An integrated multi-criteria decision-making method for hazardous waste disposal site selection

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Abstract

With the population growth and the rapid development of tech-economy, the industrialization process of cities has accelerated the generation of a large number of hazardous wastes, which has caused serious harm to human health and the ecological environment. The location of hazardous waste disposal sites plays an important role in hazardous waste management. Because of the multiple conflicting criteria and the inherent ambiguity of experts' judgments, the location of hazardous waste disposal sites is regarded as a fuzzy multi-criteria decision-making problem. This paper proposes an integrated method, which consists of a fuzzy analytic hierarchy process (FAHP) and fuzzy axiomatic design (FAD), to determine the best hazardous waste disposal site. First, from the perspective of sustainability, an evaluation index system based on economic, social, and environmental criteria is built. Then, FAHP is employed to evaluate criteria weights. In the FAD application phase, the functional requirements (FRs) are determined by the five experts from different fields, and then, we use FAD to calculate the information content of alternatives and rank them. Finally, sensitivity analysis is performed on the change of criteria weight and the change of FRs, and the results show that the proposed hybrid method is a robust decision support tool for ranking alternatives. Moreover, the proposed method is flexible and can be used to solve the problem of hazardous waste disposal site selection in other developing countries or regions.

Keywords Site selection · Hazardous waste · Sustainability · Fuzzy axiomatic design · Fuzzy analytic hierarchy process

1 Introduction

Recently, with the growth of population and the rapid development of tech-economy, the industrialization process of cities has accelerated the production of a large number of hazardous wastes (HWs) (Arikan et al., 2017; Unal et al., 2020), which has caused serious harm to people's health and ecology environment (Ghorani-Azam et al., 2016). The United

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Nations Environment Agency defines HW as: HW refers to those wastes other than radio-activity, which are caused or may cause harm to people's health or the environment due to its chemical reactivity, toxicity, explosiveness, corrosiveness, and other characteristics. In the past period time, HWs may have caused serious pollution to the environment. Therefore, protecting the environment and human health is becoming more and more complicated and is regarded as a major global challenge (Danesh et al., 2019).

The rapid development of technology has left behind some HWs that are harmful to human life and the ecosystem. HWs are potentially dangerous or may cause some risks in the future environment (Mora et al., 2021). The massive growth of urban HWs mainly leads to the following three hazards: (1) destroy the urban ecological environment. Hazardous substances will pollute water and soil under the action of the water cycle, causing serious pollution to the urban environment; (2) affect the health of urban residents. HW contains toxic and harmful substances. If it is not handled properly, it will pose a serious threat to the health of urban residents; and (3) constrain the sustainable development of cities and society. The pollution of the atmosphere, water, soil, etc., caused by the non-disposal or irregular treatment of HW will also become a bottleneck restricting urban economic and social activities. Hence, effective treatment of HW generated in cities is essential for sustainable cities and society development.

However, as people's awareness of environmental protection has increased, the sustainable development of cities and society has attracted more and more attention (Bai & Zhou, 2021). Proper disposal or recycling of HW is essential for reducing environmental pollution and is also an important part of HWs management, because inappropriate HW landfills may have a negative impact on the environment, economy, and ecology (Moghaddas & Namaghi, 2011). Unreasonable HW disposal site (HWDS) will cause water pollution, vegetation and soil pollution, carbon dioxide, methane, and other greenhouse gas emissions, which seriously affect the sustainable development of cities and society. The location of HWDS is considered as a multi-criteria decision-making (MCDM) problem. Therefore, a MCDM approach is required to evaluate and select the optimal HWDS site among different alternatives. In this sake, the purpose of this paper is to apply a MCDM method to select the optimal location of the HWDS from a sustainability perspective.

MCDM is a very useful tool that can analyze and solve complex decision-making problems involving multiple attributes. Besides, MCDM usually evaluates the best alternative among multiple conflicting criteria, so it is widely used in different fields (Kaya et al., 2020b). In view of the multi-dimensional nature of HWDS selection, MCDM provides an effective analysis framework for HWDS selection. MCDM is composed of a series of techniques and methods that allow experts in different fields to calculate the criteria weights and rank the alternatives. MCDM method, which includes analytical hierarchy process (AHP) (Wang & Yeap, 2021), fuzzy AHP, analytical network process (ANP) (Keyvanfar et al., 2021), preference ranking organization method for enrichment evaluation (PROMETHEE) (Molla et al., 2021), technique for order preference by similarity to an ideal solution (TOPSIS) (Kaya et al., 2020a), Visekriterijumsko Kompromisno Rangiranje (VIKOR) (Lin et al., 2021), weighted linear combination (WLC), decision-making trial and evaluation laboratory (DEMATEL) (Kim & Nguyen, 2021), etc., is widely used in the problem of facility location (Agrebi & Abed, 2021; Karagoz et al., 2021). There were many researchers who applied the MCDM approach and geographical information system (GIS) to evaluate and select suitable HW landfill sites (Danesh et al., 2019; Karaku et al., 2020; Stemn & Kumi-Boateng, 2019).

This paper constructs an evaluation index system for HWDS site selection, which considers both qualitative and quantitative criteria. Since human evaluation of qualitative criteria is

usually subjective and vague, it is very difficult for decision makers (DMs) to give accurate numerical values to evaluate qualitative criteria. However, this problem can be solved by fuzzy set theory, which has been widely used in practice to solve the uncertainty of human decision preference. Qualitative criteria can be evaluated by applying the linguistic terms. Axiomatic design (AD) measures the satisfaction of system functions and functional requirements (FRs) and has been considered as an MCDM method. Thus, fuzzy axiomatic design (FAD) method combining fuzzy set theory and AD is used for HWDS site selection. FAD method has two advantages: (1) FAD method can not only rank alternatives and select the optimal one, but also help DMs to analyze which criteria perform well and give suggestions for improvement based on the analysis results; (2) FAD method does not need to consider whether the dimensions and units of the evaluation index system are consistent, that is, it does not need to be normalized. Hence, FAD method has been applied for supplier selection, machine selection, transportation company selection, etc. However, according to the literature reviews, previous studies did not apply FAD method to select the best location of HWDS. In the FAHP and FAD methods, we use the triangular fuzzy numbers (TFN) to represent linguistic terms. FAHP is applied to evaluate the weights of criteria and sub-criteria, while FAD method is applied to rank all the alternatives.

The sustainable development of the city has attracted extensive attention from scholars. Thus, HWDS site selection needs to focus on sustainability, which usually includes economic, social, and environmental sustainability. This study aims to employ an integrated MCDM method of FAHP and FAD to select the best location of HWDS from the perspective of sustainability, which has been explored by very few researchers. Economic, social, and environmental criteria are given in this paper based on expert opinions and academic literature. The research contributions of this study are summarized as follows:

(1) Based on the literature survey, most studies applied GIS and MCDM to HWDS site selection. However, the integrated FAHP and FAD method has not yet been applied to select the best location of HWDS. Therefore, the proposed integrated method can not only enrich the studies on the location of HWDS, but also could be utilized in other fields.

(2) This is the first study that considers economic, social, and environmental criteria for HWDS site selection from a sustainable perspective. Thus, the evaluation index system and evaluation analysis methods are also applicable to HWDS site selection in other developing countries and regions.

(3) This paper combines FAHP and FAD methods to propose a novel comprehensive framework to evaluate HWDS sites. The application of TFN can not only accurately express linguistic terms, but also ensure the rationality of the evaluation results.

The research structure of this paper is given as follows: Literature review is presented in Sect. 2. Section 3 introduces the basic theory of FAHP and FAD methods. A specific application is given to verify the stability and the practicability of the proposed method in Sect. 4. In Sect. 5, sensitivity analysis and comparative analysis are carried out to verify the flexibility and effectiveness of the method proposed herein. Finally, conclusions and future research direction are given in Sect. 6.

2 Literature review

The location of HWDS is critical to the sustainable cities and society. Appropriate location of HWDS can benefit multiple stakeholders and promote the sustainable development of the city. In the past few years, some studies related to the site selection of waste landfills have been carried out. On the basis of considering the operating costs of the system and the risks imposed on local residents, Yu and Solvang (2016) constructed a multi-objective mixed-integer programming method to determine the location of HWDS and transportation routes. Asgari et al. (2017) proposed a HW site selection model that considers multiple waste types and several treatment technologies and developed a multi-objective model with three objective functions. Rabbani et al. (2018) proposed a multi-objective optimization model for HWDS site selection by considering the total cost, total transportation risk, and site risk and proposed a non-dominated sorting genetic algorithm and multi-objective particle swarm optimization to solve the model. Rabbani et al. (2019) proposed a multi-objective mathematical model of industrial HW locating, vehicle routing and inventory control in a random environment, which could reduce the potential risks of HW management. To reduce the risk of population exposure in HW range and ensure HW transportation, Yu et al. (2020) developed a novel stochastic bi-objective mixed-integer linear programming to support these decisions. Besides, to reduce HW transportation risk, Ma and Li (2021) developed an optimization model to determine HW weight and transportation routes.

HW management involves the site selection, collection, transportation, and disposal of waste. In addition, based on previous research, we find that HWDS site selection mainly focuses on minimizing costs and risks. In other word, the key to the site selection of HW treatment sites is to reduce environmental pollution, reduce costs, and transport risks. However, the use of mathematical models to optimize the site selection of waste landfills rarely considers qualitative criteria. Generally speaking, HWDS site selection involves a series of qualitative and quantitative criteria, while the MCDM method has advantages in dealing with them.

Based on the above literature review, we find that almost all studies related to HWDS site selection have adopted a decision-making method, that is, multi-objective decision-making, such as multi-objective programming, mixed-integer programming, and bi-level programming. These methods can consider some factors, such as the total cost of HWDS, and total risk. However, other factors (for example, the impact of HWDS on the environment, public support for HWDS, and the coordination between HWDS and urban development) cannot be included in the mathematical model. In view of this, this paper will apply MCDM method to select the optimal location of the HWDS from a sustainability perspective. MCDM method can simultaneously capture both quantitative and qualitative criteria that play a significant role in the HWDS site selection.

Currently, some studies focus on the use of MCDM method for landfill site selection. However, there are very few studies on HWDS site selection. Torabi-Kaveh et al. (2016) developed a multi-criteria decision analysis (MCDA) process, which combines GIS analysis and FAHP method to determine suitable landfill sites in Iranshahr, Iran. From the perspective of sustainability, Chauhan and Singh (2016) established an evaluation index system for medical waste disposal sites selection based on environmental, social, and economic criteria and used FAHP and TOPSIS methods to evaluate the location of medical waste disposal facilities. Most waste location issues require the MCDM method in the real world (Abd-El Monsef & Smith, 2019). Buyukozkan et al. (2019) proposed an integrated MCDM method based on AHP and VIKOR in the context of intuitionistic fuzzy to solve

the problem of HW site selection. Ocampo et al. (2019) developed an integrated MCDM method based on DEMATEL, ANP and AHP to address general facility location problems. Hence, the MCDM method is flexible in dealing with site selection and can effectively solve the problem of HWDS site selection. Stemn and Kumi-Boateng (2019) established a sustainability evaluation index system for HW landfill site selection based on geographical environment, economic, and social factors and applied GIS and MCDA method to evaluate suitable HW landfill locations in western Ghana. Rahimi et al. (2020) established an evaluation index system based on environmental, economic, and social criteria and used the GIS and group fuzzy MULTIMOORA methods to determine the location of waste landfill sites. Table 1 shows the relevant studies on waste landfill site selection.

Most of the previous literature used GIS and MCDM methods to select suitable HWDS. However, the literature on how to use the MCDM method to select the best alternative after determining the alternatives is very limited. Most previous MCDM methods ignore the probability that the standard meets the FRs, which may increase the risk of site selection failure. Thus, to fill the above research gaps, this paper developed an integrated the FAHP and FAD methods to select the best HWDS location. Besides, FAHP and FAD methods proposed herein not only enrich the application of sustainable HWDS selection, but also provide a reference for HWDS site selection in other developing countries or regions.

3 Methodology

In this section, a brief description of FAHP and FAD method is given in the following.

3.1 Fuzzy analytic hierarchy process

AHP, which was first proposed by Saaty (1986), has been used widely in many fields. Relying solely on the experts' subjective judgment may cause ambiguity and inaccuracy of

Table 1 Representative studies on site selection for sustainable waste disposal site

Studies	Methodology	Application
Kabir and Sumi (2015)	FAHP and PROMETHEE	Hazardous industrial waste transportation firm
Torabi-Kaveh et al. (2016)	GIS and FAHP	Solid waste landfill sites selection
Kharat et al. (2016)	FAHP and TOPSIS	Municipal solid waste landfill sites selection
Mahmood et al. (2017)	AHP and WLC	HW landfill site selection
Saatsaz et al. (2018)	GIS and AHP	Waste landfill site selection
Yildirim et al. (2018)	GIS and TOPSIS	Municipal solid waste landfill sites selection
Stemn and Kumi-Boateng (2019)	GIS and MCDA	HW landfill site selection
Rahimi et al. (2020)	GIS and fuzzy MULTIMOORA	Waste landfill site selection
Fatoyinbo et al. (2020)	GIS	Waste landfill site selection
Mallick (2021)	GIS and MCDA	Waste landfill site selection
This study	FAHP and FAD	Hazardous industrial waste disposal site selection

judgment, while AHP method with fuzzy theory can effectively solve this problem. Many scholars have been applied the FAHP in various studies, such as risk prediction (Zhong et al., 2021), multi-criteria supplier segmentation (Lo & Sudjatmika, 2016), and watersheds management (Sridhar & Ganapuram, 2021). Fuzzy extent analysis method, which is applied to calculate criteria weights, is given in the following.

Step 1 Develop a hierarchical structure model for the evaluation index system, and construct a pairwise comparison matrix. Assume that there are n criteria $C = \{C_1, C_2, \cdots, C_n)$, which are described by using linguistic terms. Table 5 in Appendix shows the TFNs corresponding to linguistic terms (Kahraman et al., 2006).

Step 2 Use TFN to convert each pairwise comparison matrix into a fuzzy comparison matrix. Each fuzzy comparison matrix is integrated by the geometric mean method. The integrated fuzzy number is expressed by $X_{ij} = (a_{ij}, b_{ij}, c_{ij})$.

$$a_{ij} = \left(\prod_{k=1}^{K} a_{ijk} \right)^{\frac{1}{K}} \tag{1}$$

$$b_{ij} = \left(\prod_{k=1}^{K} b_{ijk} \right)^{\frac{1}{k}} \tag{2}$$

$$c_{ij} = \left(\prod_{k=1}^{K} c_{ijk} \right)^{\frac{1}{k}} \tag{3}$$

where K is the number of DMs. $(a_{ijk}, b_{ijk}, c_{ijk})$ is the evaluation value given by DM k.

Step 3 Let $X = (x_1, x_2, \cdots, x_n)$ be an object set and $U = (u_1, u_2, \cdots, u_m)$ be a goal set. According to the literature (Chang, 1996), the first is to take each object and the second is to perform extent analysis for each goal, respectively, and then, m extent analysis values for each object can be obtained, expressed by Eq. (4).

$$M_{g_i}^1, M_{g_i}^2, \cdots, M_{g_i}^m, i = 1, 2, \cdots, n \tag{4}$$

where all the $M_{g_i}^j$ ($j = 1, 2, \cdots, m$) are TFN, whose parameters are α, β, and γ. Let $M_{g_i}^1, M_{g_i}^2, \cdots, M_{g_i}^m$ be the values of extent analysis of ith object for m goals. Thus, fuzzy synthetic value of the ith object can be obtained by Eq. (5).

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \odot \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j \right]^{-1} \tag{5}$$

where $\sum_{j=1}^{m} M_{g_i}^j$ and $\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j$ can be obtained by Eqs. (6) and (7), respectively.

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} \alpha_j, \sum_{j=1}^{m} \beta_j, \sum_{j=1}^{m} \gamma_j \right), i = 1, 2, \cdots, n \tag{6}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} \sum_{j=1}^{m} \alpha_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} \beta_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} \gamma_{ij} \right) \tag{7}$$

Then, $\left[\sum_{i=1}^{n}\sum_{j=1}^{m}M_{g_i}^{j}\right]^{-1}$ can be calculated by Eq. (8).

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m}M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{j=1}^{m}\gamma_j}, \frac{1}{\sum_{j=1}^{m}\beta_j}, \frac{1}{\sum_{j=1}^{m}\alpha_j}\right) \tag{8}$$

Step 4 After obtaining the fuzzy synthesis value S_i, a pairwise comparison is required. The degree of possibility of $S_2 = (\alpha_2, \beta_2, \gamma_2) \geq S_1 = (\alpha_1, \beta_1, \gamma_1)$ is defined as follows:

$$V(S_2 \geq S_1) = hgt(S_1 \cap S_2) = \mu_{S_2}(d) = \begin{cases} 0 & \text{, if } \alpha_1 \geq \gamma_2 \\ 1 & \text{, if } \beta_2 \geq \beta_1 \\ \frac{\alpha_1 - \gamma_2}{(\beta_2 - \gamma_2) - (\beta_1 - \alpha_1)} & \text{, otherwise} \end{cases} \tag{9}$$

where d is the ordinate of the intersection of S_1 and S_2 (Fig. A1 in Appendix).

Step 5 The degree possibility for a convex fuzzy number to be greater tank k convex fuzzy number S_i $(i = 1, 2, \cdots, k)$ can be defined by Eq. (10).

$$V(S \geq S_1, S_2, \cdots, S_k) = V[(S \geq S_1)\text{and}(S \geq S_2)\text{and}\cdots\text{and}(S \geq S_k)] = \min V(S \geq S_i) \tag{10}$$

Step 6 Let $d'(A_i) = \min V(S_i \geq S_k)$, $k = 1, 2, \ldots, n$, $i \neq k$. Then, the weight vector can be expressed by Eq. (11).

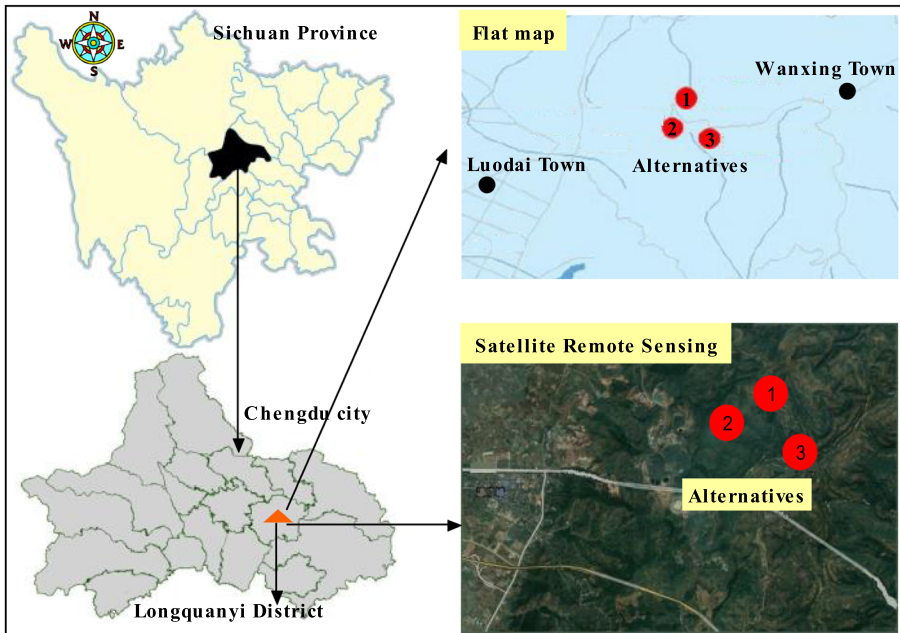$$w' = [d'(A_1), d'(A_2), \ldots, d'(A_n)]^T \tag{11}$$

Fig. 1 The geographical locations of three HWDS site alternatives

Step 7 Normalize the obtained weight vector w', and then, we give the normalized weight vector as follows:

$$w = \left(\frac{d'(A_1)}{\sum_{i=1}^{n} d'(A_n)}, \frac{d'(A_2)}{\sum_{i=1}^{n} d'(A_n)}, \cdots, \frac{d'(A_n)}{\sum_{i=1}^{n} d'(A_n)} \right)^{T} \tag{12}$$

3.2 Fuzzy axiomatic design

There are two important concepts in the axiomatic design. One is independent axiom, which requires that the independence of FRs be maintained; the other is information axiom, which requires that the information content be minimized.

Let p_i be the probability of achieving the functional requirement FR_i, and the information content IC_i can be calculated by Eq. (13).

$$IC_i = \log_2(\frac{1}{p_i}) \tag{13}$$

The area where system range and design range intersect is common range (Fig. A2), so the probability value p_i is calculated by Eq. (14).

$$p_i = \frac{\text{Common range}}{\text{System range}} \tag{14}$$

Therefore, Eq. (13) can be written as:

$$IC_i = \log_2 \left(\frac{\text{System range}}{\text{Common range}} \right) \tag{15}$$

In the FAD, linguistic terms are used to transform into TFN (Fig. A3). Then, Eq. (15) can be written as the following expression:

$$IC_i = \log_2 \left(\frac{\text{TFN of System range}}{\text{Common range}} \right) \tag{16}$$

In the real world, DMs usually assign different weights to each criterion. Therefore, we can apply Eq. (17) to calculate weighted information content of each sub-criterion.

$$IC_i^w = \begin{cases} c(IC_i)^{\frac{1}{w_i}}, 0 \le IC_i < 1 \\ (IC_i)^{w_i}, \ IC_i > 1 \\ w_i, \ IC_i = 1 \end{cases} \tag{17}$$

where I is the number of sub-criteria and $\sum_{i=1}^{I} w_i = 1, i = 1, 2, \cdots I$. IC_i^w represents the weighted information content of sub-criteria. Therefore, we can apply Eq. (18) to calculate the weighted information content of alternative k

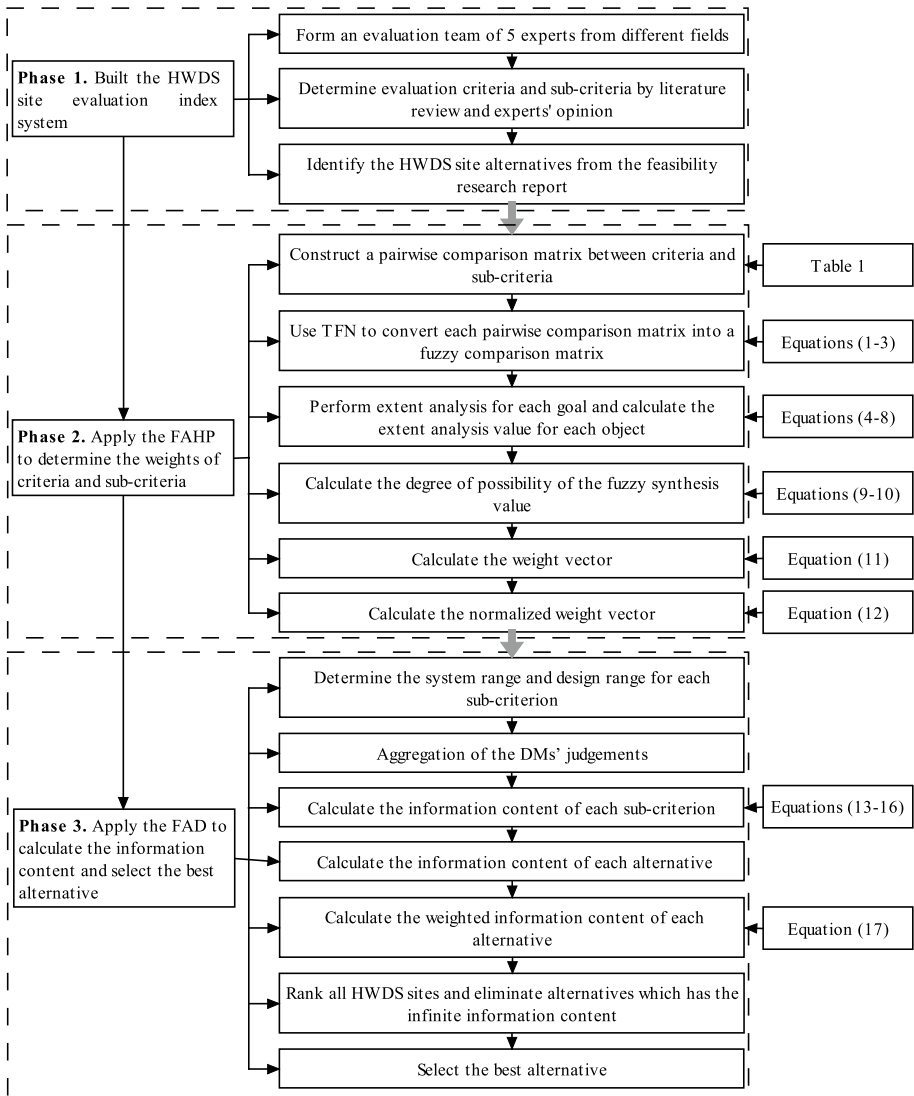$$IC_k = \sum_{i=1}^{I} IC_i^w \tag{18}$$

Phase 1. Built the HWDS site evaluation index system	Form an evaluation team of 5 experts from different fields
	Determine evaluation criteria and sub-criteria by literature review and experts' opinion
	Identify the HWDS site alternatives from the feasibility research report

Phase 2. Apply the FAHP to determine the weights of criteria and sub-criteria	Construct a pairwise comparison matrix between criteria and sub-criteria	Table 1
	Use TFN to convert each pairwise comparison matrix into a fuzzy comparison matrix	Equations (1-3)
	Perform extent analysis for each goal and calculate the extent analysis value for each object	Equations (4-8)
	Calculate the degree of possibility of the fuzzy synthesis value	Equations (9-10)
	Calculate the weight vector	Equation (11)
	Calculate the normalized weight vector	Equation (12)

Phase 3. Apply the FAD to calculate the information content and select the best alternative	Determine the system range and design range for each sub-criterion	
	Aggregation of the DMs' judgements	
	Calculate the information content of each sub-criterion	Equations (13-16)
	Calculate the information content of each alternative	
	Calculate the weighted information content of each alternative	Equation (17)
	Rank all HWDS sites and eliminate alternatives which has the infinite information content	
	Select the best alternative	

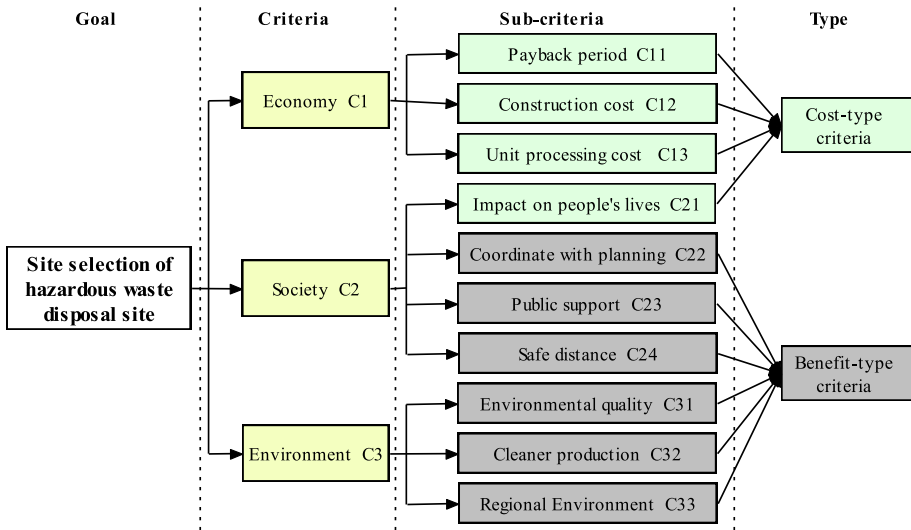**Fig. 2** Flowchart of the proposed integrated analysis framework

Fig. 3 Hierarchical structure of evaluation index system

4 Case study

In this section, a practical case is presented to demonstrate the practicality and effi-
ciency of the proposed integrated the FAHP and FAD methodology.

4.1 Case description

Chengdu, located in southwestern China, is an important city in western and the capital
of Sichuan Province. Chengdu has an area of 14,335 km^2, with a permanent popula-
tion of 16.581 million and a GDP of 1701.265 billion yuan in 2019. In recent years,
Chengdu's economy has developed rapidly, and it has played a key role in the construc-
tion of urban areas in the southwest. However, because of Chengdu rapid industrializa-
tion and urbanization, the types and quantities of industrial HW production have been
increasing, which has led to environmental problems. The amount of the industrial HW
generated in Chengdu from 2013 to 2018 is shown in Table 6. However, Chengdu's HW
disposal capacity is seriously inadequate. Therefore, the rapid increase in the number of
HWs and insufficient disposal capacity hinder the sustainable development of Chengdu.

To promote the sustainable development of city and alleviate the contradiction
between the amount of HW generated and the insufficient disposal capacity, accord-
ing to the "Construction Plan for Hazardous Waste Centralized Disposal Facilities in
Sichuan Province (2017–2022)," Chengdu will build three centralized HW disposal
facilities in Longquanyi District, Jianyang and Qionglai in stages. According to the plan,
the HWDS is first selected in the site of Longquanyi District. The proposed project is
located in Luodai Town, Longquanyi District. The project has three possible sites, and
the total area is 1.419km^2. The three possible locations have very convenient transporta-
tion, and its geographical location is shown in Fig. 1. The annual processing capacity of

the project is 122,000 tons, including 12,000 tons for comprehensive utilization, 10,000 tons for incineration (excluding medical waste), and 100,000 tons for landfill. The project site is located in the middle section of Longquan Mountain and is a valley-type landfill.

Based on the above analysis, this paper integrates the FAHP and FAD methods to propose a three-phase novel comprehensive MCDM framework for HWDS site selection problems. The main steps of the proposed framework are summarized in Fig. 2.

The first phase is to establish a HWDS site selection evaluation index system based on literature reviews and experts' opinions. The second phase is to apply FAHP method to calculate the weights of criteria and sub-criteria. The final phase is to apply FAD method to calculate the information content of all the alternatives and select the optimal HWDS site.

4.2 Evaluation index system for HWDS site selection

This study is different from previous research. Most of the previous research combined GIS and evaluation criteria to select appropriate HWDS area. However, this study is a practical case study, and government planners have identified three potential sites. Therefore, it is only necessary to select the optimal one from the three potential locations through the MCDM method. Since the potential location has been determined, the criteria in this paper are also different from previous studies.

A reasonable evaluation index system is very important for HWDS site selection. It is necessary to fully consider the various influencing factors of HWDS site selection to ensure the scientific validity of the evaluation index system. As the amount of HW continues to rise, the capacity of HW treatment facilities has been significantly insufficient. Improper disposal of HW will bring great harm to the ecological environment and human health, but also have an impact on the economy. In recent years, sustainable development has received significant attention from government and scholars. Therefore, this paper builds a HWDS site selection evaluation system from the perspective of sustainable development, which includes economic, social, and environmental criteria.

To ensure the scientific rationality of the HWDS site selection evaluation index system, a decision-making group of five experts from the fields of economy, society, ecology, engineering construction, and urban planning was formed. In addition, the evaluation index system is determined through three steps. The first step is to determine the initial evaluation index system based on the feasibility study report and literature. In the second step, experts of the decision-making group give criteria' opinions and feedback based on professional background and experience and determine important and unimportant evaluation criteria, respectively. In the third step, repeat the second step until all the experts' opinions are consistent, that is, a consensus is reached, and the HWDS evaluation index system is finally constructed. Figure 3 shows the final evaluation index system for HWDS site selection, which will be applied in the case study.

4.2.1 Economic criteria

In terms of economic criteria, the economic benefits of HWDS site selection are evaluated from the following criteria.

(1) Payback period. The investment payback period refers to the number of years to recover investment through the return flow of funds.
(2) Construction costs. It mainly includes survey and design costs, construction site preparation costs, construction costs, equipment and tools purchase costs, construction management and production preparation costs, and capital costs.
(3) Unit processing cost. The ratio of the total annual operation and maintenance cost, which includes wages, financial expenses, and maintenance expenses, to the total annual processing amount.

4.2.2 Social criteria

Four sub-criteria affiliated with the social criteria are finally determined for HWDS site selection.

(1) Impact on people's lives. Since HW is harmful to the environment and human health, it is very important to evaluate the impact of HWDS on the lives of surrounding residents. The location of HWDS that has a greater impact on people's lives is more disadvantageous, so it is important to avoid densely populated areas.
(2) Coordinate with planning. The site selection should be consistent with local development planning, environmental protection planning, and environmental function zoning.
(3) Public support. Due to the particularity of HWDS, the public may have excessive concerns. Hence, the contact with residents around the proposed site should be strengthened to obtain public support
(4) Safe distance. Ensure a safe distance between the urban area and the edge of the location area, and it must not be located in the upper wind direction of the city's dominant wind direction. In addition, ensuring a safe distance from important targets, such as heavy water conservancy and power facilities, main lines of transportation and communication, nuclear power plants, airports, etc., is very important.

4.2.3 Environmental criteria

Three sub-criteria affiliated with the environmental criteria are finally selected for HWDS site selection.

(1) Environmental quality. Assess the possible impact of HWDS on vegetation destruction, soil erosion, groundwater pollution, and air pollution during construction and operation.
(2) Cleaner production. The energy consumption, water resource consumption, pollutant generation, and discharge amount that may be required to deal with each unit of hazardous waste. The higher the degree of cleaner production, the lower the energy consumption, water resource consumption, pollutant generation, and discharge amount that may be required to deal with each unit of hazardous waste. Therefore, it is a benefit-type criterion.
(3) Regional environment. The regional environment includes the destruction of environment and the risk of HW transportation. Avoid large-scale leveling of land, deforestation, and relocation of public facilities.

4.3 Calculate weights by using FAHP

The weights of criteria and sub-criteria are determined by applying FAHP, and the detailed calculation steps are as follows:

Step 1 Construct the pairwise comparison matrix. According to the experts' opinion, the pairwise comparison matrices are constructed, and then use Table 5 to convert each individual comparison matrix into a separate fuzzy comparison matrix. Table 7 shows the fuzzy comparison matrix between the criteria. Similarly, the pairwise comparison matrices of sub-criteria are constructed (Tables 8, 9 and 10).

Step 2 Integration of the fuzzy comparison matrix. Integrate each fuzzy comparison matrix through the geometric mean process shown in Eqs. (1)–(3). Take the integrated fuzzy number X_{12} in the fuzzy comparison matrix of the criteria as an example.

Similarly, the others integrated fuzzy number can be obtained by the same way. Table 11 shows the integrated fuzzy comparison matrix of criteria. In addition, the integrated fuzzy comparison matrix of sub-criteria is shown in Tables 12, 13 and 14.

$$a_{12} = \left(\frac{1}{2} * \frac{1}{2} * \frac{3}{2} * \frac{3}{2} * \frac{3}{2}\right)^{\frac{1}{5}} = 0.97, b_{12} = (1 * 1 * 2 * 2 * 2)^{\frac{1}{5}} = 1.52,$$

$$c_{12} = \left(\frac{3}{2} * \frac{3}{2} * \frac{5}{2} * \frac{5}{2} * \frac{5}{2}\right)^{\frac{1}{5}} = 2.04$$

Step 3 Perform extent analysis for each goal and calculate the fuzzy synthetic value. Take $M_{g_i}^j$ in the integrated fuzzy comparison matrix of criteria as an example. Use Eqs. (6) and (7) to calculate $\sum_{j=1}^{m} M_{g_i}^j$ and $\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j$. Then, use Eq. (5) to calculate fuzzy synthetic value of the ith object. The detailed calculation process is given as follows:

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} \alpha_j, \sum_{j=1}^{m} \beta_j, \sum_{j=1}^{m} \gamma_j\right) = ((1 + 0.97 + 0.45), (1 + 1.52 + 0.58), (1 + 2.04 + 0.85))$$

$$= (2.41, 3.10, 3.89)$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} \sum_{j=1}^{m} \alpha_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} \beta_{ij}, \sum_{i=1}^{n} \sum_{j=1}^{m} \gamma_{ij}\right) = (7.40, 9.54, 12.26)$$

$$S_{C_1} = \sum_{j=1}^{m} M_{g_i}^j \odot \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j\right]^{-1} = (2.41, 3.10, 3.89) \odot \left(\frac{1}{12.26}, \frac{1}{9.54}, \frac{1}{7.40}\right) = (0.197, 0.325, 0.526)$$

Similarly, the others fuzzy synthetic values can be obtained by the same way. $S_{C_2} = (0.175, 0.273, 0.468)$, $S_{C_3} = (0.217, 0.354, 0.563)$.

Step 4 Calculate the degree of possibility of fuzzy synthesis value. The synthetic fuzzy value of criteria is compared by using Eq. (9). To explain the calculation steps in detail, this study takes the fuzzy synthetic value of criteria $S_{C_1} = (0.197, 0.325, 0.526)$, $S_{C_2} = (0.183, 0.308, 0.516)$, and $S_{C_3} = (0.223, 0.367, 0.616)$ as an example.

Table 2 The local, global weight, and ranking of the criteria and sub-criteria

Criteria	Weights	Sub-criteria	Local weights	Global weights	Rank
Economic (C_1)	0.324	Payback period (C_{11})	0.408	0.132	2
		Construction costs (C_{12})	0.228	0.074	8
		Unit processing cost (C_{13})	0.364	0.118	4
Society (C_2)	0.307	Impact on people's lives (C_{21})	0.291	0.089	7
		Coordinate with planning (C_{22})	0.101	0.031	10
		Public support (C_{23})	0.377	0.116	5
		Safe distance (C_{24})	0.231	0.071	9
Environment (C_3)	0.369	Environmental quality (C_{31})	0.408	0.151	1
		Cleaner production (C_{32})	0.258	0.095	6
		Regional environment (C_{33})	0.334	0.123	3

$$V\left(S_{C_1} \geq S_{C_2}\right) = 1.000, V\left(S_{C_1} \geq S_{C_3}\right) = 0.878$$

$$V\left(S_{C_2} \geq S_{C_1}\right) = 0.949, V\left(S_{C_2} \geq S_{C_3}\right) = 0.832$$

$$V\left(S_{C_3} \geq S_{C_1}\right) = 1.000, V\left(S_{C_3} \geq S_{C_2}\right) = 1.000$$

*Step 5 The weight vector can be obtained by using Eqs. (*10 and11*) First, use Eq. (10)* to obtain $V = \{minV(S_{C_1} \geq S_{C_2}, S_{C_1} \geq S_{C_3}), minV(S_{C_2} \geq S_{C_1}, S_{C_2} \geq S_{C_3}), minV(S_{C_3} \geq S_{C_1}, S_{C_3} \geq S_{C_2})\}$. Finally, $w' = (0.878, 0.832, 1.000)$.

*Step 6 Normalize the weight vector by using Eq. (*12*).* Finally, criteria weights can be obtained $W = \left(\frac{0.878}{0.878+0.832+1.000}, \frac{0.832}{0.878+0.832+1.000}, \frac{1.000}{0.878+0.832+1.000}\right) = (0.324, 0.307, 0.369)$. Similarly, the local weight vector of the sub-criteria could be obtained (Tables 12, 13 and 14). Finally, we can obtain the global sub-criteria weights (Table 2).

Table 2 shows that the priority of criteria weights is environmental, economic, and social criteria in this order. Since the local government and enterprises have been committed to the sustainable development of HW management, more weight is given to environmental criteria.

4.4 Select the best alternative by using FAD method

Step 1 Determine the design range (FRs) of each sub-criterion. The expert evaluation group uses the seven conversion scale numerical approximation systems in Fig. 4 and Fig. 5 to convert linguistic terms into TFN. Table 15 gives the DMs' judgments on FRs for the sub-criteria. Use Eq. (19) to obtain the aggregation values of FRs. *K* is the number of the experts. W_j is the fuzzy average. Therefore, we can get the final TFN of each FR.

Table 3 Unweighted and weighted information contents of alternatives for each sub-criterion

	A_i	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	$\sum$IC	Rank
Unweighted	A_1	0.585	0.644	1.645	1.241	1.570	0.670	0.860	2.055	1.333	2.130	12.733	3
	A_2	0.585	0.946	0.815	0.909	1.111	1.111	1.830	1.111	0.678	1.074	10.170	2
	A_3	0.585	0.644	0.815	0.909	1.570	1.111	0.860	1.111	1.830	0.585	10.020	1
Weighted	A_1	0.017	0.003	1.060	1.019	1.014	0.031	0.119	1.115	1.028	1.098	6.504	3
	A_2	0.017	0.472	0.177	0.343	1.003	1.012	1.044	1.016	0.017	1.009	6.111	2
	A_3	0.017	0.003	0.177	0.343	1.014	1.012	0.119	1.016	1.059	0.013	4.774	1

$$W_j = \frac{1}{k}\left(\sum_{k=1}^{K} W_j^k\right), W_j^k = \left(\alpha_j^k, \beta_j^k, \gamma_j^k\right) \tag{19}$$

Step 2 Determine the system range of all alternatives. There are three alternative sites $A_i(i = 1, 2, 3)$ in this case study. The DMs need to apply FAD method to select the best one. The DMs' linguistic evaluation of each sub-criterion is shown in Table 16 and employs Eq. (19) to aggregate the DMs' judgments. The DMs' judgments on alternatives are aggregated in Table 17.

Step 3 Determine the information content of all alternatives. The unweighted and weighted information content of each sub-criterion of the alternatives is calculated by Eqs. (16) and (17), respectively. Table 3 shows the unweighted and weighted information content.

Table 3 shows that regardless of whether the information content of alternative is weighted, A_3 has the minimal information content, and the ranking of alternatives from best to worst is $A_3 > A_2 > A_1$. Thus, A_3 is selected as the optimal location of HWDS.

5 Results and discussion

In this section, to verify the robustness of the proposed hybrid FAHP and FAD method, it is necessary to conduct a sensitivity analysis. Therefore, sensitivity analysis was performed on the change of criteria weight and the change of FRs.

5.1 Sensitivity analysis of criteria weight changes

Since the weights of criteria and sub-criteria largely are dependent on the subjective judgment of DMs, to verify the stability of the global ranking of alternatives, criteria weights can be changed. In this paper, the weights of economic, social, and environmental criteria are changed to verify the stability of the proposed method. Table 18 shows the combined scenarios of different criteria weights.

This paper discusses the impact of changes in criteria weights on the results in three scenarios. In each scenario, two criteria weights are changed and the rest is kept unchanged, and each scenario is composed of five different combinations of criteria weights. Figure 6 shows the information content of alternatives in the context of different criteria weight combinations.

Figure 6 shows that, in Scenario 1, the weight of economic criteria decreases from 0.6 to 0.2, the weight of social criteria increases from 0.2 to 0.6, and the weight of environmental criteria remains unchanged. As a result, the information content of A_1 and A_3 decreases, while the information content of A_2 increases. In Scenario 2, the weight of economic criteria decreases from 0.6 to 0.2, the weight of environmental criteria increases from 0.2 to 0.6, and the weight of social criteria remains unchanged. As a result, the information content of A_2 and A_3 is reduced, while the information content of A_1 is basically unchanged. In Scenario 3, the weight of social criteria decreases from 0.6 to 0.2, the weight of environmental criteria increases from 0.2 to 0.6, and the weight of economic criteria remains unchanged. As a result, the information contents of A_1, A_2, and A_3 are all reduced. However, it is clear from Fig. 6 that the optimal ranking under the three scenarios has not changed, which shows its stability.

5.2 Sensitivity analysis of FRs changes

To analyze the effect of changes in FRs of each sub-criterion on the results, it is necessary to perform a sensitivity analysis of FRs. Figure 7 shows the changes of FRs of different cost-type criteria, and Fig. 8 shows the changes of FRs of different benefit-type criteria.

Figure 7 shows that, in Scenario 1 and Scenario 2, as the FRs of sub-criteria C_{11} and C_{12} increase, their information content decreases first and then remains unchanged. The main reason is that as FRs increase, the smallest system range of alternatives has been included in the FRs. In Scenario 3 and Scenario 4, the ranking of A_1 and A_2 alternates, which shows that A_1 and A_2 are sensitive to changes in FRs of C_{13} and C_{21}. However, no matter how the cost-type criteria change, the information content of A_3 is the smallest, that is, A_3 is the optimal site.

Figure 8 shows that, in Scenario 5, Scenario 6, Scenario 7, Scenario 8, and Scenario 10, as the FRs of the sub-criteria increase, the information content gradually increases. In Scenario 9, the ranking of A_1 and A_2 alternates, which indicates that A_1 and A_2 are sensitive to changes in FRs of C_{32}. However, no matter how the benefit-type criteria change, the information content of A_3 is the smallest. Therefore, A_3 is selected as the optimal site.

Each sub-criterion of A_3 has the good performance. Thus, A_3 is not sensitive to changes in the FRs and the weights of criteria. Figures 7 and 8 show that A_3 has the minimum information content in all scenarios, which shows the stability of the proposed method.

5.3 Comparative analysis

To highlight the advantages of the method proposed herein, a comparative analysis was made by three MCDM methods mentioned in Table 1, namely the PROMETHEE, TOPSIS, and MULTIMOORA. Table 4 shows the ranking results of alternatives calculated by applying the other three MCDM methods.

Through different methods, the dominant relationship between A_2 and A_3 is different. The TOPSIS, MULTIMOORA, and the proposed methods in this paper obtain $A_2 \prec A_3$; only the method proposed by the PROMETHEE obtains $A_3 \prec A_2$. The TOPSIS is a method of ranking according to the closeness of a limited number of evaluation objects to the ideal solutions, which is to evaluate the relative pros and cons of the existing objects. The PROMETHEE method obtains the net flow by calculating the positive flow and negative flow of the alternative. The larger the net flow, the better the alternative. To improve the robustness of the method, three aggregation operators are used in the MULTIMOORA method to obtain the best alternative.

However, the above three methods fail to consider the probability of success for each criterion, so there is still the risk of choosing a failed alternative. By comparing the research method of this paper with the other three MCDM methods, the main advantages of this method can be summarized as follows: (1) The method proposed herein considers the probability of success for each criterion, thus reducing the risk of choosing a failed alternative, and (2) the method proposed herein has a visualized calculation process, and the calculation is simple and practical.

Table 4 Comparison results with other three MCDM methods

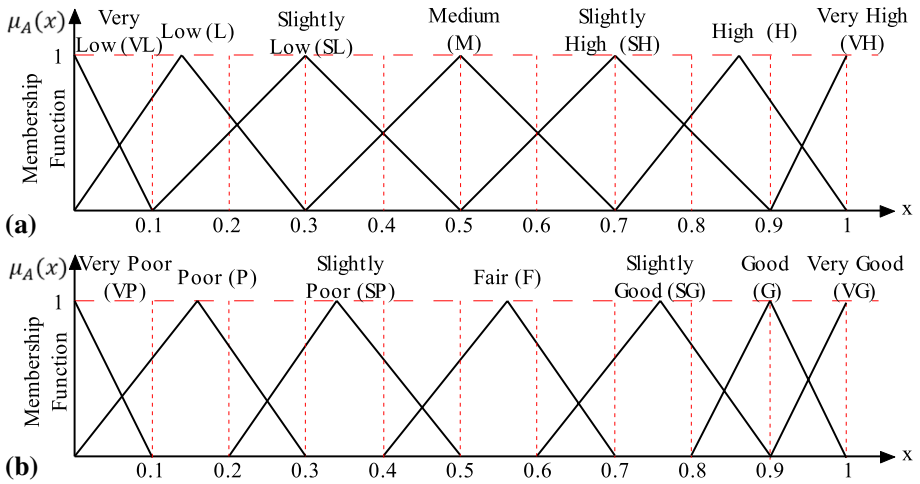|	PROMETHEE				TOPSIS		MULTIMOORA		
	Positive flow	Negative flow	Net flow	Rank	Relative closeness	Rank	Weighted ratio system	Weighted reference point	Weighted full multiplicative	Rank
A_1	0.2979	0.2992	− 0.0013	3	0.3104	3	0.4039	0.0381	1.4865	3
A_2	0.2990	0.2982	0.0009	1	0.6738	2	0.4273	0.0141	1.6392	2
A_3	0.2986	0.2981	0.0005	2	0.6753	1	0.4298	0.0116	1.6866	1

Fig. 4 The numerical approximation system for tangible and intangible criteria: **a** the numerical approximation system for tangible criteria; **b** the numerical approximation system for intangible criteria
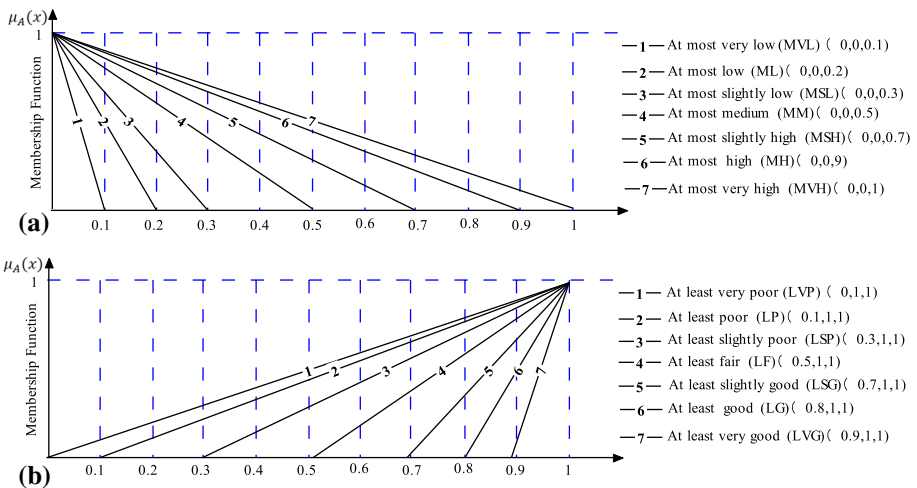

Fig. 5 The membership functions of FRs of tangible and intangible criteria: **a** the membership functions of FRs of tangible criteria; **b** the membership functions of FRs of intangible criteria

6 Conclusions

HWDS site selection has become an important and interesting topic in HW management research. To mitigate the increasing amount of HW, the government is considering selecting more HWDS to mitigate environmental pollution and threats to human health. From the perspective of sustainability, this paper builds a systematic evaluation index system based on economic, social, and environmental criteria, determines criteria weights, and applies the proposed hybrid FAHP and FAD methods to Chengdu to select the optimal HWDS site. The hybrid evaluation method adopted herein shows quite satisfactory results.
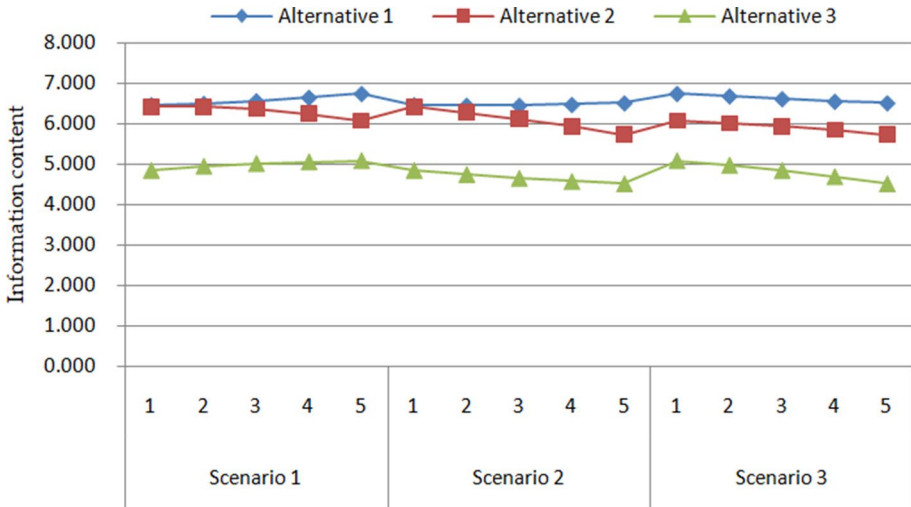
Fig. 6 Information content of alternatives in the context of different criteria weight combinations
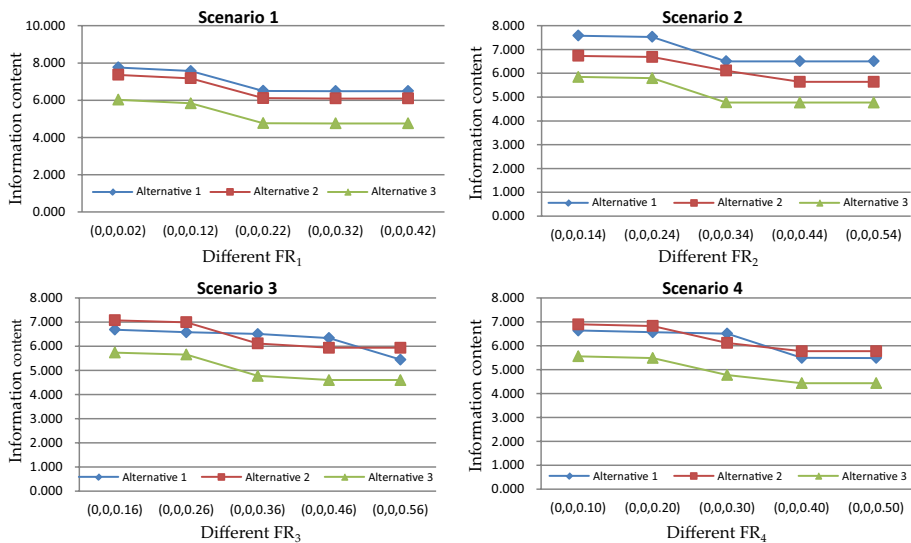

Fig. 7 Scenarios for changing FRs of different cost-type criteria

Finally, A_3 was selected as the best HWDS site. In addition, a software support system, which may be helpful in evaluating other site selection or selection issues, needs to be
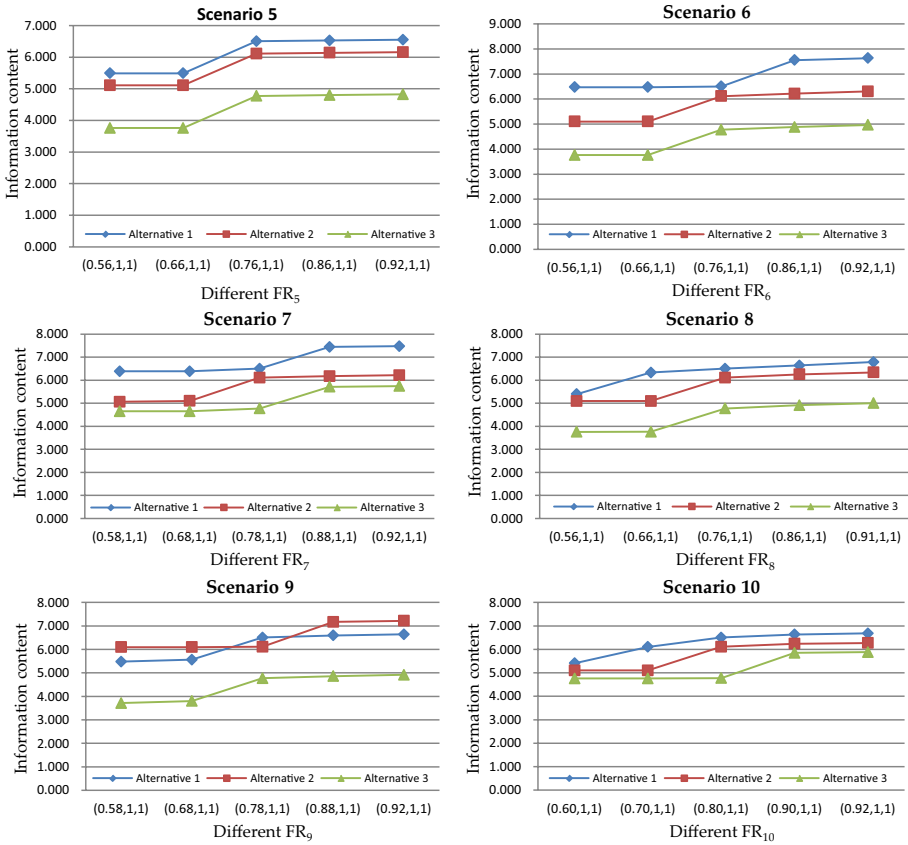
Fig. 8 Scenarios for changing FRs of different benefit-type criteria

developed. Hence, this paper tries to use FAHP and FAD technologies to propose an integrated framework to evaluate the location problem. By integrating fuzzy set theory with AHP and axiomatic design, the ambiguity of DMs' judgment may be removed. Sensitivity analysis was performed on the change of criteria weights and the change of FRs, and the results show that the proposed hybrid method is a robust decision support tool for ranking alternatives. Moreover, the proposed method is flexible and could be employed to solve other MCDM problems.

The difference from other research literatures is that the results of this paper are based on the selection of the optimal HWDS from a given number of alternatives, and the opinions are based on subjective decisions from DMs in different fields. The hybrid method proposed in this paper can be applied to more case studies to obtain more reliable results, thereby further proving its stability. Second, rejection of alternatives that do not satisfy one of the FRs seems to be the main limitation of the AD method, because alternatives with "infinitive" values cannot be compared. For future research, if all the alternatives do not satisfy the FRs, the improved AD method should be considered to evaluate the alternatives.

Appendix

Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18.

Table 5 The TFNs corresponding to linguistic terms

Linguistic terms	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal (JE)	(1, 1, 1)	(1, 1, 1)
Equally important (EI)	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more important (WMI)	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly more important (SMI)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very strongly more important (VSMI)	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important (AMI)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Table 6 Industrial hazardous waste production in Chengdu from 2013 to 2018 (unit: tons)

Year	2013	2014	2015	2016	2017	2018
Industrial HW production	154,605	206,458	206,201	222,625	261,371	275,600

Data source: Chengdu Municipal Solid Waste Pollution Prevention and Control Information.

Table 7 Fuzzy comparison matrix between the criteria

Criteria	DMs	Economic (C_1)	Society (C_2)	Environment (C_3)
Economic (C_1)	DM_1	(1, 1, 1)	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)
	DM_2		(1/2, 1, 3/2)	(2/5, 1/2, 2/3)
	DM_3		(3/2, 2, 5/2)	(1/2, 2/3, 1)
	DM_4		(3/2, 2, 5/2)	(2/3, 1, 2)
	DM_5		(3/2, 2, 5/2)	(1/3, 2/5, 1/2)
Society (C_2)	DM_1	(2/3, 1, 2)	(1, 1, 1)	(1, 3/2, 2)
	DM_2	(2/3, 1, 2)		(1, 3/2, 2)
	DM_3	(2/5, 1/2, 2/3)		(1, 3/2, 2)
	DM_4	(1, 3/2, 2)		(1/2, 1, 3/2)
	DM_5	(1, 3/2, 2)		(1/2, 1, 3/2)
Environment (C_3)	DM_1	(3/2, 2, 5/2)	(1/2, 2/3, 1)	(1, 1, 1)
	DM_2	(3/2, 2, 5/2)	(1/2, 2/3, 1)	
	DM_3	(1, 3/2, 2)	(1/2, 2/3, 1)	
	DM_4	(1/2, 1, 3/2)	(2/3, 1, 2)	
	DM_5	(2, 5/2, 3)	(2/3, 1, 2)	

Table 8 Fuzzy comparison matrix with respect to economic (C_1)

Sub-criteria	DMs	Payback period (C_{11})	Construction costs (C_{12})	Unit processing cost (C_{13})
Payback period (C_{11})	DM_1	(1, 1, 1)	(1, 3/2, 2)	(1, 3/2, 2)
	DM_2		(1, 3/2, 2)	(1, 3/2, 2)
	DM_3		(1, 3/2, 2)	(1, 3/2, 2)
	DM_4		(1/2, 1, 3/2)	(1, 3/2, 2)
	DM_5		(1/2, 1, 3/2)	(1/2, 1, 3/2)
Construction costs (C_{12})	DM_1	(1/2, 2/3, 1)	(1, 1, 1)	(2/5, 1/2, 2/3)
	DM_2	(1/2, 2/3, 1)		(2/5, 1/2, 2/3)
	DM_3	(1/2, 2/3, 1)		(2/3, 1, 2)
	DM_4	(2/3, 1, 2)		(2/5, 1/2, 2/3)
	DM_5	(2/3, 1, 2)		(2/3, 1, 2)
Unit processing cost (C_{13})	DM_1	(1/2, 2/3, 1)	(3/2, 2, 5/2)	(1, 1, 1)
	DM_2	(1/2, 2/3, 1)	(3/2, 2, 5/2)	
	DM_3	(1/2, 2/3, 1)	(1/2, 1, 3/2)	
	DM_4	(1/2, 2/3, 1)	(3/2, 2, 5/2)	
	DM_5	(2/3, 1, 2)	(1/2, 1, 3/2)	

Table 9 Fuzzy comparison matrix with respect to society (C_2)

Sub-criteria	DMs	Impact on people's lives (C_{21})	Coordinate with regional planning (C_{22})	Public support (C_{23})	Safe distance (C_{24})
Impact on people's lives (C_{21})	DM_1	(1, 1, 1)	(3/2, 2, 5/2)	(2/7, 1/3, 2/5)	(1/2, 1, 3/2)
	DM_2		(3/2, 2, 5/2)	(2/7, 1/3, 2/5)	(1/2, 1, 3/2)
	DM_3		(2, 5/2, 3)	(1/3, 2/5, 1/2)	(3/2, 2, 5/2)
	DM_4		(2, 5/2, 3)	(2/5, 1/2, 2/3)	(2, 5/2, 3)
	DM_5		(1/2, 1, 3/2)	(1/2, 2/3, 1)	(3/2, 2, 5/2)
Coordinate with regional planning (C_{22})	DM_1	(2/5, 1/2, 2/3)	(1, 1, 1)	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)
	DM_2	(2/5, 1/2, 2/3)		(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)
	DM_3	(1/3, 2/5, 1/2)		(2/3, 1, 2)	(1/2, 2/3, 1)
	DM_4	(1/3, 2/5, 1/2)		(2/5, 1/2, 2/3)	(2/3, 1, 2)
	DM_5	(2/3, 1, 2)		(2/5, 1/2, 2/3)	(2/3, 1, 2)
Public support (C_{23})	DM_1	(5/2, 3, 7/2)	(3/2, 2, 5/2)	(1, 1, 1)	(1/2, 1, 3/2)
	DM_2	(5/2, 3, 7/2)	(3/2, 2, 5/2)		(1/2, 1, 3/2)
	DM_3	(2, 5/2, 3)	(1/2, 1, 3/2)		(1/2, 1, 3/2)
	DM_4	(3/2, 2, 5/2)	(3/2, 2, 5/2)		(1/2, 1, 3/2)
	DM_5	(1, 3/2, 2)	(3/2, 2, 5/2)		(3/2, 2, 5/2)
Safe distance (C_{24})	DM_1	(2/3, 1, 2)	(3/2, 2, 5/2)	(2/3, 1, 2)	(1, 1, 1)
	DM_2	(2/3, 1, 2)	(3/2, 2, 5/2)	(2/3, 1, 2)	
	DM_3	(2/5, 1/2, 2/3)	(1, 3/2, 2)	(2/3, 1, 2)	
	DM_4	(1/3, 2/5, 1/2)	(1/2, 1, 3/2)	(2/3, 1, 2)	
	DM_5	(2/5, 1/2, 2/3)	(1/2, 1, 3/2)	(2/5, 1/2, 2/3)	

Table 10 Fuzzy comparison matrix with respect to environment (C_3)

Sub-criteria	DMs	Environmental quality (C_{31})	Cleaner production (C_{32})	Regional environment (C_{33})
Environmental quality (C_{31})	DM_1	(1, 1, 1)	(1/2, 1, 3/2)	(1, 3/2, 2)
	DM_2		(1/2, 1, 3/2)	(1, 3/2, 2)
	DM_3		(3/2, 2, 5/2)	(1, 3/2, 2)
	DM_4		(3/2, 2, 5/2)	(1/2, 1, 3/2)
	DM_5		(3/2, 2, 5/2)	(1/2, 1, 3/2)
Cleaner production (C_{32})	DM_1	(2/3, 1, 2)	(1, 1, 1)	(1/2, 2/3, 1)
	DM_2	(2/3, 1, 2)		(1/2, 2/3, 1)
	DM_3	(2/5, 1/2, 2/3)		(1/2, 2/3, 1)
	DM_4	(2/5, 1/2, 2/3)		(2/3, 1, 2)
	DM_5	(2/5, 1/2, 2/3)		(2/3, 1, 2)
Regional environment (C_{33})	DM_1	(1/2, 2/3, 1)	(1, 3/2, 2)	(1, 1, 1)
	DM_2	(1/2, 2/3, 1)	(1, 3/2, 2)	
	DM_3	(1/2, 2/3, 1)	(1, 3/2, 2)	
	DM_4	(2/3, 1, 2)	(1/2, 1, 3/2)	
	DM_5	(2/3, 1, 2)	(1/2, 1, 3/2)	

Table 11 The integrated fuzzy comparison matrix of the criteria

Criteria	Economic (C_1)	Society (C_2)	Environment (C_3)	Weights
Economic (C_1)	(1, 1, 1)	(0.97, 1.52, 2.04)	(0.45, 0.58, 0.85)	0.324
Society (C_2)	(0.49, 0.66, 1.03)	(1, 1, 1)	(0.76, 1.28, 1.78)	0.307
Environment (C_3)	(1.18, 1.72, 2.24)	(0.56, 0.78, 1.32)	(1, 1, 1)	0.369

Table 12 Local weights and integrated fuzzy comparison matrix with respect to economic (C_1)

Sub-criteria	Payback period (C_{11})	Construction costs (C_{12})	Unit processing cost (C_{13})	Weights
Payback period (C_{11})	(1, 1, 1)	(0.76, 1.28, 1.78)	(0.87, 1.38, 1.89)	0.408
Construction costs (C_{12})	(0.56, 0.78, 1.32)	(1, 1, 1)	(0.49, 0.66, 1.03)	0.228
Unit processing cost (C_{13})	(0.53, 0.72, 1.15)	(0.97, 1.52, 2.04)	(1, 1, 1)	0.364

Table 13 Local weights and integrated fuzzy comparison matrix with respect to society (C_2)

Sub-criteria	Impact on people's lives (C_{21})	Coordinate with planning (C_{22})	Public support (C_{23})	Safe distance (C_{24})	Weights
Impact on people's lives (C_{21})	(1, 1, 1)	(1.35, 1.90, 2.43)	(0.35, 0.43, 0.56)	(1.02, 1.58, 2.11)	0.291
Coordinate with planning (C_{22})	(0.41, 0.53, 0.74)	(1, 1, 1)	(0.44, 0.57, 0.83)	(0.51, 0.70, 1.12)	0.101
Public support (C_{23})	(1.80, 2.32, 2.84)	(1.20, 1.74, 2.26)	(1, 1, 1)	(0.62, 1.15, 1.66)	0.377
Safe distance (C_{24})	(0.47, 0.63, 0.98)	(0.89, 1.43, 1.95)	(0.60, 0.87, 1.61)	(1, 1, 1)	0.231

Table 14 Local weights and integrated fuzzy comparison matrix with respect to environment (C_3)

Sub-criteria	Environmental quality (C_{31})	Cleaner production (C_{32})	Regional environment (C_{33})	Weights
Environmental quality (C_{31})	(1, 1, 1)	(0.97, 1.52, 2.04)	(0.76, 1.28, 1.78)	0.408
Cleaner production (C_{32})	(0.49, 0.66, 1.03)	(1, 1, 1)	(0.56, 0.78, 1.32)	0.258
Regional environment (C_{33})	(0.56, 0.78, 1.32)	(0.76, 1.28, 1.78)	(1, 1, 1)	0.334

Table 15 DMs' judgments on FRs for the sub-criteria and comprehensive judgments for FRs

	At most (cost-type criteria)			At least (benefit-type criteria)						
	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}
DM_1	VL	M	M	M	SG	F	SG	SG	G	G
DM_2	VL	SL	L	SL	SG	G	G	G	G	G
DM_3	L	L	SL	SL	G	G	VG	SG	G	G
DM_4	L	M	SL	L	G	G	SG	G	G	G
DM_5	M	L	M	L	G	VG	G	G	SG	G
FRs	(0,0,0.22)	(0,0,0.34)	(0,0,0.36)	(0,0,0.30)	(0.76,1,1)	(0.76,1,1)	(0.78,1,1)	(0.76,1,1)	(0.78,1,1)	(0.80,1,1)

Table 16 DMs' judgments for alternatives with respect to sub-criteria

A_i	DMs	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}
A_1	DM_1	L	L	M	SL	SG	G	G	SG	G	G
	DM_2	L	L	SL	L	SG	G	G	SG	SG	SG
	DM_3	L	SL	SL	SL	SG	SG	SG	SG	G	G
	DM_4	VL	L	VL	L	G	G	G	SG	SG	SG
	DM_5	VL	L	SL	L	G	G	G	G	G	SG
A_2	DM_1	VL	SL	SL	SL	G	G	SG	SG	VG	G
	DM_2	VL	L	SL	L	G	G	SG	SG	G	G
	DM_3	L	L	L	L	SG	G	G	G	SG	G
	DM_4	L	SL	L	L	G	SG	G	G	G	G
	DM_5	L	L	L	L	SG	SG	SG	G	G	SG
A_3	DM_1	VL	L	SL	SL	G	G	G	SG	G	G
	DM_2	VL	L	SL	L	SG	G	G	SG	SG	G
	DM_3	L	L	L	L	SG	G	G	G	G	G
	DM_4	L	SL	L	L	G	SG	G	G	SG	G
	DM_5	L	L	L	L	SG	SG	SG	G	SG	G

Table 17 Aggregation on DMs' judgments for alternatives

	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}
A_1	(0,0.11,0.22)	(0.02,0.18,0.34)	(0.12,0.29,0.46)	(0.04,0.21,0.38)	(0.68,0.81,0.94)
A_2	(0,0.11,0.22)	(0.04,0.21,0.38)	(0.04,0.21,0.38)	(0.02,0.18,0.34)	(0.72,0.84,0.96)
A_3	(0,0.11,0.22)	(0.02,0.18,0.34)	(0.04,0.21,0.38)	(0.02,0.18,0.34)	(0.68,0.81,0.94)

	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}
A_1	(0.76,0.87,0.98)	(0.76,0.87,0.98)	(0.64,0.78,0.92)	(0.72,0.84,0.96)	(0.68,0.81,0.94)
A_2	(0.72,0.84,0.96)	(0.68,0.81,0.94)	(0.72,0.84,0.96)	(0.78,0.87,0.98)	(0.76,0.87,0.98)
A_3	(0.72,0.84,0.96)	(0.76,0.87,0.98)	(0.72,0.84,0.96)	(0.68,0.81,0.94)	(0.80,0.90,1.00)

Table 18 Scenarios with different criteria weights

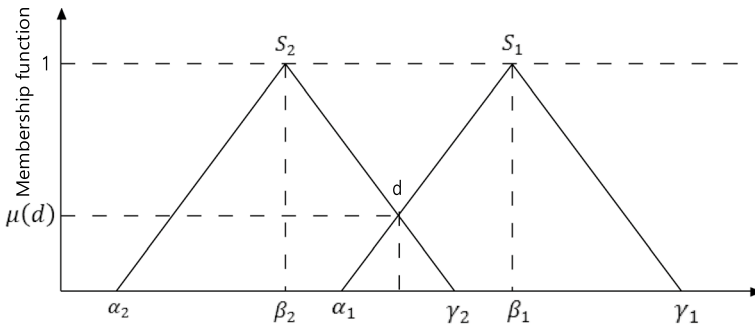| Weight	Scenario 1					Scenario 2					Scenario 3				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
W_{C1}	0.6	0.5	0.4	0.3	0.2	0.6	0.5	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2
W_{C2}	0.2	0.3	0.4	0.5	0.6	0.2	0.2	0.2	0.2	0.2	0.6	0.5	0.4	0.3	0.2
W_{C3}	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.5	0.6	0.2	0.3	0.4	0.5	0.6

Figures 9, 10, and 11.

Fig. 9 The intersection between S_1 and S_2

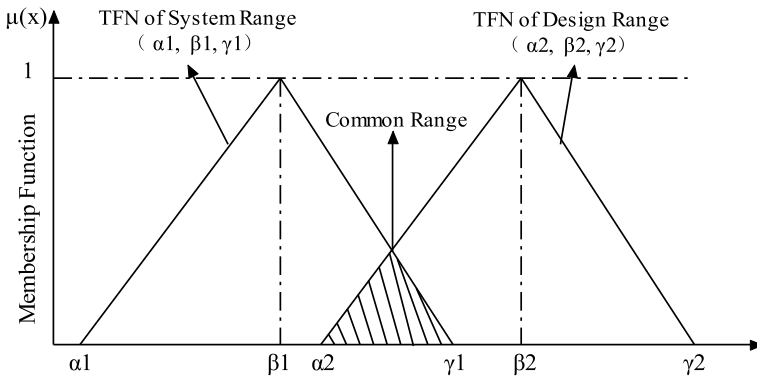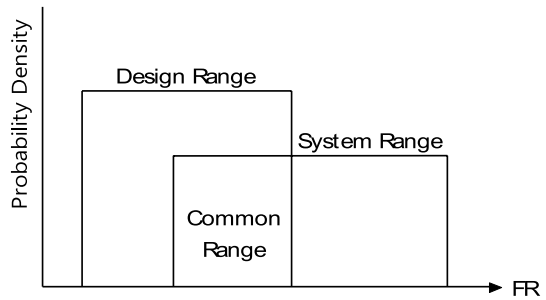**Fig. 10** Examples of interrelationships between system, design and common range

Fig. 11 Example of representation methods in the context of TFNs

References

Abd-El Monsef, H., & Smith, S. E. (2019). Integrating remote sensing, geographic information system, and analytical hierarchy process for hazardous waste landfill site selection. *Arabian Journal of Geosciences., 12*, 14.

Agrebi, M., & Abed, M. (2021). Decision-making from multiple uncertain experts: Case of distribution center location selection. *Soft Computing., 25*, 4525–4544.

Arikan, E., Simsit-Kalender, Z. T., & Vayvay, O. (2017). Solid waste disposal methodology selection using multi-criteria decision making methods and an application in Turkey. *Journal of Cleaner Production., 142*, 403–412.

Asgari, N., Rajabi, M., Jamshidi, M., Khatami, M., & Farahani, R. Z. (2017). A memetic algorithm for a multi-objective obnoxious waste location-routing problem: A case study. *Annals of Operations Research., 250*, 279–308.

Bai, X., & Zhou, J. H. (2021). Study on landscape construction of ecological garden based on ecological perspective. *Fresenius Environmental Bulletin., 30*, 402–405.

Buyukozkan, G., Gocer, F., & Karabulut, Y. (2019). A new group decision making approach with IF AHP and IF VIKOR for selecting hazardous waste carriers. *Measurement, 134*, 66–82.

Chang, D.-Y. (1996). Applications of the Extent Analysis Method on Fuzzy AHP. *European Journal of Operational Research., 95*, 649–655.

Chauhan, A., & Singh, A. (2016). A hybrid multi-criteria decision making method approach for selecting a sustainable location of healthcare waste disposal facility. *Journal of Cleaner Production., 139*, 1001–1010.

Danesh, G., Monavari, S. M., Omrani, G. A., Karbasi, A., & Farsad, F. (2019). Compilation of a model for hazardous waste disposal site selection using GIS-based multi-purpose decision-making models. *Environmental Monitoring and Assessment., 191*, 14–28.

Fatoyinbo, I. O., Bello, A. A., Olajire, O. O., Oluwaniyi, O. E., Olabode, O. F., Aremu, A. L., Omoniyi, L. A. (2020). Municipal solid waste landfill site selection: a geotechnical and geoenvironmental-based geospatial approach. *Environmental Earth Sciences*. 79.

Ghorani-Azam, A., Riahi-Zanjani, B., Balali-Mood, M. (2016). Effects of air pollution on human health and practical measures for prevention in Iran. *Journal of Research in Medical Sciences the Official Journal of Isfahan University of Medical Sciences*. 21.

Kabir, G., & Sumi, R. S. (2015). Hazardous waste transportation firm selection using fuzzy analytic hierarchy and PROMETHEE methods. *International Journal of Shipping and Transport Logistics., 7*, 115–136.

Kahraman, C., Ertay, T., & Buyukozkan, G. (2006). A fuzzy optimization model for QFD planning process using analytic network approach. *European Journal of Operational Research., 171*, 390–411.

Karagoz, S., Deveci, M., Simic, V., Aydin, N. (2021). Interval type-2 Fuzzy ARAS method for recycling facility location problems. *Applied Soft Computing*. 102.

Karaku, C. B., Demirolu, D., Oban, A., & Uluta, A. (2020). Evaluation of GIS-based multi-criteria decision-making methods for sanitary landfill site selection: the case of Sivas city, Turkey. *Journal of Material Cycles and Waste Management., 22*, 254–272.

Kaya, Ö., Alemdar, K. D., & Çodur, M. Y. (2020a). A novel two stage approach for electric taxis charging station site selection. *Sustainable Cities and Society., 62*, 102396.

Kaya, Ö., Tortum, A., Alemdar, K. D., & Çodur, M. Y. (2020b). Site selection for EVCS in Istanbul by GIS and multi-criteria decision-making. *Transportation Research Part D: Transport and Environment., 80*, 102271.

Keyvanfar, A., Shafaghat, A., Ismail, N., Mohamad, S., Ahmad, H. (2021). Multifunctional retention pond for stormwater management: A decision-support model using Analytical Network Process (ANP) and Global Sensitivity Analysis (GSA). *Ecological Indicators*. 124.

Kharat, M. G., Kamble, S. J., Raut, R. D., Kamble, S. S., & Dhume, S. M. (2016). Modeling landfill site selection using an integrated fuzzy MCDM approach. *Modeling Earth Systems and Environment., 2*, 16.

Kim, S. Y., Nguyen, M. V. (2021). Mapping the complexity of international development projects using DEMATEL technique. *Journal Of Management In Engineering*. 37.

Lin, M. W., Chen, Z. Y., Xu, Z. S., Gou, X. J., & Herrera, F. (2021). Score function based on concentration degree for probabilistic linguistic term sets: An application to TOPSIS and VIKOR. *Information Sciences., 551*, 270–290.

Lo, S. C., & Sudjatmika, F. V. (2016). Solving multi-criteria supplier segmentation based on the modified FAHP for supply chain management: A case study. *Soft Computing., 20*, 4981–4990.

Ma, H. G., & Li, X. (2021). Multi-period hazardous waste collection planning with consideration of risk stability. *Journal of Industrial and Management Optimization., 17*, 393–408.

Mahmood, K., Batool, S. A., Chaudhary, M. N., & Ul-Haq, Z. (2017). Ranking criteria for assessment of municipal solid waste dumping sites. *Archives of Environmental Protection., 43*, 95–105.

Mallick, J. (2021). Municipal solid waste landfill site selection based on fuzzy-AHP and geoinformation techniques in Asir Region Saudi Arabia. *Sustainability.* 13.

Moghaddas, N. H., & Namaghi, H. H. (2011). Hazardous waste landfill site selection in Khorasan Razavi Province Northeastern Iran. *Arabian Journal of Geosciences, 4*, 103–113.

Molla, M. U., Giri, B. C., & Biswas, P. (2021). Extended PROMETHEE method with Pythagorean fuzzy sets for medical diagnosis problems. *Soft Computing., 25*, 4503–4512.

Mora, S. L. C., Pelaez, J. L. S., & Rodriguez, P. C. G. (2021). Selection's criteria for a non-hazardous solid waste disposal site. Review of Latin American environmental norms and their contrast with the Ecuadorian regulation. *Revista Internacional De Contaminacion Ambiental., 37*, 39–53.

Ocampo, L. A., Himang, C. M., Kumar, A., & Brezocnik, M. (2019). A novel multiple criteria decision-making approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy AHP for mapping collection and distribution centers in reverse logistics. *Advances in Production Engineering & Management., 14*, 297–322.

Rabbani, M., Heidari, R., Farrokhi-Asl, H., & Rahimi, N. (2018). Using metaheuristic algorithms to solve a multi-objective industrial hazardous waste location-routing problem considering incompatible waste types. *Journal of Cleaner Production., 170*, 227–241.

Rabbani, M., Heidari, R., & Yazdanparast, R. (2019). A stochastic multi-period industrial hazardous waste location-routing problem: Integrating NSGA-II and Monte Carlo simulation. *European Journal of Operational Research., 272*, 945–961.

Rahimi, S., Hafezalkotob, A., Monavari, S. M., Hafezalkotob, A., & Rahimi, R. (2020). Sustainable landfill site selection for municipal solid waste based on a hybrid decision-making approach: Fuzzy group BWM-MULTIMOORA-GIS. *Journal of Cleaner Production., 248*, 15.

Saatsaz, M., Monsef, I., Rahmani, M., & Ghods, A. (2018). Site suitability evaluation of an old operating landfill using AHP and GIS techniques and integrated hydrogeological and geophysical surveys. *Environmental Monitoring And Assessment, 190*(3), 1–31. https://doi.org/10.1007/s10661-018-6505-x.

Saaty, T. L. (1986). Axiomatic foundation of the analytic hierarchy process. *Management Science., 32*, 841–855.

Sridhar, P., Ganapuram, S. (2021). Morphometric analysis using fuzzy analytical hierarchy process (FAHP) and geographic information systems (GIS) for the prioritization of watersheds. *Arabian Journal Of Geosciences.* 14.

Stemn, E., & Kumi-Boateng, B. (2019). Hazardous waste landfill site selection in Western Ghana: An integration of multi-criteria decision analysis and geographic information system. *Waste Management & Research., 37*, 723–736.

Torabi-Kaveh, M., Babazadeh, R., Mohammadi, S. D., & Zaresefat, M. (2016). Landfill site selection using combination of GIS and fuzzy AHP, a case study: Iranshahr Iran. *Waste Management & Research., 34*, 438–448.

Unal, M., Cilek, A., & Guner, E. D. (2020). Implementation of fuzzy, Simos and strengths, weaknesses, opportunities and threats analysis for municipal solid waste landfill site selection: Adana City case study. *Waste Management & Research., 38*, 45–64.

Wang, F., Yeap, S. P. (2021). Using magneto-adsorbent for methylene Blue removal: A decision-making via analytical hierarchy process (AHP). *Journal Of Water Process Engineering.* 40.

Yildirim, V., Memisoglu, T., Bediroglu, S., & Colak, E. (2018). Municipal solid waste landfill site selection using multi-criteria decision making and GIS: Case study of Bursa province. *Journal of Environmental Engineering and Landscape Management., 26*, 107–119.

Yu, H., & Solvang, W. D. (2016). An improved multi-objective programming with augmented epsilon-constraint method for hazardous waste location-routing problems. *International Journal of Environmental Research and Public Health., 13*, 21.

Yu, H., Sun, X., Solvang, W. D., Laporte, G., Lee, C. K. M. (2020). A stochastic network design problem for hazardous waste management. *Journal Of Cleaner Production.* 277.

Zhong, Y. W., Li, H. L., Chen, L. L. (2021). Construction project risk prediction model based on EW-FAHP and one dimensional convolution neural network. *Plos One.* 16.