	0.144	0.243	0.477	0.627	0.144	0.243	0.479	0.538	0.452	0.454
C10	0.546	0.661	0.364	0.368	0.559	0.703	0.128	0.222	0.539	0.649	0.364	0.369	0.539	0.649	0.364	0.369
C11	0.656	0.789	0.091	0.186	0.592	0.735	0.116	0.209	0.539	0.649	0.364	0.369	0.456	0.508	0.461	0.493

Table 4
Weighted Normalized matrix.

	A1				A2				A3				A4			
Crit.	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U	μ^L	μ^U	ν^L	ν^U
C1	0.761	0.816	0.839	0.880	0.764	0.808	0.912	0.914	0.787	0.828	0.912	0.913	0.784	0.823	0.912	0.913
C2	0.805	0.855	0.821	0.866	0.809	0.846	0.911	0.912	0.756	0.800	0.911	0.913	0.753	0.753	0.940	0.948
C3	0.564	0.639	0.948	0.969	0.582	0.652	0.938	0.961	0.741	0.742	0.932	0.947	0.762	0.782	0.925	0.933
C4	0.577	0.645	0.944	0.965	0.583	0.651	0.936	0.959	0.568	0.636	0.953	0.971	0.722	0.746	0.933	0.951
C5	0.782	0.833	0.833	0.874	0.777	0.819	0.911	0.912	0.764	0.815	0.893	0.920	0.744	0.760	0.929	0.943
C6	0.785	0.826	0.913	0.914	0.789	0.818	0.925	0.925	0.767	0.799	0.925	0.925	0.760	0.760	0.938	0.943
C7	0.786	0.825	0.911	0.912	0.773	0.827	0.833	0.875	0.805	0.855	0.821	0.866	0.716	0.719	0.936	0.955
C8	0.820	0.869	0.803	0.857	0.784	0.836	0.830	0.872	0.777	0.817	0.910	0.911	0.734	0.768	0.926	0.944
C9	0.762	0.816	0.846	0.885	0.751	0.806	0.850	0.888	0.751	0.806	0.850	0.888	0.741	0.742	0.940	0.949
C10	0.787	0.828	0.912	0.913	0.791	0.842	0.830	0.872	0.784	0.823	0.912	0.913	0.714	0.716	0.946	0.961
C11	0.827	0.874	0.802	0.857	0.805	0.855	0.821	0.866	0.786	0.825	0.911	0.912	0.756	0.769	0.930	0.940

Step 5. Normalize the aggregated IVq-ROF decision matrix considering the type of each criterion. Decision matrix is normalized using Equation (23).

Step 6. Construct the weighted normalized IVq-ROF decision matrix. The weighted normalized IVq-ROF decision matrix is established by using Equations 24 and 25. As a result, the weighted normalized matrix is shown in Table 4.

Step 7. Determine the negative ideal solution. The negative ideal solution is determined for weighted normalized IVq-ROF decision matrix as in Equations 26 and 27. The results are shown in Table 5.

Step 8. Compute the IVq-ROF weighted Euclidean (*ED*) and IVq-ROF weighted Hamming (*HD*) distances. To obtain the most appropriate IoT based waste management system alternative, distances from negative ideal solution are calculated using Equations 28–31.

Step 9. Construct the relative assessment matrix (*RA*). Considering *ED* and *HD* values for each IoT based waste management system alternative, the RA matrix is established by applying Equations 32–34. RA matrix is obtained as in Table 6.

Step 10. Determine the assessment score (*AS*) for each alternative option. Assessment score of each IoT based waste management system alternative can be calculated as shown in Equation (35). The results are

Table 5
IVq-ROF negative-ideal solution.

Criteria	μ^L	μ^U	ν^L	ν^U
C1	0.761	0.808	0.912	0.914
C2	0.753	0.753	0.940	0.948
C3	0.564	0.639	0.948	0.969
C4	0.568	0.636	0.953	0.971
C5	0.744	0.760	0.929	0.943
C6	0.760	0.760	0.938	0.943
C7	0.716	0.719	0.936	0.955
C8	0.734	0.768	0.926	0.944
C9	0.741	0.742	0.940	0.949
C10	0.714	0.716	0.946	0.961
C11	0.756	0.769	0.930	0.940

Table 6
RA matrix for the smart waste collection system based on IoT alternatives.

—	Relative assessment (RA)			
	A1	**A2**	**A3**	**A4**
A1	0.000	1.294	1.361	1.892
A2	−1.294	0.000	−0.008	0.597
A3	−1.361	0.008	0.000	0.531
A4	−1.892	−0.597	−0.531	0.000

Table 7
AS and ranking of alternatives.

	Entropy and CODAS based on IVq-ROF	
Alternatives	**AS**	**Rank**
A1	4.547	1
A2	−0.705	2
A3	−0.821	3
A4	−3.020	4

shown in Table 7.

Step 11. Rank all IoT based waste management system alternatives based on decreasing values of assessment scores. Once all IoT based waste management system alternatives are ranked based on decreasing values of ASs, the optimal one is selected. The results are shown in Table 7. The optimal ranking of these four major smart waste collection system based on IoT alternatives is A1 ≻ A2≻ A3≻ A4. Therefore, RFID, GIS and GPRS integration of waste management system (A1) is the best option for the municipal in Istanbul since it achieve sustainable development goals for the smart waste collection system based on IoT.

According to the results, RFID, GIS and GPRS integration of waste management system is selected as the best smart waste collection system based on IoT technology to optimize daily processes in municipal waste management system in terms of economic, social, and environmental aspects. While the proposed system provides an internet or web based solution for waste collection, transport and monitoring, it shows satisfactory performance in terms of high speed data transmission, precision, real-time data communication and reliability. The system has capability to ensure the proper collection and management of waste using data intelligently. RFID technology provides a real-time information on the fill level of the containers, helps the truck driver to go where it is needed, when it is needed, by acting in a planned, not random manner. Moving with the signal received from RFID, the driver finds the optimal route using GIS, not manually. The communication between the tracking unit and the server and vehicle position tracking GSM and GIS integration is used. Thus, the movement of the truck is monitored by the center in real-time with GPS. As a result, the selected system results in high economic and social benefits as well as a great reduction in environmental and air pollution emitted through conventional systems.

5. Discussions of results

To confirm the validity and the feasibility of the proposed framework in this section Sensitivity and Comparative analysis are conducted.

5.1. Sensitivity analysis

To check the priority ranking consistency of the modified Entropy and CODAS method on the basis of IVq-ROFSs, Sensitivity Analysis is performed in this subsection. Since the weight of DMs significantly effects the ranking results, the change for the weight of DMs can be evaluated in the sensitivity analysis. Accordingly, the aim of the sensitivity analysis is to demonstrate changes of the ranking of alternatives due to variation of DMs weights. Thus, it is revealed that the significance of the impact of each DM on the preference values of the alternatives. For the base case scenario, the weights of DMs are determined as equal. The remaining of the scenarios are formed as keeping weight of four DMs' weight constant and varying the last ones' weight considering his/her experience and job responsibility. Results of the sensitivity analysis for each scenario are compared in Fig. 4. According to results, it can be easily observed that A1 is always the best and A4 is the worst option for all scenarios. In addition, in all scenarios, except of the Scenario 1 and Scenario 6 the same ranking order for the alternatives is obtained. This

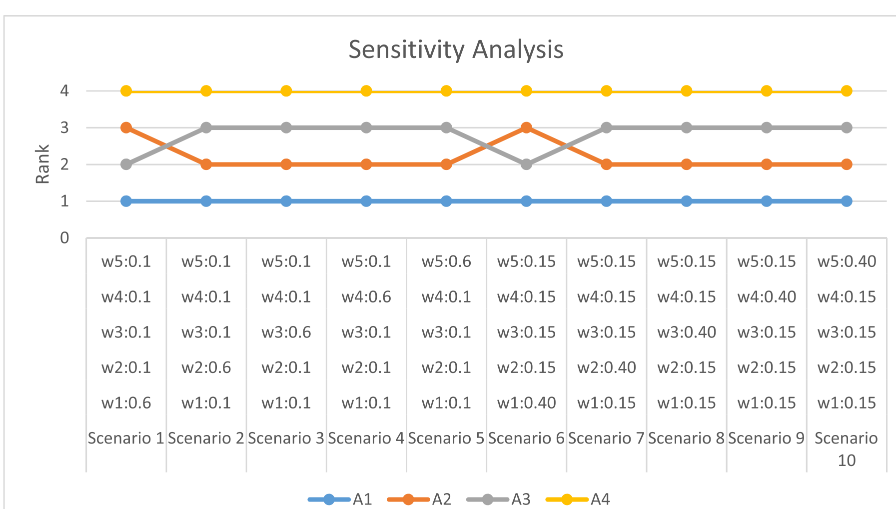
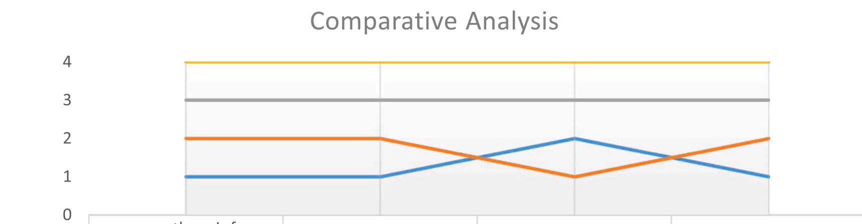


Fig. 4. The Sensitivity Analysis results based on scenarios.



	q-rung orthopair fuzzy TOPSIS by Alkan and Kahraman (2021)	IVq−ROFHA operator by Ju et al. (2019)	IVPF-TOPSIS by Seker and Aydın (2020)	Proposed Method
A1	1	1	2	1
A2	2	2	1	2
A3	3	3	3	3
A4	4	4	4	4

Fig. 5. Results of comparative analyses.

proves that alternative rankings are only sensitive to the change of the first DM weight according to generated scenarios. Therefore, there is no serious bias on the influence of ratings given by second, third, fourth and fifth DMs. As a result, sensitivity analysis shows the robustness and reliability of the results for the proposed framework.

5.2. *Comparative analysis*

In order to test the reliability and feasibility of the proposed method, the proposed method is compared with two different q-ROF-based MCDM methods and one MCDM method based on IVPFSs. The same decision data in Section 4 is used in the comparative analyses. Accordingly, the comparative analysis are performed using q-rung orthopair fuzzy TOPSIS method proposed by Alkan and Kahraman [75] with $q = 5$, and Interval valued q-rung orthopair fuzzy hybrid averaging (IVq−ROFHA) operator proposed by Ju et al. [57] with $q = 5$. Lastly, the proposed approach is compared with MCDM method based on IVPF proposed by Seker and Aydin [76]. To compare with the study presented by Alkan and Kahraman [75], the scales used for IVq-ROF-CODAS are converted to q-ROF scale for the comparison purpose. As a result, the same ranking results for alternatives are obtained. Then, the same problem is compared with Interval valued q-rung orthopair fuzzy hybrid averaging (IVq−ROFHA) operator proposed by Ju et al. [57]. The ranking results aren't varied. To perform comparative analysis the IVq-ROF scale is converted to IVPF scale for TOPSIS method based on IVPF introduced by Seker and Aydin [76]. The overall ranking obtained with IVPF-TOPSIS is A2, A1, A3 A4. The results of the comparative analyses applied by using q-ROF-based MCDM methods and IVPF based MCDM are illustrated in Fig. 5. As a result, while relatively consistent results obtained based on modified IVq-ROF Entropy and CODAS method, there is slightly difference on raking results based on IVPF-TOPSIS. While third and last ranking order haven't changed, the ranking order of the A1 and A2 alternatives have changed. This is inevitable since IVq-ROFS provides further advantages in meeting the uncertainties and deficiencies in a wider area due to knowledge and inconsistencies among DM groups in decision making problems. Thus, comparative analyses prove robustness and superiority of the proposed approach in the selecting the most appropriate IoT technology based smart waste collection system and can be used in practical and real-life decision-making problems.

6. Conclusion

Waste management is one of the most important problems in developed/developing countries. Furthermore, waste collection and transportation are considered to be the most important and costly steps in waste management, as they require a labor-intensive processes. However, the current practices for waste management in municipals shows that waste collection have been carried out in an unhealthy and inefficient way, manually. Therefore, the need for smart system solutions is increasing day by day. This paper aimed to reduce the cost and minimize the pollution of the environment by providing real-time collection of waste by integrating IoT-based technologies for waste collection and transportation systems. For this aim, this paper presented the selection of the most suitable smart waste collection system based on IoT technology for the local municipal in Istanbul using CODAS method and modified Entropy measure on the basis of IVq-ROFSs. IVq-ROF CODAS method was used since the effective waste management requires complex decision-making process due to both quantitative and qualitative factors and need multiple stakeholders to find the most optimal decisions. Due to many conflicting factors and uncertain information as a nature of the problem, IVq-ROFSs were used to handle uncertainty better by allowing DMs to make an assessment in a wider area. In order to obtain the weight vector of criteria for decision making process, modified IVq-ROF Entropy method was also developed to calculate relative weight of evaluation criteria objectively. To the author' knowledge, there is no study applying Entropy and CODAS on the basis of IVq-ROFSs method for decision making problems in waste management. Since ICT and IoT systems bring more economic, social, and environmental benefits for waste management, the proposed method has optimally touched the economic, social, and environmental aspects for the selection of suitable smart waste collection system based on IoT technology.

Accordingly, the most appropriate alternative was selected as RFID, GIS and GPRS integration that is suitable for a healthy, hygienic and modern city design with the least cost and less harm to the environment. In addition, sensitivity analysis showed the validity of modified Entropy and CODAS integration on the basis of IVq-ROFSs method. The obtained results and all scenarios in sensitivity analysis showed that while A1 remains the best alternative, A4 is the worst alternative. Comparative analysis also verified the results of the proposed approach. Although the study has the contributions highlighted above, there are some limitations of this study that can be considered as suggestions for future studies. The first limitation of this study is related to the number of DMs. To deal with this limitation, future studies can be expanded by receiving more DMs opinions. In addition, since criteria weights significantly affect the results obtained, the proposed approach can be extended with a more comprehensive weight technique method that considers both subjective and objective criteria weights. Based on the encouraging results obtained through verification and validation, the proposed approach also can be applied to support critical long-term decisions for different country specific management problems such as transportation, energy, waste management, etc.

Author statement

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Data availability

Data will be made available on request.

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