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ORIGINAL PAPER

Analyzing blockchain-based waste management investments in smart cities using quantum picture fuzzy rough modelling

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Abstract

Blockchain-based waste management investments are key to increase the performance for achieving sustainable growth for both businesses and the country's economy. In this context, a new study should be conducted to identify the most important variables. Accordingly, the purpose of this study is to examine blockchain-based waste management investments via a novel model. The scope of this study is the smart cities that are defined as settlements that aim to improve the quality of life and ensure sustainability by using technology to manage and improve services. Firstly, artificial intelligence (AI) methodology is taken into consideration to compute the weights of the experts. Secondly, the weights of the criteria for blockchain-based waste management investments are computed. Finally, selected investment alternatives for smart cities are ranked with Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) methodology. Additionally, a comparative analysis is also performed by technique for order preference by similarity (TOPSIS). In addition to this issue, a sensitivity analysis is also conducted with four different cases to check the coherency of the analysis results. The main contribution of this study is the calculation of the expert weights by AI. It is identified that participating in waste to energy schemes has the greatest significance. Similarly, optimizing the lifecycle management has also high weight. It is also defined that integration of physical and digital infrastructures is the most critical alternative. Moreover, urban innovativeness is another critical factor for this situation.

Keywords Artificial intelligence-based decision-making · Quantum picture fuzzy rough modelling · Blockchain-based waste management · Energy investments

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Introduction

Waste management investments are projects that involve the disposal of waste in a way that does not harm the environment. These projects include different processes such as collecting, recycling and effectively disposing of waste. It is possible to talk about many different benefits of these projects. Waste management investments are vital for preventing environmental pollution. By effectively disposing of these wastes, damage to the ecosystem can be reduced. On the other hand, reuse of waste reduces the need for raw materials. In other words, thanks to successful waste management, it is possible to use natural resources sustainably (Baralla et al. 2023). Similarly, reusing waste also helps in reducing the cost of raw materials significantly. This helps to increase the financial performance of the projects. In addition, many countries have specific legal regulations on waste management. These investments help businesses comply with these legal regulations. Thus, it is possible to minimize the risk of possible criminal sanctions (Jiang et al. 2023). In summary, waste management plays a vital role in achieving sustainable development goals.

Blockchain-based projects can be developed to ensure that waste management investments continue their activities effectively. These projects represent the use of blockchain technology in tracking waste-related processes (Arsyad et al. 2022). In other words, it states that blockchain technology should be considered in monitoring, recycling, and disposal of waste. There are some benefits to using the blockchain system in this process. Blockchain provides reliable and transparent data sharing regarding the process (Singh et al. 2023). Thus, all processes of waste management can be recorded. On the other hand, in this system, a digital identity can be defined for each type of waste. This technology also allows the entire process to be tracked clearly. In this way, it is possible to detect a problem encountered in the waste management process at early levels. This allows the necessary measures to be taken in a timely manner to quickly solve the problem. Additionally, data security can be ensured by using the blockchain system in waste management processes. Cryptographic techniques used in this technology can prevent private data from falling into the hands of unauthorized persons (Rao and Sujatha 2023). Finally, thanks to this advanced technology, efficiency in waste management processes can be increased. This also enables the costs of projects to be reduced.

Some variables are important regarding blockchain-based waste management projects. Monitoring the regeneration of waste has an important role in improving the performance of these investments (Guo et al. 2021). In this way, it is possible to increase the efficiency of recycling processes. On the other hand, participating in the waste-to-energy system has a great influence on blockchain-based waste management investments (Das et al., 2024). These systems aim to increase electricity production by using waste. In other words, by using waste, it is possible to reduce environmental damage in energy production. Moreover, the peer-to-peer energy trading system is also very necessary in the development of these projects. In this case, the production of energy from renewable sources also helps environmental sustainability (Hasan et al. 2023).

The effectiveness of waste management systems is very important for achieving sustainable growth for both businesses and the country's economy. Blockchain-based waste management investments are also key to increasing the performance of this process. Therefore, to increase the effectiveness of these investments, improvements must be made to the indicators. However, each improvement may cause costs to increase. In other words, making too many improvements can lead to an increase in costs that will negatively affect the performance of businesses (Bułkowska et al. 2023). Therefore, businesses need to focus on the factors that matter most first. Nevertheless, it seems that very few studies in the literature analyze this process. In this context, a new study should be conducted to identify the most important variables affecting the performance of blockchain-based waste management investments.

Accordingly, this study evaluates blockchain-based waste management investments via a novel model. In this model, an evaluation is mainly performed for smart cities. Therefore, it is aimed to identified which factors should be priorities to provide effective waste management strategies for smart cities. These cities can be defined as the settlements that aim to improve the quality of life and ensure sustainability by using technology to manage and improve services. In the first stage of the proposed model, artificial intelligence methodology is taken into consideration to calculate the weights of the experts. In the second stage, the weights of the criteria for blockchain-based waste management investments by M-SWARA. Next, selected investment alternatives for smart cities are ranked with VIKOR. Additionally, a comparative analysis is also performed by TOPSIS. In addition to this issue, a sensitivity analysis is also conducted with four different cases to check the coherency of the analysis results.

The main contributions of this study are given below.

(i) The most important novelty of this study is the adoption of AI to the model. It is possible to talk about many advantages of this situation. Fuzzy logic and multi-criteria decision-making methods can be taken into consideration to analyze uncertain and complex situations. By incorporating artificial intelligence into this process, it is possible to reduce the uncertainty in the process. In the model proposed in this study, expert opinions are analyzed by using artificial intelligence methodology. In this context, not every expert's assessment is equally accepted.

(ii) The development of the M-SWARA method is one of the important contributions of this study to the literature. The SWARA method has many advantages, such as being able to evaluate weights gradually. On the other hand, the failure to consider the causal relationship between the criteria is considered one of the most important disadvantages. To overcome this deficiency, some improvements are applied to the classical SWARA technique. In this way, impact relation map can be created with the newly developed M-SWARA technique.

Literature review is indicated in the second part. The proposed model is explained in the third part. The final parts give information about the results, discussion and conclusion.

Literature review

Monitoring the regeneration of waste is significant for blockchain-based waste management projects. The regeneration of waste helps to increase the efficiency of recycling processes.

Naqash et al. (2023) stated that thanks to the regeneration of waste, less raw materials are needed. This situation contributes to less consumption of natural resources. Castiglione et al. (2023) showed that monitoring the regeneration of waste allows reducing environmental impacts. By performing this monitoring effectively, it is possible to clearly determine which materials can be recycled (Movaffaghi and Yitmen 2023). This helps to accurately detect the processes that cause environmental problems. Additionally, Dhingra et al. (2023) identified that waste regeneration increases the transparency of supply chain processes. Thus, it can be accurately determined at which stages of the supply process waste occurs (Yang et al. 2023). This allows the performance of blockchain-based waste management investments to increase. Saad et al. (2023) concluded that the regeneration of waste must be monitored to comply with legal regulations. This reduces the possibility of financial penalties arising from practices contrary to legal processes.

Participating in waste to energy schemes is necessary to increase the effectiveness of blockchain-based waste management investments. Zghaibeh (2023) underlined that these systems aim to increase electricity production by using waste. In other words, by using waste, it is possible to reduce environmental damage in energy production. In addition to this situation, Sambare et al. (2023) denoted that waste-to-energy systems also enable the amount of waste to be reduced. This both reduces environmental pollution and contributes to the protection of natural resources. Debnath et al. (2023) demonstrated that participating in the waste-to-energy system also allows all processes to be controlled via the blockchain system. In this way, waste can be managed much more effectively. Likewise, these systems also help reduce energy costs. According to Scott eet al. (2023), using waste as a resource in the energy production process contributes to the consumption of less raw materials. Moreover, waste-to-energy also helps increase energy security. This contributes to energy independence by increasing local production (Calandra et al. 2023).

Peer to peer energy trading system is also critical with respect to the blockchain-based waste management investments. Kumar and Chopra (2023) underlined that this trading system enables direct exchange of energy between individuals and businesses. This helps to use renewable energy more. Patil et al. (2023) highlighted that peer-to-peer energy trading system allows more energy to be produced within the country. Producing this energy from renewable sources also helps environmental sustainability. Similarly, according to Dursun et al. (2023), energy produced within the country also reduces countries' energy imports. Since the current account balance will be positively affected by this issue, the country's economy will be stronger. Thanks to blockchain systems, every stage of the peer-to-peer energy trading system can be followed in detail. This contributes to increasing transparency in the trading system. Alhasan and Hamdan (2023) showed that since this will increase confidence, more investors can focus on these projects. Peer-to-peer energy trading allows energy users to sell energy directly to each other. This situation allows energy producers to earn more income. On the other hand, Alnuaimi et al. (2023) stated that energy supply and demand balance can be achieved thanks to peer-to-peer energy trading systems. This condition also helps to ensure stability in energy prices.

Life cycle management should be optimized for blockchain-based waste management investments. Wankmüller et al. (2023) defined that life cycle management covers the processes from the moment waste is created to the moment it is destroyed. For these processes to be managed effectively, waste must be identified and classified correctly. According to Oyebode et al. (2023), this situation contributes to a more successful integration of the blockchain system into waste management processes. On the other hand, life cycle management of waste involves the effective use of materials and resources (Dabic-Miletic and Simic 2023). This issue has an impact on increasing the efficiency of projects. Moreover, Samadhiya et al. (2023) identified that life cycle management significantly supports the improvement of production processes. In this way, it is possible to minimize waste production. Amitha and Pamba (2023) stated that thanks to the effective life cycle management of waste, compliance with legal processes can be achieved more successfully. Hence, the risk of having legal punishment can be minimized by the help of this situation.

By considering these studies, it is seen that there are some essential criteria for blockchain-based waste management investments in smart cities. There are some investment alternatives for smart cities to improve these projects. Efficient public services can help make waste management processes transparent and reliable (Khanh et al. 2023). Circular economy practices also play a key role to increase clean energy projects (Kumar et al. 2023; Joshi et al. 2023). This condition has a positive influence for the effective waste management (Biancardi et al. 2021; Phiri et al. 2023). Integration of physical and digital infrastructures and urban innovativeness can also consider for smart cities to improve the blockchain-based waste management processes (Holanda Filho et al. 2023). As a result of these evaluations, four different criteria can be identified regarding the blockchain-based waste management investments in smart cities (Ferreira et al. 2023). The details are demonstrated in Table 1.

The waste remanufacturing process has a very important role in increasing the effectiveness of waste management investments. The most important advantage of remanufacturing is less consumption of natural resources. This contributes significantly to ensuring resource efficiency (Ferreira et al. 2023). Moreover, participation in waste-to-energy systems plays a critical role in increasing the effectiveness of

Table 1 Criteria set for blockchain-based waste management investments

Criteria	References
Monitoring the remanufacturing of waste	Ferreira et al. (2023)
Participating in waste to energy schemes	Khanh et al. (2023)
Facilitating peer to peer energy trading	Kumar and Chopra (2023)
Optimizing the lifecycle management	Joshi et al. (2023)

waste management investments. One of the most important benefits of this process is the reduction in the amount of waste. This both increases the amount of energy produced and contributes to reducing environmental pollution (Khanh et al. 2023). Furthermore, peer to peer energy trading offers an innovative approach to increase the effectiveness of waste management investments. This can increase the cost effectiveness of waste management projects (Kumar and Chopra 2023). Thus, it is possible to increase the profitability of projects. In addition to them, life cycle management optimization is also necessary to increase the effectiveness of waste management investments (Joshi et al. 2023). This method significantly supports minimizing waste production. Thus, it is possible to use resources more efficiently.

The main conclusions of the literature review are given below. Effective waste management plays an important role for the sustainable development of the countries. In this context, necessary actions should be taken to minimize this problem. However, each action to make improvements causes cost increase for the companies. In other words, having improvements for all variables can lead to incredible cost increases that create significant financial problems for these companies. Due to this situation, companies should focus on the most crucial indicators to provide cost effectiveness while taking the actions to solve these problems. In this process, there is a need for a new study that identifies the most critical items for the improvements of the blockchain-based waste management investments. Nonetheless, there are limited studies to focus on this issue in the literature. To satisfy this missing part, a new model is generated in this study to understand the most significant criteria of effective blockchain-based waste management investments in smart cities.

Materials and methods

This study aims to examine blockchain-based waste management investments in smart cities. To achieve this objective, a novel fuzzy decision-making model is created that has three different stages as denoted in Fig. 1.

The approaches considered in the proposed model are explained in the following subtitles.

Calculating the weights of the experts by AI

Step 1 is related to the definition of the demographic information of the decision makers. One of the most criticized issues in decision-making models is that the importance of these people is considered equal in the analysis of expert opinions (Biswas et al. 2024a). However, these experts may differ from each other in many aspects. For example, the opinions of an expert with more work experience should also be taken into account with a higher weight of importance (Kousar et al. 2024; Kannan et al. 2024). In this context, in this model, demographic differences of experts are analyzed with the help of artificial intelligence. In other words, using the K-means clustering algorithm, experts are divided into different clusters (Ikotun et al. 2023). To achieve this goal, optimal clusters are determined using the elbow method. By plotting the within-cluster sum of squares (WCSS) against the number of clusters, the details can be identified (Gratsos et al. 2023). This situation is detailed in Eq. (1).

$$WCSS = \sum_{j=1}^{k} \sum_{x_i \in C_j} d(x_i, c_j)^2 \tag{1}$$

Step 2 shows the calculation of the optimal k value. *Step 3* includes the application of this algorithm. This situation is demonstrated in Eq. (2).

$$d(x_i, x_j) = \sqrt{\sum_{l=1}^{n} (x_{il} - x_{jl})^2} \tag{2}$$

Within this context, $a_i = j$ means that x_i belongs to cluster j. After that, cluster centres are updated as detailed in Eq. (3).

$$c_j = \frac{1}{| C_j |} \sum_{x_i \in C_j} x_i \tag{3}$$

Within this context, C_j determines data points. *Step 4* underlines the calculation of the weights of these people by using Eqs. (4–6).

$$s_j = \frac{1}{n} \sum_{l=1}^{n} \sigma_{jl} \tag{4}$$

$$\sigma_{jl} = \sqrt{\frac{1}{|C_j|} \sum\nolimits_{x_i \in C_j} \left(x_{il} - \bar{x}_{jl}\right)^2} \tag{5}$$

$$\bar{x}_{jl} = \frac{1}{|C_j|} \sum\nolimits_{x_i \in C_j} x_{il} \tag{6}$$

Equation (7) is considered for the calculation process of the cluster weights (w_j) where $| C_j |$ is the size of cluster j and the weights can be defined in Eq. (8).

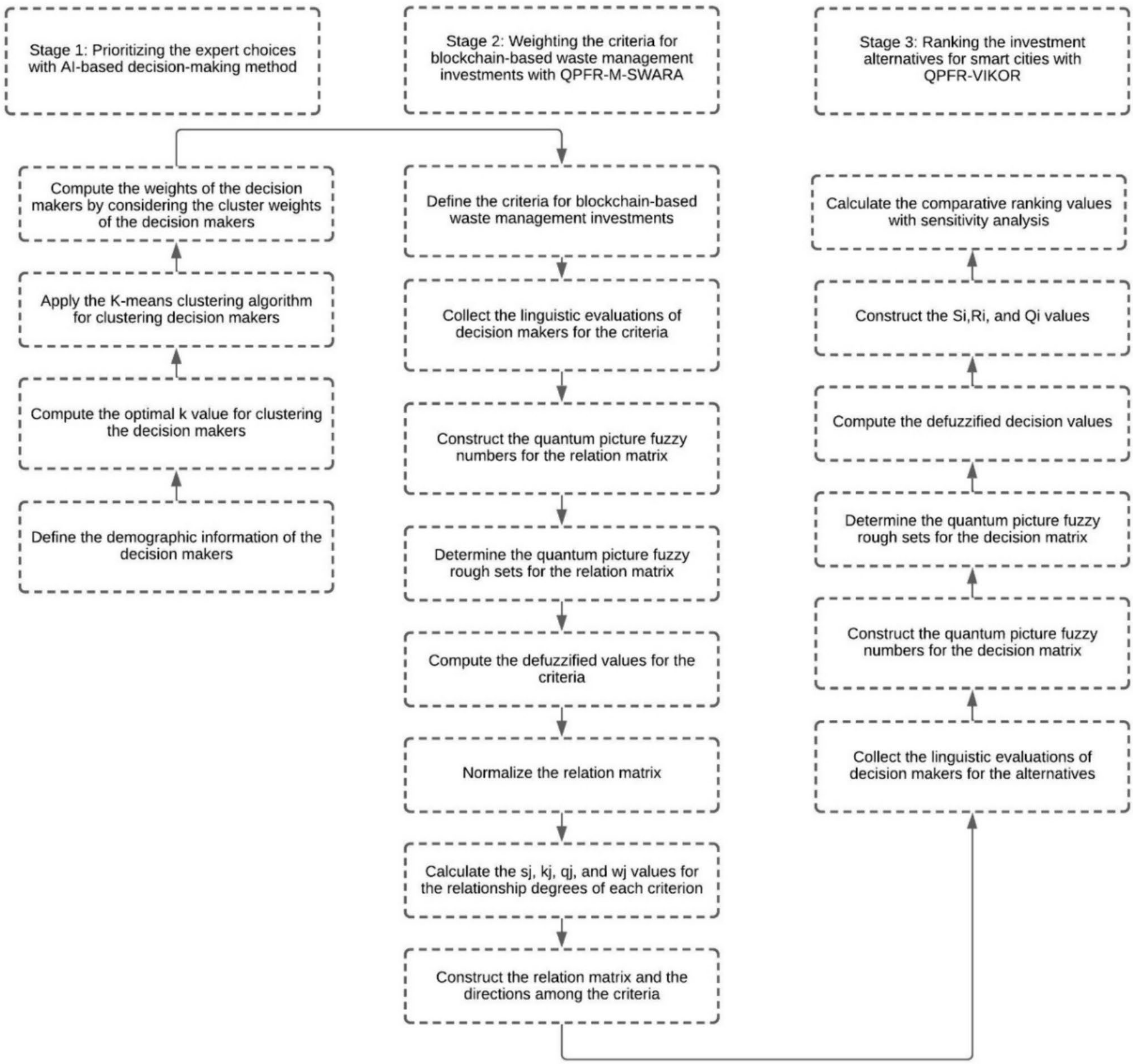

Fig. 1 The flowchart of hybrid model. *Source*: Created by authors

$$w_j = \mid C_j \mid \times s_j \tag{7}$$

$$w_{tj} = \frac{1}{\mid C_j \mid} \frac{w_j}{\sum_{w_j \in C_j} w_j} \tag{8}$$

M-SWARA

Secondly, the weights of the criteria for blockchain-based waste management investments. Quantum theory is a physics theory developed to explain the interactions of atoms and particles. According to this theory, the relationship between the position and momentum of an atom is quite delicate. This situation causes the uncertainty in the process to increase. Quantum theory also helps minimize this uncertainty. Considering this advantage, this technique is integrated with fuzzy multi-criteria decision-making methodology (Damjanovic et al. 2022). This contributes to minimizing the uncertainty in the process (Al-Binali et al. 2023). The details are shown in Eqs. (9–11).

$$Q(|u>) = \varphi e^{j\theta} \tag{9}$$

$$|C> = \left\{ |u_1>, |u_2>, \ldots, |u_n> \right\} \tag{10}$$

$$\sum_{|u>\subseteq|C>} |Q(|u>)| = 1 \tag{11}$$

In this process, C explains a collection of exhaustive events represented by $|u_i>$. Picture fuzzy sets represent an advanced form of triangular fuzzy numbers (Zhao et al. 2023). Equation (12) indicates triangular sets.

$$A = \left\{ \langle x, \mu_A(x) \rangle | x \in X \right\} \tag{12}$$

Within this context, A shows the fuzzy sets, X defines a universe. Equation (13) indicates intuitionistic sets.

$$A = \left\{ \langle x, \mu_A(x), v_A(x) \rangle | x \in X \right\} \tag{13}$$

In this process, v_A represents the non-membership function. Moreover, Eq. (14) defines the picture fuzzy sets (He and Wang 2023).

$$A = \left\{ \langle x, \mu_A(x), n_A(x), v_A(x), h_A(x) \rangle | x \in X \right\} \tag{14}$$

General operations are explained in Eqs. (15–19).

$$A \subseteq B \text{ if } \mu_A(x) \leq \mu_B(x) \text{ and } n_A(x) \leq n_B(x) \text{ and } v_A(x) \geq v_B(x), \ \forall x \in X \tag{15}$$

$$A = B \text{ if } A \subseteq B \text{ and } B \subseteq A \tag{16}$$

$$A \cup B = \left\{ \left(x, max\left(\mu_A(x), \mu_B(x)\right), min\left(n_A(x), n_B(x)\right), min\left(v_A(x), v_B(x)\right) \right) | x \in X \right\} \tag{17}$$

$$A \cap B = \left\{ \left(x, min\left(\mu_A(x), \mu_B(x)\right), min\left(n_A(x), n_B(x)\right), max\left(v_A(x), v_B(x)\right) \right) | x \in X \right\} \tag{18}$$

$$coA = \overline{A} = \left\{ \left(x, v_A(x), n_A(x), \mu_A(x) \right) | x \in X \right\} \tag{19}$$

On the other side, rough numbers are an extension of rough set theory. Lower ($\underline{PPX}(C_i)$), upper ($\overline{PPX}(C_i)$) and ($BDR(C_i)$) are explained in Eqs. (20–22) (Pamučar et al. 2023).

$$\underline{PPX}(C_i) = \cup\left\{ Y \in X / R(Y) \leq C_i \right\} \tag{20}$$

$$\overline{PPX}(C_i) = \cup\left\{ Y \in X / R(Y) \geq C_i \right\} \tag{21}$$

$$BDR(C_i) = \cup\left\{ Y \in X / R(Y) \neq C_i \right\} \tag{22}$$

Equations (23–25) give information about the limits.

$$\underline{Lim}(C_i) = \sqrt[N_L]{\prod_{i=1}^{N_L} Y \in \underline{PPX}(C_i)} \tag{23}$$

$$\overline{Lim}(C_i) = \sqrt[N_U]{\prod_{i=1}^{N_U} Y \in \overline{PPX}(C_i)} \tag{24}$$

$$RN(C_i) = \underline{Lim}(C_i), \overline{Lim}(C_i) \tag{25}$$

In this process, N_L and N_U represent the number of objects for $\underline{PPX}(C_i)$ and $\overline{PPX}(C_i)$. QPFRSs are given in Eq. (26).

$$|C_A> = \left\{ \begin{array}{l} \langle u, (\underline{Lim}(C_{i\mu_A}), \overline{Lim}(C_{i\mu_A})(u), \left[\underline{Lim}(C_{in_A}), \overline{Lim}(C_{in_A})\right](u), \\ \left[\underline{Lim}(C_{iv_A}), \overline{Lim}(C_{iv_A})\right](u), \left[\underline{Lim}(C_{ih_A}), \overline{Lim}(C_{ih_A})\right](u)) \Big| u \in 2^{|C_A>} \end{array} \right\} \tag{26}$$

Equations (27–28) define the PFR numbers.

Lower Limits of PFR numbers

$$\begin{cases} \underline{Lim}(C_{i\mu_A}) = \frac{1}{N_{L\mu_A}} \sum_{i=1}^{N_{L\mu_A}} Y \in \underline{PPX}(C_{i\mu_A}) \\ \underline{Lim}(C_{in_A}) = \frac{1}{N_{Ln_A}} \sum_{i=1}^{N_{Ln_A}} Y \in \underline{PPX}(C_{in_A}) \\ \underline{Lim}(C_{iv_A}) = \frac{1}{N_{Lv_A}} \sum_{i=1}^{N_{Lv_A}} Y \in \underline{PPX}(C_{iv_A}) \\ \underline{Lim}(C_{ih_A}) = \frac{1}{N_{L\pi_A}} \sum_{i=1}^{N_{L\pi_A}} Y \in \underline{PPX}(C_{ih_A}) \end{cases} \tag{27}$$

Upper Limits of PFR numbers

$$\begin{cases} \overline{Lim}(C_{i\mu_A}) = \frac{1}{N_{U\mu_A}} \sum_{i=1}^{N_{U\mu_A}} Y \in \overline{PPX}(C_{i\mu_A}) \\ \overline{Lim}(C_{in_A}) = \frac{1}{N_{Un_A}} \sum_{i=1}^{N_{Un_A}} Y \in \overline{PPX}(C_{in_A}) \\ \overline{Lim}(C_{iv_A}) = \frac{1}{N_{Uv_A}} \sum_{i=1}^{N_{Uv_A}} Y \in \overline{PPX}(C_{iv_A}) \\ \overline{Lim}(C_{ih_A}) = \frac{1}{N_{U\pi_A}} \sum_{i=1}^{N_{U\pi_A}} Y \in \overline{PPX}(C_{ih_A}) \end{cases} \tag{28}$$

In these equations, $N_{L\mu_A}$,N_{Ln_A}, N_{Lv_A}, N_{Lh_A} denote the number of elements in $\underline{PPX}(C_{i\mu_A})$, $\underline{PPX}(C_{in_A})$, $\underline{PPX}(C_{iv_A})$, $\underline{PPX}(C_{ih_A})$ while $N_{U\mu_A}$,N_{Un_A}, N_{Uv_A}, N_{Uh_A} are given for $\overline{PPX}(C_{i\mu_A})$, $\overline{PPX}(C_{in_A})$, $\overline{PPX}(C_{iv_A})$, $\overline{PPX}(C_{ih_A})$ as in Eqs. (29–36).

$$\underline{PPX}(C_{i\mu_A}) = \cup\left\{ Y \in X / \widetilde{R}(Y) \leq C_{i\mu_A} \right\} \tag{29}$$

$$\underline{PPX}(C_{in_A}) = \cup\left\{ Y \in X / \widetilde{R}(Y) \leq C_{in_A} \right\} \tag{30}$$

$$\underline{PPX}(C_{iv_A}) = \cup\left\{ Y \in X / \widetilde{R}(Y) \leq C_{iv_A} \right\} \tag{31}$$

$$\underline{PPX}\left(C_{ih_A}\right) = \cup\left\{ Y \in X/\widetilde{R}(Y) \leq C_{ih_A} \right\} \tag{32}$$

$$\overline{PPX}\left(C_{i\mu_A}\right) = \cup\left\{ Y \in X/\widetilde{R}(Y) \leq C_{i\mu_A} \right\} \tag{33}$$

$$\overline{PPX}\left(C_{in_A}\right) = \cup\left\{ Y \in X/\widetilde{R}(Y) \leq C_{in_A} \right\} \tag{34}$$

$$\overline{PPX}\left(C_{iv_A}\right) = \cup\left\{ Y \in X/\widetilde{R}(Y) \leq C_{iv_A} \right\} \tag{35}$$

$$\overline{PPX}\left(C_{ih_A}\right) = \cup\left\{ Y \in X/\widetilde{R}(Y) \leq C_{ih_A} \right\} \tag{36}$$

Within this framework, $\tilde{C}_i = \left(C_{i\mu_A}, C_{in_A}, C_{iv_A}, C_{ih_A}\right)$ and $\tilde{R}$ are the collection of $\left\{\tilde{C}_1, \tilde{C}_2, \ldots, \tilde{C}_n\right\}$. Equation (37) and (38) highlight general definitions.

$$C = \left[C_\mu.e^{j2\pi.\alpha}, C_n.e^{j2\pi.\gamma}, C_v.e^{j2\pi.\beta}, C_h.e^{j2\pi.T}\right] \tag{37}$$

$$\varphi^2 = \left|C_\mu\left(|u_i>\right)\right| \tag{38}$$

The amplitude of the membership function C_μ of quantum fuzzy sets is demonstrated with φ^2. In this proposed model, golden ratio (G) is considered to compute degrees. Equations (39) and (40) give information about these issues.

$$C_n = \frac{C_\mu}{G} \tag{39}$$

$$C_h = \frac{C_v}{G} \tag{40}$$

The phase angles of the degrees are demonstrated in Eqs. (41–43).

$$\alpha = \left|C_\mu\left(|u_i>\right)\right| \tag{41}$$

$$\gamma = \frac{\alpha}{G} \tag{42}$$

$$T = \frac{\beta}{G} \tag{43}$$

The operations of quantum picture fuzzy rough numbers are defined in Eqs. (44–47).

$$\lambda * \tilde{A}_c = \left\{ \begin{array}{l} \left[\underline{Lim}\left(C_{\mu_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{\mu_{\tilde{A}}}\right)\lambda\, e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\bar{\alpha}_{\tilde{A}}}{2\pi}\right)\lambda}\right], \left[\underline{Lim}\left(C_{n_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{n_{\tilde{A}}}\right)\lambda\, e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\bar{\gamma}_{\tilde{A}}}{2\pi}\right)\lambda}\right] \\ \left[\underline{Lim}\left(C_{v_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{v_{\tilde{A}}}\right)\lambda\, e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\bar{\beta}_{\tilde{A}}}{2\pi}\right)\lambda}\right], \left[\underline{Lim}\left(C_{h_{\tilde{A}}}\right)\lambda, \overline{Lim}\left(C_{h_{\tilde{A}}}\right)\lambda\, e^{j2\pi.\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)\lambda, \left(\frac{\bar{T}_{\tilde{A}}}{2\pi}\right)\lambda}\right] \end{array} \right\}, \lambda > 0 \tag{44}$$

$$\tilde{A}_c^\lambda = \left\{ \begin{array}{l} \left[\underline{Lim}\left(C_{\mu_{\tilde{A}}}\right)^\lambda, \overline{Lim}\left(C_{\mu_{\tilde{A}}}\right)^\lambda\right] e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)^\lambda, \left(\frac{\bar{\alpha}_{\tilde{A}}}{2\pi}\right)^\lambda}, \left[\underline{Lim}\left(C_{n_{\tilde{A}}}\right)^\lambda, \overline{Lim}\left(C_{n_{\tilde{A}}}\right)^\lambda\right] e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)^\lambda, \left(\frac{\bar{\gamma}_{\tilde{A}}}{2\pi}\right)^\lambda}, \\ \left[\underline{Lim}\left(C_{v_{\tilde{A}}}\right)^\lambda, \overline{Lim}\left(C_{v_{\tilde{A}}}\right)^\lambda\right] e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)^\lambda, \left(\frac{\bar{\beta}_{\tilde{A}}}{2\pi}\right)^\lambda}, \left[\underline{Lim}\left(C_{h_{\tilde{A}}}\right)^\lambda, \overline{Lim}\left(C_{h_{\tilde{A}}}\right)^\lambda\right] e^{j2\pi.\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)^\lambda, \left(\frac{\bar{T}_{\tilde{A}}}{2\pi}\right)^\lambda}, \end{array} \right\}, \lambda > 0 \tag{45}$$

$$\tilde{A}_c \cup \tilde{B}_c = \left\{ \begin{array}{l} \left[min\left(\underline{Lim}\left(C_{\mu_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{\mu_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{\alpha}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{\mu_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\bar{\alpha}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{\mu_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\bar{\alpha}_{\tilde{B}}}{2\pi}\right)}\right)\right] \\ \left[min\left(\underline{Lim}\left(C_{n_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{n_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{\gamma}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{n_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\bar{\gamma}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{n_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\bar{\gamma}_{\tilde{B}}}{2\pi}\right)}\right)\right] \\ \left[min\left(\underline{Lim}\left(C_{v_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{v_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{\beta}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{v_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\bar{\beta}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{v_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\bar{\beta}_{\tilde{B}}}{2\pi}\right)}\right),\right] \\ \left[min\left(\underline{Lim}\left(C_{h_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\underline{T}_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}\left(C_{h_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\underline{T}_{\tilde{B}}}{2\pi}\right)}\right), max\left(\overline{Lim}\left(C_{h_{\tilde{A}}}\right)e^{j2\pi.\left(\frac{\bar{T}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}\left(C_{h_{\tilde{B}}}\right)e^{j2\pi.\left(\frac{\bar{T}_{\tilde{B}}}{2\pi}\right)}\right)\right] \end{array} \right\} \tag{46}$$

$$\tilde{A}_c \cap \tilde{B}_c = \left\{ \begin{array}{l} \left[max\left(\underline{Lim}(C_{\mu_{\tilde{A}}}) e^{j2\pi.\left(\frac{\alpha_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}(C_{\mu_{\tilde{B}}}) e^{j2\pi.\left(\frac{\alpha_{\tilde{B}}}{2\pi}\right)} \right), min\left(\overline{Lim}(C_{\mu_{\tilde{A}}}) e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}(C_{\mu_{\tilde{B}}}) e^{j2\pi.\left(\frac{\overline{\alpha}_{\tilde{B}}}{2\pi}\right)} \right) \right] \\ \left[max\left(\underline{Lim}(C_{n_{\tilde{A}}}) e^{j2\pi.\left(\frac{\gamma_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}(C_{n_{\tilde{B}}}) e^{j2\pi.\left(\frac{\gamma_{\tilde{B}}}{2\pi}\right)} \right), min\left(\overline{Lim}(C_{n_{\tilde{A}}}) e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}(C_{n_{\tilde{B}}}) e^{j2\pi.\left(\frac{\overline{\gamma}_{\tilde{B}}}{2\pi}\right)} \right) \right] \\ \left[max\left(\underline{Lim}(C_{v_{\tilde{A}}}) e^{j2\pi.\left(\frac{\beta_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}(C_{v_{\tilde{B}}}) e^{j2\pi.\left(\frac{\beta_{\tilde{B}}}{2\pi}\right)} \right), min\left(\overline{Lim}(C_{v_{\tilde{A}}}) e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}(C_{v_{\tilde{B}}}) e^{j2\pi.\left(\frac{\overline{\beta}_{\tilde{B}}}{2\pi}\right)} \right) \right] \\ max\left(\underline{Lim}(C_{h_{\tilde{A}}}) e^{j2\pi.\left(\frac{\tau_{\tilde{A}}}{2\pi}\right)}, \underline{Lim}(C_{h_{\tilde{B}}}) e^{j2\pi.\left(\frac{\tau_{\tilde{B}}}{2\pi}\right)} \right), min\left(\overline{Lim}(C_{h_{\tilde{A}}}) e^{j2\pi.\left(\frac{\overline{\tau}_{\tilde{A}}}{2\pi}\right)}, \overline{Lim}(C_{h_{\tilde{B}}}) e^{j2\pi.\left(\frac{\overline{\tau}_{\tilde{B}}}{2\pi}\right)} \right) \end{array} \right\} \quad (47)$$

SWARA method is considered to weight the indicators. In this process, the calculations are made with the help of the hierarchical priorities of the decision makers. In this proposed model, this model is improved, and causal directions can be taken into consideration. This new methodology is named as M-SWARA (Mikhaylov et al. 2023). The pseudo-code of the extended weighting methodology is seen below.

Table 2 The details of experts

Experts	Education	Year of experience	Income (USD)	Age	Sector
DM1	2 (Master)	20	2500	55	2 (Production)
DM2	1 (Bachelor)	14	3000	46	3 (Education)
DM3	3 (PhD)	29	4000	58	1 (Service)
DM4	3 (PhD)	20	3500	47	1 (Service)
DM5	3 (PhD)	18	3000	54	2 (Production)

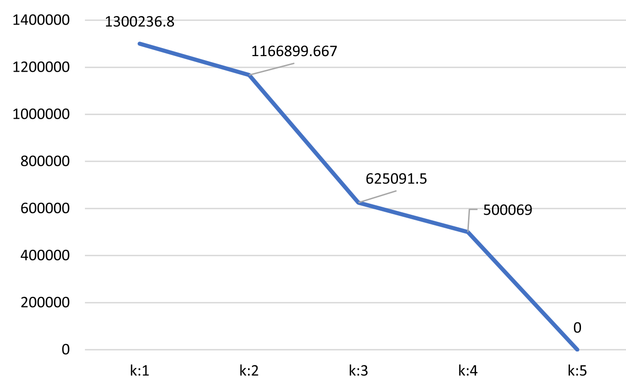

Fig. 2 WCSS values

Table 3 WCSS values

K = 1		K = 2		K = 3		K = 4		K = 5	
Cluster 1	WCSS	Cluster 1	WCSS	Cluster 1	WCSS	Cluster 1	WCSS	Cluster 1	WCSS
DM1	490,009.24	DM1	250,016.5	DM1	0	DM1	0	DM1	0
DM2	40,077.84	DM4	250,016.5	Cluster 2	WCSS	Cluster 2	WCSS	Cluster 2	WCSS
DM3	640,114.44	Cluster 2	WCSS	DM2	62,511.25	DM2	0	DM2	0
DM4	90,026.04	DM2	111,198.44	DM4	62,511.25	Cluster 3	WCSS	Cluster 3	WCSS
DM5	40,009.24	DM3	444,549.44	Cluster 3	WCSS	DM3	250,034.5	DM3	0
		DM5	111,118.78	DM3	250,034.5	DM5	250,034.5	Cluster 4	WCSS
				DM5	250,034.50	Cluster 4	WCSS	DM4	0
						DM4	0	Cluster 5	WCSS
								DM5	0
Total	1,300,236.8	Total	1,166,899.667	Total	625,091.5	Total	500,069	Total	0

Algorithm 1: The pseudo-code of the extended weighting methodology.

Input: Criteria values $c_{ij}, i \in [1,n], j \in [1,n]$; where n equals number of criteria C, weights of DMs $w_i, k \in [1,k]$; where k is number of DMs

Output: Weight of Criteria $W_i, i \in [1,n]$

Begin

(1) Construct an expert weighted QPFR for the relationship matrix

$$C = \left[c_{ij}\right]_{n\times n}$$

$$C \leftarrow W x C$$

(2) Calculate defuzzified values

$$Defc_i \leftarrow \frac{\left(\begin{array}{c}\underline{Lim}(C_{\mu_i}) - \underline{Lim}(C_{n_i}) + \underline{Lim}(C_{\mu_i}).\left(\underline{Lim}(C_{v_i}) - \underline{Lim}(C_{h_i})\right) + \left(\frac{\underline{\alpha}_{ij}}{2\pi}\right) - \left(\frac{\underline{\gamma}_{ij}}{2\pi}\right) + \left(\frac{\underline{\alpha}_{ij}}{2\pi}\right).\left(\left(\frac{\underline{\beta}_{ij}}{2\pi}\right) - \left(\frac{\underline{T}_{ij}}{2\pi}\right)\right) + \\ \overline{Lim}(C_{\mu_i}) - \overline{Lim}(C_{n_i}) + \overline{Lim}(C_{\mu_i}).\left(\overline{Lim}(C_{v_i}) - \overline{Lim}(C_{h_i})\right) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right) - \left(\frac{\overline{\gamma}_{ij}}{2\pi}\right) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right).\left(\left(\frac{\overline{\beta}_{ij}}{2\pi}\right) - \left(\frac{\overline{T}_{ij}}{2\pi}\right)\right)\end{array}\right)}{2}$$

(3) Define the elements of normalized decision matrix

(4) Determine values of k, q

$$k_j \leftarrow 1 \; for \; j = 1; \; s_j + 1 \text{ for j > 1 } [s_{j-1} = s_j, \; q_{j-1} = q_j; \; s_j = 0, \; k_{j-1} = k_j]$$

$$q_j \leftarrow 1 \; for \; j = 1; \frac{q_{j-1}}{k_j} \text{ for j > 1 } \; \forall j \in [1,2,\ldots,n]$$

(5) Calculate the weights of criteria

$$W_j \leftarrow \frac{q_j}{\sum_{k=1}^{n} q_k} \;\; \forall j \in [1,2,\ldots,n]$$

(6) Present the stable values of relation matrix with large 2t+1 value

(7) Illustrate the directions of the criteria

End

VIKOR

VIKOR is considered to rank different alternatives based on their significance for a subject (Dağıstanlı, 2024; Sahoo et al. 2024). In this study, this technique is extended with the quantum picture fuzzy rough sets. The pseudo-code of the extended ranking methodology is presented as follows.

Algorithm 2: The pseudo-code of the extended ranking methodology.

Input: Alternative criteria values $x_{ij}, i \in [1, m], j \in [1, n]$; where m equals number of alternatives A, and n equals number of criteria C; weights of DMs $w_i, k \in [1, k]$; where k is number of DMs

Output: Rank of alternatives $A_i, i \in [1, m]$

Begin

(1) Define the expert weighted QPFRS for the decision matrix

$$X = [x_{ij}]_{m \times n}$$

C←WxX

(2) Calculate the defuzzified values

$$Defc_i \leftarrow \frac{\left(\begin{array}{l}\underline{Lim}(C_{\mu_i}) - \underline{Lim}(C_{n_i}) + \underline{Lim}(C_{\mu_i}).\left(\underline{Lim}(C_{v_i}) - \underline{Lim}(C_{h_i})\right) + \left(\frac{\underline{\alpha}_{ij}}{2\pi}\right) - \left(\frac{\underline{\gamma}_{ij}}{2\pi}\right) + \left(\frac{\underline{\alpha}_{ij}}{2\pi}\right).\left(\left(\frac{\underline{\beta}_{ij}}{2\pi}\right) - \left(\frac{\underline{T}_{ij}}{2\pi}\right)\right) + \\ \overline{Lim}(C_{\mu_i}) - \overline{Lim}(C_{n_i}) + \overline{Lim}(C_{\mu_i}).\left(\overline{Lim}(C_{v_i}) - \overline{Lim}(C_{h_i})\right) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right) - \left(\frac{\overline{\gamma}_{ij}}{2\pi}\right) + \left(\frac{\overline{\alpha}_{ij}}{2\pi}\right).\left(\left(\frac{\overline{\beta}_{ij}}{2\pi}\right) - \left(\frac{\overline{T}_{ij}}{2\pi}\right)\right)\end{array}\right)}{2}$$

(3) Construct the best and worst values

$$\tilde{f}_J^* \leftarrow \max_i \tilde{x}_{ij}$$
$$\tilde{f}_j^- \leftarrow \min_i \tilde{x}_{ij}$$

(4) Present the criteria weight vector

$$W = [w_1, w_2, .., w_j], j \in [1,2, \dots, n], \sum_{j=1}^{n} w_j = 1$$

(5) Define the mean group utility and maximal degrees

$$\left.\begin{array}{l}\tilde{S}_j \leftarrow \sum_{i=1}^{n} \widetilde{w}_j \frac{\left(\left|\tilde{f}_j^* - \tilde{x}_{ij}\right|\right)}{\left(\left|\tilde{f}_j^* - \tilde{f}_j^-\right|\right)} \\ \tilde{R}_j \leftarrow max_j \left[\widetilde{w}_j \frac{\left(\left|\tilde{f}_j^* - \tilde{x}_{ij}\right|\right)}{\left(\left|\tilde{f}_j^* - \tilde{f}_j^-\right|\right)}\right]\end{array}\right., \forall j \in [1, n]$$

(6) Calculate the final ranking results

$$\tilde{Q}_i \leftarrow v\,(\tilde{S}_i - \tilde{S}^*)/(\tilde{S}^- - \tilde{S}^*) + (1 - v)\,(\tilde{R}_i - \tilde{R}^*)/(\tilde{R}^- - \tilde{R}^*)$$

(7) Rank the alternatives

$A_i, i \in [1, m]$ ←rank the alternatives based on the ascending order of Q_i values

(8) Check the assumptions

$$Q(A^{(2)}) - Q(A^{(1)}) \geq 1/(j - 1)$$

(9) Compare the results with sensitivity analysis

End

Results and discussion

This study evaluates blockchain-based waste management investments in smart cities via a novel proposed model. The following parts explain the main findings.

Computing the weights of the experts via AI (Stage 1)

Step 1 is related to the definition of the demographic information of the decision makers. Their demographic information is demonstrated in Table 2.

Table 4 Iteration results

Expert	TN-C1	TN-C2	TN-C3	LS
Iteration 1 (DM 1-LS 1; DM2-LS 2; DM 3-LS 3)				
Initial cluster centres				
DM1	0.00	500.12	1500.03	1
DM2	500.12	0.00	1000.19	2
DM3	1500.03	1000.19	0.00	3
DM4	1000.03	500.20	500.04	3
DM5	500.01	9.22	1000.07	2
Average of data points				
DM1	0.00	666.70	1500.03	1
DM2	500.12	166.74	1000.19	2
DM3	1500.03	833.46	0.00	3
DM4	1000.03	333.35	500.20	2
DM5	500.01	166.74	1000.07	2
Iteration 2 (DM 1-LS 1; DM2-LS 2; DM 4-LS 3)				
Initial Cluster Centers				
DM1	0.00	500.12	1000.03	1
DM2	500.12	0.00	500.04	2
DM3	1500.03	1000.19	500.20	3
DM4	1000.03	500.04	0.00	3
DM5	500.01	9.22	500.05	2
Expert	TN—C1	TN—C2	TN—C3	Cluster Assignment
Average of Data Points				
DM1	0.00	500.04	1250.01	1
DM2	500.12	4.61	750.11	2
DM3	1500.03	1000.12	250.10	3
DM4	1000.03	500.03	250.10	3
DM5	500.01	4.61	750.03	2

Distance: TN; Cluster: LS

Table 5 The standard deviations

Cluster centre	Size	Education	Experience	Salary
C1	1	0	0	0
C2	2	1.00	2.00	0.00
C3	2	0	4.5	250
Cluster centre	Age	Sector	Mean	Weight
C1	0	0	0	0
C2	4.00	0.50	1.50	3
C3	5.5	0	52	104

Table 1 indicates that three experts have PhD degrees whereas others have master and bachelor's degrees. These people have minimum 14 years of working experience. They have worked in different industries such as production, education, and service.

Step 2 focuses on computation of the optimal k value. It is utilized the K-means clustering algorithm, and optimal clusters were determined using the elbow method. Equation (1) elaborates on the calculation of WCSS. Therefore, the values in the table are seen in Table 3.

The explanation of the meaning of these values is crucial. The WCSS values signify the sum of squared distances between data points and their assigned cluster centers. These values are fundamental in determining the optimal number of clusters (k) for our dataset. A lower WCSS indicates better cluster cohesion, implying that the data points within each cluster are closely related. By explaining the significance of WCSS, we highlight the importance of selecting the optimal k value, a key step in our decision-making model. Figure 2 demonstrates the WCSS values.

In Step 3, the algorithm is applied. In the initial iteration, the K-means clustering algorithm is applied with the initial cluster centers, and each decision maker (DM) is assigned to the nearest cluster based on the Euclidean distances. The distances of each DM to the initial cluster centers (C1, C2, C3) are calculated, and cluster assignments are determined based on the minimum distance. The results are presented in the table, indicating the cluster assignments and distances for each DM. The distances, cluster assignments, and average data points are recalculated for each DM. The results are presented in the table for the second iteration.

Table 4 illustrates the step-by-step process of the K-means clustering algorithm, specifically highlighting the distance calculations, cluster assignments, and average data points for each DM in each iteration. The distances reflect how close each DM is to the cluster centers, and cluster assignments show which cluster each DM belongs to. *Step 4* computes the weights of these people. The calculation results are presented in Table 5.

Table 6 denotes the weights of these people. The weights indicate the influence or priority of each decision-maker within their respective clusters.

The values indicate that DM3 and DM4 have greatest weights (0.49).

Table 6 The weights for expert prioritization

Expert	Weights
DM1	0.00
DM2	0.01
DM3	0.49
DM4	0.49
DM5	0.01

Table 7 Criteria and codes

Criteria	Codes
Monitoring the remanufacturing of waste	C1
Participating in waste to energy schemes	C2
Facilitating peer to peer energy trading	C3
Optimizing the lifecycle management	C4

Weighting the criteria for blockchain-based waste management investments with QPFR-M-SWARA (Stage 2)

In this stage, the weights of the criteria for blockchain-based waste management investments are computed.

Step 5 defines the criteria for blockchain-based waste management investments. By considering the literature review results, four different criteria are selected with respect to effectiveness of the blockchain-based waste management investments. Table 7 explains the details of these indicators.

Step 6 is related to the evaluations for these criteria. In this context, the scales in Table 8 are taken into consideration. This scale is proposed by the authors to define the linguistic assessments of the decision makers and their related possibility degrees with the quantum picture fuzzy

Table 8 Linguistic scales. *Source:* Kou et al. (2024); Liu et al. (2024)

Scales for criteria	Scales for alternatives	Possibility degrees	Fuzzy numbers
No (N)	Weakest (w)	0.40	$\left[\begin{array}{l}\sqrt{0.16e^{j2\pi.0.4}},\\ \sqrt{0.10e^{j2\pi.0.25}},\\ \sqrt{0.46e^{j2\pi.0.22}},\\ \sqrt{0.28e^{j2\pi.0.13}}\end{array}\right]$
Some (S)	Poor (p)	0.45	$\left[\begin{array}{l}\sqrt{0.20e^{j2\pi.0.45}},\\ \sqrt{0.13e^{j2\pi.0.28}},\\ \sqrt{0.42e^{j2\pi.0.17}},\\ \sqrt{0.25e^{j2\pi.0.10}}\end{array}\right]$
Medium (M)	Fair (f)	0.50	$\left[\begin{array}{l}\sqrt{0.25e^{j2\pi.0.50}},\\ \sqrt{0.15e^{j2\pi.0.31}},\\ \sqrt{0.37e^{j2\pi.0.12}},\\ \sqrt{0.23e^{j2\pi.0.07}}\end{array}\right]$
High (H)	Good (g)	0.55	$\left[\begin{array}{l}\sqrt{0.30e^{j2\pi.0.55}},\\ \sqrt{0.19e^{j2\pi.0.34}},\\ \sqrt{0.32e^{j2\pi.0.07}},\\ \sqrt{0.19e^{j2\pi.0.04}}\end{array}\right]$
Very high (VH)	Best (b)	0.60	$\left[\begin{array}{l}\sqrt{0.36e^{j2\pi.0.6}},\\ \sqrt{0.22e^{j2\pi.0.37}},\\ \sqrt{0.26e^{j2\pi.0.02}},\\ \sqrt{0.16e^{j2\pi.0.01}}\end{array}\right]$

Table 9 Evaluations

	C1	C2	C3	C4		C1	C2	C3	C4
DM2						DM4			
C1		M	S	H	C1		M	M	H
C2	S		VH	M	C2	M		H	M
C3	M	VH		M	C3	M	VH		M
C4	H	M	M		C4	H	M	M	
DM3						DM5			
C1		M	S	H	C1		M	M	VH
C2	M		H	M	C2	S		VH	M
C3	M	H		M	C3	H	VH		H
C4	H	M	M		C4	H	M	M	

sets. The proposed linguistic scales are given into 5 scales as "no, some, medium, high, and very high" for criteria and "weakest, poor, fair, good, and best for alternatives.

Table 9 identifies the evaluations.

Step 7 focuses on the construction of fuzzy numbers as in Table 10.

Step 8 determines QPFR numbers for the relation matrix. Table 11 gives information about these values. As an example, the elements for C2 at the row and C1 at the column are defined as $\underline{Lim}\left(C_{\mu_{ij}}\right)$=0.20; $\overline{Lim}\left(C_{\mu_{ij}}\right)$=0.25; $\underline{Lim}\left(C_{n_{ij}}\right)$=0.13; $\overline{Lim}\left(C_{n_{ij}}\right)$=0.15; $\underline{Lim}\left(C_{v_{ij}}\right)$=0.37; $\overline{Lim}\left(C_{v_{ij}}\right)$=0.42; $\underline{Lim}\left(C_{h_{ij}}\right)$=0.23; $\overline{Lim}\left(C_{h_{ij}}\right)$=0.25; $\underset{-ij}{\alpha}$=0.45; $\overline{\alpha}_{ij}$=0.50; $\underset{-ij}{\gamma}$=0.28; $\overline{\gamma}_{ij}$=0.31; $\underset{-ij}{\beta}$=0.12; $\overline{\beta}_{ij}$=0.17; $\underline{T}_{ij}$=0.07; $\overline{T}_{ij}$=0.10. According to the Eq. (55), the fuzzy sets is constructed as

$$\left[\begin{array}{l} \left[\sqrt{0.20}, \sqrt{0.25}\right] e^{j2\pi.[0.45,0.50]}, \\ \left[\sqrt{0.13}, \sqrt{0.15}\right] e^{j2\pi.[0.28,0.31]}, \\ \left[\sqrt{0.37}, \sqrt{0.42}\right] e^{j2\pi.[0.12,0.17]}, \\ \left[\sqrt{0.23}, \sqrt{0.25}\right] e^{j2\pi.[0.07,0.10]} \end{array}\right]$$

In *Step 9*, the defuzzification process is applied. The values in Table 12 are derived from these equations, reflecting the outcomes of the decision-making model. By using these values, the computation process continues with the steps of M-SWARA to weights of the criteria as well as the impact-relation degrees among them.

In *Step 10,* the values are normalized as in Table 13, where each entry signifies the strength of the relationship between corresponding criteria. Each item is divided to the sum of the related row for computing the normalized values of the matrix.

Step 11 is related to the calculation of the essential values as shown in Table 14.

Step 12 focuses on the construction of the relation matrix and the directions among the criteria. By considering the significant values, the weights of the criteria and the causal directions can be computed. Table 15 explains the details of the impact directions.

It is concluded that monitoring the remanufacturing of waste (C1) and participating in waste to energy schemes (C2) are the most influenced indicators. On the other side, facilitating peer to peer energy trading (C3) and optimizing the lifecycle management (C4) have an impact on both C1 and C2. Moreover, the weights are indicated in Table 16.

Table 16 states that participating in waste to energy schemes (C2) has the greatest weight (0.259). Similarly, optimizing the lifecycle management (C4) has also high weight (0.256). However, monitoring the remanufacturing of waste (C1) and facilitating peer to peer energy trading (C3) have lower importance in this regard by comparing with other indicators. These results pave the way that companies should mainly focus on the actions to generate energy by using the wastes.

Ranking the investment alternatives for smart cities with QPFR-VIKOR (Stage 3)

In this stage, the investment alternatives for smart cities are ranked. *Step 13* collects the evaluations. In this step of the proposed model, four different alternatives are identified for smart cities that are efficient public services (A1), circular economy practices (A2), integration of physical and digital infrastructures (A3) and urban innovativeness (A4). Table 17 denotes the details of the evaluations for the alternatives.

In *Step 14 and 15*, fuzzy numbers are computed for the decision matrix is constructed as in Tables 20 and 21. *Step 16* is related to the calculation of the defuzzified decision values. Table 18 explains the details of these values.

Step 17 includes the construction critical values as in Table 19.

Table 10 Fuzzy numbers

	C1	C2	C3	C4
DM2				
C1	–	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.20}e^{j2\pi.0.45}, \sqrt{0.13}e^{j2\pi.0.28}, \sqrt{0.42}e^{j2\pi.0.17}, \sqrt{0.25}e^{j2\pi.0.10}\right]$	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$
C2	$\left[\sqrt{0.20}e^{j2\pi.0.45}, \sqrt{0.13}e^{j2\pi.0.28}, \sqrt{0.42}e^{j2\pi.0.17}, \sqrt{0.25}e^{j2\pi.0.10}\right]$	–	$\left[\sqrt{0.36}e^{j2\pi.0.6}, \sqrt{0.22}e^{j2\pi.0.37}, \sqrt{0.26}e^{j2\pi.0.02}, \sqrt{0.16}e^{j2\pi.0.01}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$
C3	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.20}e^{j2\pi.0.45}, \sqrt{0.13}e^{j2\pi.0.28}, \sqrt{0.42}e^{j2\pi.0.17}, \sqrt{0.25}e^{j2\pi.0.10}\right]$	–	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$
C4	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	–
DM3				
C1	–	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.20}e^{j2\pi.0.45}, \sqrt{0.13}e^{j2\pi.0.28}, \sqrt{0.42}e^{j2\pi.0.17}, \sqrt{0.25}e^{j2\pi.0.10}\right]$	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$
C2	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	–	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$
C3	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$	–	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$
C4	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	–
	C1	C2	C3	C4
DM4				
C1	–	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$
C2	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$	–	$\left[\sqrt{0.30}e^{j2\pi.0.55}, \sqrt{0.19}e^{j2\pi.0.34}, \sqrt{0.32}e^{j2\pi.0.07}, \sqrt{0.19}e^{j2\pi.0.04}\right]$	$\left[\sqrt{0.25}e^{j2\pi.0.50}, \sqrt{0.15}e^{j2\pi.0.31}, \sqrt{0.37}e^{j2\pi.0.12}, \sqrt{0.23}e^{j2\pi.0.07}\right]$

Table 10 (continued)

	C1	C2	C3	C4
C3	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.36}e^{j2\pi.0.6}, \\ \sqrt{0.22}e^{j2\pi.0.37}, \\ \sqrt{0.26}e^{j2\pi.0.02}, \\ \sqrt{0.16}e^{j2\pi.0.01} \end{bmatrix}$	–	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$
C4	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi.0.55}, \\ \sqrt{0.19}e^{j2\pi.0.34}, \\ \sqrt{0.32}e^{j2\pi.0.07}, \\ \sqrt{0.19}e^{j2\pi.0.04} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$	–
DM5				
C1	–	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.36}e^{j2\pi.0.6}, \\ \sqrt{0.22}e^{j2\pi.0.37}, \\ \sqrt{0.26}e^{j2\pi.0.02}, \\ \sqrt{0.16}e^{j2\pi.0.01} \end{bmatrix}$
C2	$\begin{bmatrix} \sqrt{0.20}e^{j2\pi.0.45}, \\ \sqrt{0.13}e^{j2\pi.0.28}, \\ \sqrt{0.42}e^{j2\pi.0.17}, \\ \sqrt{0.25}e^{j2\pi.0.10} \end{bmatrix}$	–	$\begin{bmatrix} \sqrt{0.36}e^{j2\pi.0.6}, \\ \sqrt{0.22}e^{j2\pi.0.37}, \\ \sqrt{0.26}e^{j2\pi.0.02}, \\ \sqrt{0.16}e^{j2\pi.0.01} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$
C3	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi.0.55}, \\ \sqrt{0.19}e^{j2\pi.0.34}, \\ \sqrt{0.32}e^{j2\pi.0.07}, \\ \sqrt{0.19}e^{j2\pi.0.04} \end{bmatrix}$	$\begin{bmatrix} \sqrt{0.36}e^{j2\pi.0.6}, \\ \sqrt{0.22}e^{j2\pi.0.37}, \\ \sqrt{0.26}e^{j2\pi.0.02}, \\ \sqrt{0.16}e^{j2\pi.0.01} \end{bmatrix}$	–	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi.0.55}, \\ \sqrt{0.19}e^{j2\pi.0.34}, \\ \sqrt{0.32}e^{j2\pi.0.07}, \\ \sqrt{0.19}e^{j2\pi.0.04} \end{bmatrix}$
C4	$\begin{bmatrix} \sqrt{0.30}e^{j2\pi.0.55}, \\ \sqrt{0.19}e^{j2\pi.0.34}, \\ \sqrt{0.32}e^{j2\pi.0.07}, \\ \sqrt{0.19}e^{j2\pi.0.04} \end{bmatrix}$	A	$\begin{bmatrix} \sqrt{0.25}e^{j2\pi.0.50}, \\ \sqrt{0.15}e^{j2\pi.0.31}, \\ \sqrt{0.37}e^{j2\pi.0.12}, \\ \sqrt{0.23}e^{j2\pi.0.07} \end{bmatrix}$	-

Integration of physical and digital infrastructures (A3) is the most critical alternative. In *Step 18*, a comparative analysis is also performed by TOPSIS (Biswas et al. 2024). Figure 3 gives information about the comparative evaluation results.

Figure 3 indicates that the findings are quite similar for both VIKOR and TOPSIS. This situation denotes the reliability of the results. In other words, it is understood that the results of the proposed model are coherent. In summary, digital innovativeness plays the most crucial role with respect to the investment alternatives for smart cities. Integration of digital technologies into waste management processes can increase efficiency. This significantly contributes to reducing the costs of businesses. As a result, the profitability of businesses may increase, which provides businesses with a significant competitive advantage. Digital innovations enable the application of big data analysis in waste management. This contributes significantly to a very comprehensive analysis. Thus, processes can be optimized much more easily. In addition to this issue, a sensitivity analysis is also conducted with four different cases to check the coherency of the analysis results. Figure 4 demonstrates the results of the sensitivity analysis.

Figure 4 demonstrates the validity and coherency of the proposed model. There are four different cases in the sensitivity analysis. This situation checks the appropriateness of the ranking results by considering these different conditions. In all different conditions, the ranking results are the same. Because the results are not changing, it is understood that the proposed model provides appropriate results. It is determined that integration of physical and digital infrastructures (A3) is the most critical alternative. Furthermore, urban innovativeness (A4) is another critical factor for this situation. However, efficient public services (A1) and circular economy practices (A2) are on the last ranks. Since the sensitivity analysis demonstrates the accuracy of the analysis results, effective strategies can be presented to the companies by considering these ranking results.

Discussion

Participation in waste to energy schemes is determined as the most important criterion for blockchain-based waste management investments. Waste-to-energy systems produce electricity or heat energy by using waste. The most important advantage

Table 11 Fuzzy rough numbers

	C1	C2	C3	C4
C1	–	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$	$\left[\sqrt{0.30},\sqrt{0.30}\right]e^{j2\pi.[0.55,0.55]}$, $\left[\sqrt{0.19},\sqrt{0.19}\right]e^{j2\pi.[0.34,0.34]}$, $\left[\sqrt{0.32},\sqrt{0.32}\right]e^{j2\pi.[0.07,0.07]}$, $\left[\sqrt{0.19},\sqrt{0.19}\right]e^{j2\pi.[0.34,0.34]}$
C2	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$	–	$\left[\sqrt{0.30},\sqrt{0.30}\right]e^{j2\pi.[0.55,0.55]}$, $\left[\sqrt{0.19},\sqrt{0.19}\right]e^{j2\pi.[0.34,0.34]}$, $\left[\sqrt{0.32},\sqrt{0.32}\right]e^{j2\pi.[0.07,0.07]}$, $\left[\sqrt{0.19},\sqrt{0.19}\right]e^{j2\pi.[0.04,0.04]}$	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$
C3	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$	$\left[\sqrt{0.36},\sqrt{0.36}\right]e^{j2\pi.[0.60,0.60]}$, $\left[\sqrt{0.22},\sqrt{0.22}\right]e^{j2\pi.[0.37,0.37]}$, $\left[\sqrt{0.26},\sqrt{0.26}\right]e^{j2\pi.[0.02,0.02]}$, $\left[\sqrt{0.16},\sqrt{0.16}\right]e^{j2\pi.[0.01,0.01]}$	–	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$
C4	$\left[\sqrt{0.30},\sqrt{0.30}\right]e^{j2\pi.[0.55,0.55]}$, $\left[\sqrt{0.19},\sqrt{0.19}\right]e^{j2\pi.[0.34,0.34]}$, $\left[\sqrt{0.32},\sqrt{0.32}\right]e^{j2\pi.[0.07,0.07]}$, $\left[\sqrt{0.19},\sqrt{0.19}\right]e^{j2\pi.[0.04,0.04]}$	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$	$\left[\sqrt{0.25},\sqrt{0.25}\right]e^{j2\pi.[0.50,0.50]}$, $\left[\sqrt{0.15},\sqrt{0.15}\right]e^{j2\pi.[0.31,0.31]}$, $\left[\sqrt{0.37},\sqrt{0.37}\right]e^{j2\pi.[0.12,0.12]}$, $\left[\sqrt{0.23},\sqrt{0.23}\right]e^{j2\pi.[0.07,0.07]}$	–

Table 12 Defuzzified numbers

	C1	C2	C3	C4
C1	0	0.346	0.331	0.371
C2	0.332	0	0.396	0.346
C3	0.340	0.420	0	0.340
C4	0.381	0.346	0.346	0

Table 13 Normalized numbers

	C1	C2	C3	C4
C1	0.000	0.330	0.315	0.354
C2	0.309	0.000	0.369	0.322
C3	0.309	0.382	0.000	0.309
C4	0.355	0.322	0.322	0.000

of this process is that natural resources are consumed much less when producing energy. This enables sustainability to be achieved in the energy production process. Peng et al. (2023) mentioned that the waste-to-energy system also helps reduce the amount of waste. Using the resulting wastes in the energy production process also means destroying these wastes. This contributes to reducing the amount of waste that is harmful to the environment. Silva et al. (2023) defined that by using the blockchain system, all stages of the waste-to-energy system can be systematically monitored. This helps find a quick solution to a possible problem. Thus, the effectiveness of waste management processes can be increased. Furthermore, Xu et al. (2023) concluded that waste-to-energy systems can reduce energy costs. Similarly, Wang et al. (2023) underlined that thanks to this system, reductions in the amount of carbon emissions can occur. Song et al. (2023) and Lei et al. (2023) demonstrated that regeneration of waste allows efficient management of recycling processes. Similarly, de Lima et al. (2023) mentioned that the regeneration of waste supports the sustainable use of natural resources.

Based on these results, some managerial implications and policy implications can be presented. With respect to the managerial implications, firstly, technology investments should be increased. For this purpose, investments related to the advanced waste-to-energy technologies should be prioritized. Additionally, effective risk management also plays an

Table 14 Sj, kj, qj, and wj values for the relationship degrees of each criterion

C1	Sj	kj	qj	wj	C2	Sj	Kj	Qj	Wj
C4	0.354	1.000	1.000	0.430	C3	0.369	1.000	1.000	0.428
C2	0.330	1.330	0.752	0.324	C4	0.322	1.322	0.756	0.324
C3	0.315	1.315	0.571	0.246	C1	0.309	1.309	0.578	0.248
C3	Sj	kj	qj	wj	C4	Sj	Kj	qj	Wj
C2	0.382	1.000	1.000	0.362	C1	0.355	1.000	1.000	0.363
C1	0.309	1.000	1.000	0.362	C2	0.322	1.000	1.000	0.363
C4	0.309	1.309	0.764	0.276	C3	0.322	1.322	0.756	0.274

Table 15 Relation matrix

	C1	C2	C3	C4	Causal relationship
C1		0.324	0.246	0.430	C1 → C4
C2	0.248		0.428	0.324	C2 → C3
C3	0.362	0.362		0.276	C3 → C1,C2
C4	0.363	0.363	0.274		C4 → C1,C2

Table 16 Stable matrix

	C1	C2	C3	C4
C1	0.244	0.244	0.244	0.244
C2	0.259	0.259	0.259	0.259
C3	0.241	0.241	0.241	0.241
C4	0.256	0.256	0.256	0.256

important role in this framework. In this process, technical, environmental, and financial risks should be evaluated for these investments. This situation help to minimize financial losses of these investments. Regulatory compliance is also critical for this issue. Necessary actions should be taken to comply with local and international regulations. On the other side, regarding the policy implications, incentive programs should be conducted. In this process, tax breaks, or subsidies can stimulate investment. Research and development works should also be increased related to the waste-to-energy technologies. These studies have a positive contribution to minimize the costs of these projects. This situation plays a crucial role to increase financial sustainability of these investments.

It is determined that advanced technological infrastructure is of great importance regarding blockchain-based waste management investments. Owing to advanced technology, it is possible to reliably record all waste management processes. Qureshi et al. (2023) determined that this issue allows investors to focus on these projects. On the other hand, according to Karuppiah and Sankaranarayanan (2023) and Chowdhury et al. (2023), an advanced technological infrastructure can provide strong data security for waste management processes. In this way, unauthorized persons can be prevented from accessing private information in the process. Mondal et al. (2023) stated that this situation has a positive contribution to increase the waste management investments. Moreover, advanced technological infrastructure can make waste management processes faster. This situation helps to increase the efficiency in the process.

Table 18 Defuzzified numbers

	C1	C2	C3	C4
A1	0.396	0.323	0.323	0.396
A2	0.358	0.358	0.318	0.385
A3	0.385	0.346	0.381	0.371
A4	0.346	0.346	0.378	0.381

Table 17 Evaluations

	C1	C2	C3	C4		C1	C2	C3	C4
	DM2					DM4			
A1	G	G	F	B	A1	G	G	P	B
A2	G	G	P	P	A2	G	G	P	P
A3	P	P	G	B	A3	P	P	G	B
A4	G	F	B	F	A4	G	G	G	G
	DM3					DM5			
A1	G	G	F	B	A1	G	G	F	G
A2	G	G	F	F	A2	G	G	P	P
A3	F	F	G	B	A3	P	P	G	G
A4	G	F	B	F	A4	G	P	B	P

Table 19 Si, Ri, and Qi values

	Si	Ri	Qi (v:0.1)	Qi (v:0.2)	Qi (v:0.3)	Qi (v:0.4)
A1	0.479	0.259	0.955	0.911	0.866	0.821
A2	0.547	0.241	0.100	0.200	0.300	0.400
A3	0.396	0.255	0.718	0.638	0.558	0.478
A4	0.493	0.244	0.225	0.272	0.318	0.365
	Qi (v:0.5)	Qi (v:0.6)	Qi (v:0.7)	Qi (v:0.8)	Qi (v:0.9)	Qi (v:1)
A1	0.777	0.732	0.687	0.642	0.598	0.553
A2	0.500	0.600	0.700	0.800	0.900	1.000
A3	0.399	0.319	0.239	0.159	0.080	0.000
A4	0.412	0.459	0.505	0.552	0.599	0.645

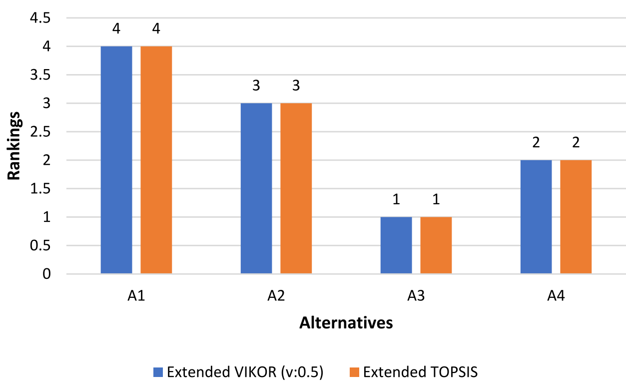

Fig. 3 Comparative evaluation results

Furthermore, Onungwe et al. (2023) underlined that thanks to blockchain-based solutions, it is possible to reduce unnecessary transactions. In this way, it is possible to reduce costs. On the other hand, many researchers in the literature emphasize that the integration of circular economy projects should be ensured to increase the effectiveness of blockchain-based waste management investments. Circular economy projects encourage waste reduction and recycling. In this way, it is possible to use resources much more efficiently.

Conclusion

Accordingly, this study evaluates blockchain-based waste management investments in smart cities via a novel proposed model that has three different stages. In the first stage of the proposed, artificial intelligence methodology is taken into consideration to identify the expert weights. In the second stage, the weights of the criteria for blockchain-based waste management investments are identified. Moreover, selected investment alternatives for smart cities are ranked. Additionally, a comparative analysis is also performed by TOPSIS. In addition to this issue, a sensitivity analysis is also conducted with four different cases to check the coherency of the analysis results. It is identified that participating in waste to energy schemes has the greatest significance. Similarly, optimizing the lifecycle management has also high weight. It is also defined that integration of physical and digital infrastructures is the most critical alternative. Furthermore, urban innovativeness is another critical factor for this situation.

To increase the effectiveness of waste management investments, participation in waste to energy projects should be encouraged. Thus, significant benefits can be achieved in terms of both energy production and waste management. It is possible to offer some policy suggestions to improve this issue. In this context, financial incentives play a very important role. Thanks to these incentives, it is possible to reduce the costs of businesses. It also enables cost effectiveness and financial sustainability of projects. Increasing research and development studies also supports achieving this goal. Thanks to research studies, it becomes easier to achieve technological improvements in waste management processes. By using advanced technologies, the efficiency of the waste management process can be increased. In other words, thanks to these new technologies, waste management can be achieved at a lower cost.

In this model, the weights of the experts can be calculated via AI. This condition contributes to increasing the efficiency and accuracy of analysis processes. However, the main limitation of this study is that a general assessment has been performed to evaluate the effectiveness of the blockchain-based waste management investments in smart cities. Thus, in the future studies, different country groups can be evaluated. For instance, a comparative evaluation for developing and developed economies can pave the way for the investors in their investment decisions. In addition to this issue, the proposed model has some limitations. VIKOR and TOPSIS are considered to rank different alternatives. However, these ranking models are criticized because of some reasons. Thus, in the following studies, a new ranking model can be identified.

Appendix

See Tables 20 and 21.

Table 20 Quantum picture fuzzy numbers for the decision matrix

	C1	C2	C3	C4
DM2				
A1	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$
A2	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$
A3	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
A4	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
DM3				
A1	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
A2	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$
A3	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
A4	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
	C1	C2	C3	C4
DM4				
A1	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$
A2	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$

Table 20 (continued)

	C1	C2	C3	C4
A3	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$
A4	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.36}e^{j2\pi.0.6},\\ \sqrt{0.22}e^{j2\pi.0.37},\\ \sqrt{0.26}e^{j2\pi.0.02},\\ \sqrt{0.16}e^{j2\pi.0.01}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
DM5				
A1	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
A2	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.20}e^{j2\pi.0.45},\\ \sqrt{0.13}e^{j2\pi.0.28},\\ \sqrt{0.42}e^{j2\pi.0.17},\\ \sqrt{0.25}e^{j2\pi.0.10}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
A3	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$
A4	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.25}e^{j2\pi.0.50},\\ \sqrt{0.15}e^{j2\pi.0.31},\\ \sqrt{0.37}e^{j2\pi.0.12},\\ \sqrt{0.23}e^{j2\pi.0.07}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$	$\begin{bmatrix}\sqrt{0.30}e^{j2\pi.0.55},\\ \sqrt{0.19}e^{j2\pi.0.34},\\ \sqrt{0.32}e^{j2\pi.0.07},\\ \sqrt{0.19}e^{j2\pi.0.04}\end{bmatrix}$

Table 21 QPFR numbers for the decision matrix

	C1	C2	C3	C4
A1	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.60]}$,	$\left[\sqrt{0.20}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.45,0.50]}$,	$\left[\sqrt{0.20}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.45,0.50]}$,	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.60]}$,
	$\left[\sqrt{0.19}, \sqrt{0.22}\right] e^{j2\pi \cdot [0.34,0.37]}$,	$\left[\sqrt{0.13}, \sqrt{0.15}\right] e^{j2\pi \cdot [0.28,0.31]}$,	$\left[\sqrt{0.13}, \sqrt{0.15}\right] e^{j2\pi \cdot [0.28,0.31]}$,	$\left[\sqrt{0.19}, \sqrt{0.22}\right] e^{j2\pi \cdot [0.34,0.37]}$,
	$\left[\sqrt{0.26}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.02,0.07]}$,	$\left[\sqrt{0.37}, \sqrt{0.42}\right] e^{j2\pi \cdot [0.12,0.17]}$,	$\left[\sqrt{0.37}, \sqrt{0.42}\right] e^{j2\pi \cdot [0.12,0.17]}$,	$\left[\sqrt{0.26}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.02,0.07]}$,
	$\left[\sqrt{0.16}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.01,0.04]}$	$\left[\sqrt{0.23}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.07,0.10]}$	$\left[\sqrt{0.23}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.07,0.10]}$	$\left[\sqrt{0.16}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.01,0.04]}$
A2	$\left[\sqrt{0.25}, \sqrt{0.30}\right] e^{j2\pi \cdot [0.50,0.55]}$,	$\left[\sqrt{0.25}, \sqrt{0.30}\right] e^{j2\pi \cdot [0.50,0.55]}$,	$\left[\sqrt{0.20}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.45,0.50]}$,	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.60]}$,
	$\left[\sqrt{0.15}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.31,0.34]}$,	$\left[\sqrt{0.15}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.31,0.34]}$,	$\left[\sqrt{0.13}, \sqrt{0.15}\right] e^{j2\pi \cdot [0.28,0.31]}$,	$\left[\sqrt{0.19}, \sqrt{0.22}\right] e^{j2\pi \cdot [0.34,0.37]}$,
	$\left[\sqrt{0.32}, \sqrt{0.37}\right] e^{j2\pi \cdot [0.07,0.12]}$,	$\left[\sqrt{0.32}, \sqrt{0.37}\right] e^{j2\pi \cdot [0.07,0.12]}$,	$\left[\sqrt{0.37}, \sqrt{0.42}\right] e^{j2\pi \cdot [0.12,0.17]}$,	$\left[\sqrt{0.26}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.02,0.07]}$,
	$\left[\sqrt{0.19}, \sqrt{0.23}\right] e^{j2\pi \cdot [0.04,0.07]}$	$\left[\sqrt{0.19}, \sqrt{0.23}\right] e^{j2\pi \cdot [0.04,0.07]}$	$\left[\sqrt{0.23}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.07,0.10]}$	$\left[\sqrt{0.16}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.01,0.04]}$
A3	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.60]}$,	$\left[\sqrt{0.25}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.50,0.50]}$,	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.55]}$,	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.55]}$,
	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.34,0.37]}$,	$\left[\sqrt{0.15}, \sqrt{0.15}\right] e^{j2\pi \cdot [0.31,0.31]}$,	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.34,0.34]}$,	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.34,0.34]}$,
	$\left[\sqrt{0.26}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.02,0.07]}$,	$\left[\sqrt{0.37}, \sqrt{0.37}\right] e^{j2\pi \cdot [0.12,0.12]}$,	$\left[\sqrt{0.32}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.07,0.07]}$,	$\left[\sqrt{0.32}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.07,0.07]}$,
	$\left[\sqrt{0.16}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.01,0.04]}$	$\left[\sqrt{0.23}, \sqrt{0.23}\right] e^{j2\pi \cdot [0.07,0.07]}$	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.04,0.04]}$	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.04,0.04]}$
A4	$\left[\sqrt{0.25}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.50,0.50]}$,	$\left[\sqrt{0.25}, \sqrt{0.25}\right] e^{j2\pi \cdot [0.50,0.50]}$,	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.55]}$,	$\left[\sqrt{0.30}, \sqrt{0.36}\right] e^{j2\pi \cdot [0.55,0.55]}$,
	$\left[\sqrt{0.15}, \sqrt{0.15}\right] e^{j2\pi \cdot [0.31,0.31]}$,	$\left[\sqrt{0.15}, \sqrt{0.15}\right] e^{j2\pi \cdot [0.31,0.31]}$,	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.34,0.34]}$,	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.34,0.34]}$,
	$\left[\sqrt{0.37}, \sqrt{0.37}\right] e^{j2\pi \cdot [0.12,0.12]}$,	$\left[\sqrt{0.37}, \sqrt{0.37}\right] e^{j2\pi \cdot [0.12,0.12]}$,	$\left[\sqrt{0.32}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.07,0.07]}$,	$\left[\sqrt{0.32}, \sqrt{0.32}\right] e^{j2\pi \cdot [0.07,0.07]}$,
	$\left[\sqrt{0.23}, \sqrt{0.23}\right] e^{j2\pi \cdot [0.07,0.07]}$	$\left[\sqrt{0.23}, \sqrt{0.23}\right] e^{j2\pi \cdot [0.07,0.07]}$	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.04,0.04]}$	$\left[\sqrt{0.19}, \sqrt{0.19}\right] e^{j2\pi \cdot [0.04,0.04]}$

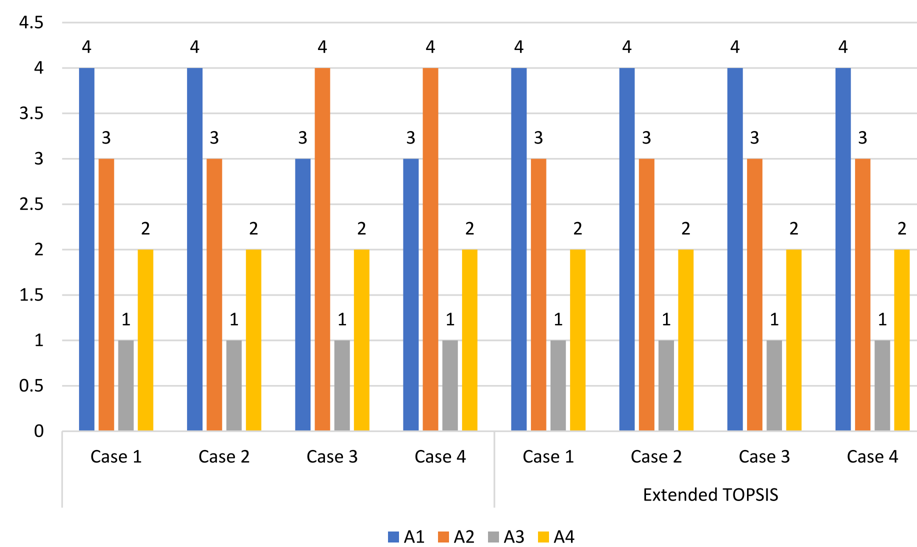

Fig. 4 Sensitivity analysis results

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Declarations

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