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Developing a sustainability-oriented multi-criteria game theoretical decision analysis framework: A case study of sludge management

Abstract

Decision-making process can be influenced by many factors, including the interests and preferences of stakeholders, their interactions, as well as the considered criteria. This study constructs a methodology framework based on game theory and multi-criteria decision making (MCDM) approach to address the decision-making problem with conflicting interests of different parties for sustainable sludge management. The proposed framework compares the overall sustainability performances of the alternatives for the corresponding stakeholder based on the life cycle sustainability impacts and the weight of each criterion. The weights of considered criteria are determined by the opinions of different groups of stakeholders. Then, game theory is applied to assist the stakeholders share the costs and benefits and guide them to reach a consensus on the final selection for the sludge management technology. A case study applying the proposed framework to analyze the game between sludge treatment facility and the government was carried out. Four different sludge valorization technologies were selected as the alternative strategies for both players, including incineration for electricity production followed by landfill (S1), incineration for power generation followed by cement production (S2), biogas from sludge digestion for electricity generation by fuel cells (S3) and biogas from sludge digestion for electricity generation by combustion (S4). Results show that both the sludge treatment facility and the government may mutually benefit from S3 if the sludge treatment facility pays a tipping fee of $0.19-7.59 per kWh net electricity generation. Sensitivity analysis was also carried out to study the influence of weighting variations and parameter uncertainty on the final strategy selection and results revealed the stability of the proposed framework. The outcome of the framework can contribute to the sustainable decision-making process for the involved players and reach an agreement more efficiently.

Keywords: Sludge-to-energy technology, Game theory, Multi-criteria decision-making, Sustainability assessment, Fuzzy best-worst method.

1. Introduction

The increasing population and urbanization trend are accompanied by a large amount of sewage production, followed by considerable amount of sludge generation. Sewage sludge has been regarded as a type of resource which can be used for land application, energy recycling and renewable energy generation, and construction materials production (Asian Development Bank, 2012). According to the previous research and reports (Ding, 2017; Wei et al., 2020; Yang et al., 2015), the total sludge production in China presented a significant increasing trend from 2007 to 2019, while the total amount of treatment and the increase of treatment rate cannot keep pace with the sludge production. It was recorded that over 70% of sludge was released into the environment without receiving proper treatment and disposal (Ding, 2017). Due to the coexisting of harmful compositions and valuable matters or recyclables (Rulkens, 2008), effective treatment measures are necessary for sludge management to reduce or eliminate the possible negative environmental impact and potential threats toward human health, as well as conducting energy recovery and resource recycling for better sustainable development.

During the recent decades, significant development has been made in different sludge treatment technologies, like sludge incineration with power generation, which contributes a lot to the thorough treatment of sludge as well as energy recovery form the waste (Zhao, 2018). Many advanced technologies have also been developed and gradually caused wide attention in research field to discuss the feasibility and potential for commercial application of these technologies, such as pyrolysis and gasification (Syed-Hassan et al., 2017). Since different technologies usually show different merits and shortcomings on different aspects, conducting reliable evaluation for the alternatives to promote the sustainable decision-making process of sludge management is necessary and essential.

Multi-criteria decision-making (MCDM) methods can help to address the decision-making problem with the consideration of multiple criteria. However, solely using MCDM is questionable when dealing with the problems that consider the interactions between decision-makers and conflicting interests, which are common in the practice (Soltani et al., 2016). Therefore, a game theoretical-based MCDM framework is constructed to address the decision-making problem considering the interactions between stakeholders and further promote the sustainable decision-making process of sludge management.

2. Literature review

Currently, the major methods for sludge treatment and disposal include composting, anaerobic digestion (AD), dewatering, drying, incineration, and landfilling (Wei et al., 2020). There are also some less commonly applied technologies under commercial scale or emerging sludge treatment technologies that are still in the development stage, such as anaerobic fermentation, microbial fuel cells for sludge treatment with electricity generation, pyrolysis and gasification, and supercritical water gasification (SCWG) (Liu et al., 2020a). Biofuels, waste heat, electricity, and valuable chemicals can be recycled or regenerated during the process of different sludge treatment technique routes. Consider the different features of diverse techniques, it is necessary to discuss the sustainability performance of sludge treatment technique routes in detail for sustainable sludge management. Life cycle sustainability assessment (LCSA) is a powerful tool to evaluate sustainability for the investigated system from the perspective of environment, economy, and society considering entire life cycle stages (Ciroth et al., 2011). It can provide a reliable reference for sustainability evaluation since it considers the possible influence along all the life stages within the system boundaries, not just the influence of a single process, which may be ignored by other evaluation methods. Hence, LCSA consisting of LCA (life cycle assessment), LCC (life cycle costing), and SLCA (social life cycle assessment), especially LCA and LCC, has been frequently used for sustainability evaluation and further providing reference information for decision-makers.

Although the sustainability performance data can on different aspects be obtained based on the LCSA methods, stakeholders still need to figure out how to integrate the results together in order to generate an overall ranking. Multi-criteria decision-making (MCDM) methods advantaging in the performance integration of multi-aspects, rather than only considering one specific aspect, can quantify the sustainability indicators and generate a ranking for selection. Therefore, prioritization problem for sludge-to-energy technologies can be modeled as a sustainability-oriented multi-criteria decision analysis (MCDA) problem. Plenty of MCDA can be applied to analyze the trade-off and assist to find out an optimal alternative to realize their targets (Kumar et al., 2017; Soltani et al., 2016). However, more complex situations may be encountered in the practice because besides multiple criteria, the conflicting interests of the involved stakeholders should also be considered. For example, the sludge treatment facilities may focus more on the treatment charges and economic profits, while the government may emphasize more on the entire harmless disposal rate and possible environmental impact, and the residents may consider more about social influence, like odor and job creation (Soltani et al., 2016). To face with the challenges above, game theory aiming to address the influence of interactions between stakeholders and conflicting interests is introduced into the decision-making process to help the decision-makers reach an agreement on their “sustainable” goals (Aplak and Sogut, 2013).

Many efforts have been conducted on using game theory and MCDM for decision-making problems in different fields. Soltani et al. (2016) constructed a decision-making framework by using LCA, LCC, AHP (analytic hierarchy process), and game theory to generate a suitable strategy for municipal solid waste (MSW) treatment in Canada. A hybrid MCDM method based on SWARA-WASPAS (step-wise weight assessment ratio analysis, weighted aggregated sum product assessment) and game theory was built up and applied to explore the optimal mixed strategy for personal selection (Hashemkhani Zolfani and Banihashemi, 2014). Fuzzy TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) and game theory were combined for energy management to find a best strategy (Aplak and Sogut, 2013). A fuzzy game theory method was developed to deal with the dwelling selection problem considering the features of traditional single flat dwelling house and loft flat dwelling house (Medineckiene et al., 2011). Ding and Liu (2019) combined zero-sum game with best-worst method (BWM) and Pythagorean fuzzy uncertain linguistic variables (PFULVS) to solve the emergency decision-making problem.

Game theory combined with MCDM methods can also be further improved or extended and applied in supply chain management, energy policy management, environmental science, and sustainable development. Some studies have investigated the model of game theory and MCDM for solid waste management and energy management. However, most of the research focused more on some specific solid waste or general municipal solids waste (Aplak and Sogut, 2013; Grimes-Casey et al., 2007; Soltani et al., 2016), few of them investigated the situation of sludge management. Meanwhile, the major concern of the previous research was two-player game, such as industry and environment (Aplak and Sogut, 2013), and the municipality and the cement industry (Soltani et al., 2016), with the consideration of environmental and economic outcomes. The interests of the public were rarely discussed. In fact, sometimes the social impacts are not only concerned by the public or the residues, but also the government and the industry, although the emphasis may vary. Some social influence, such as acceptance of the public, is still important for the local sludge management, leading to the necessity of the consideration of more dimensions in sustainability in order to promote the sustainable management on sludge-to-energy technologies.

According to above literature review, the major research gaps for group decision-making analysis on sludge management can be summarized as follows:

- Rare research spent efforts on the group decision-making for sludge-to-energy technologies selection by game theory.
- Environmental and economic performances are still the focus for sustainability evaluation for alternative selection. The interests of the public or the social impacts are rarely discussed.

Aiming to fill the research gaps mentioned above, the research is conducted to build up a decision analysis framework which combines game theory and MCDA methods for solving sludge management problem. The major contributions of this work include the following two aspects: i) the constructed game theoretic-based decision-making framework is applied for sustainable sludge management problem with the consideration of the interactions between stakeholders, which can promote the decision-making process involving different groups of stakeholders; ii) besides environmental and economic pillars, social impacts and technological performances are integrated in the sustainability evaluation to generate an overall sustainability index for the sludge management strategy recommendation. Meanwhile, the proposed framework can flexibly address the fuzzy preferences of the decision-makers in individual or groups. In addition, a two-player game is conducted in the case study for sludge management which can be further extended into multi-player game under more complicated situation.

3. Methodology

In this section, the constructed framework is introduced in detail,. The methodology framework is presented in Figure 1 to illustrate the major steps of this model. Step 1 and Step 2 are applied to obtain the performance data on sustainability indicator of the investigated strategy, which are introduced in the Section 3.1 and Section 3.2, respectively. Criteria system for the sustainability evaluation is also constructed in Section 3.2 to prepare for the decision-making analysis. Based on the performance data, game-theoretic decision-making analysis consisting of three sub-steps can be conducted to analyze the costs and benefits for the involved stakeholders, which are described in Section 3.3. Weighting method for the criteria system is introduced in Section 3.3.2. Then, according to the performance data and weights of criteria, the integrated sustainability index can be obtained by using MCDM method, which is described in detail in Section 3.3.2. The integrated sustainability index is the basis of payoff matrix for the further game theory analysis, which is presented in Section 3.3.3. Section 3.4 describes the step for mutual agreement which can help the stakeholders reach a consensus on the ultimate selection.

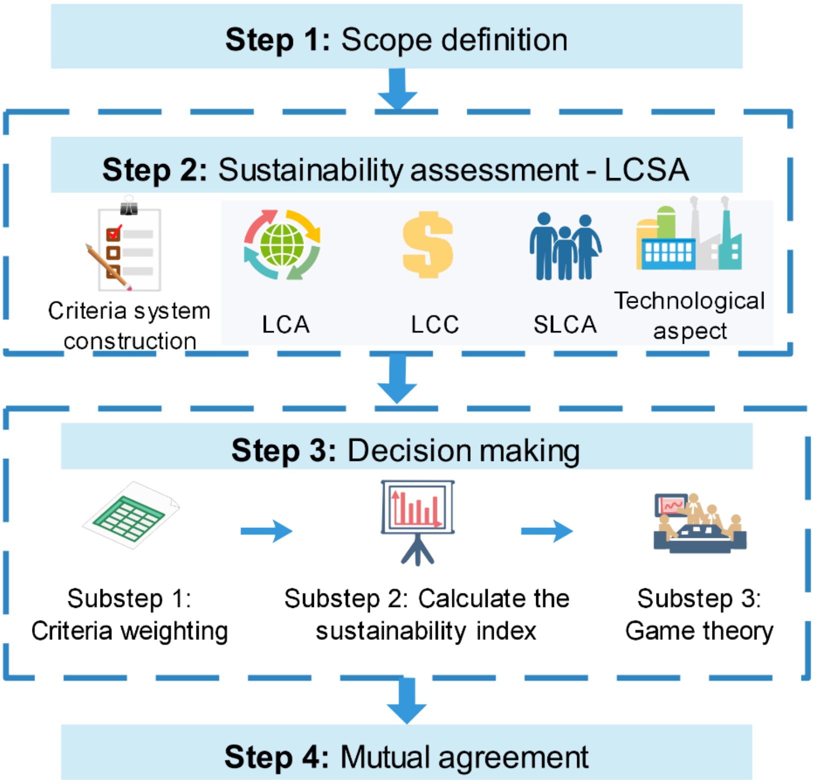

Figure 1 Methodology framework of this research

3.1. Scope definition

Reliable sustainability assessment is necessary for conducting convincing decision-making analysis in sustainability management field. Life cycle sustainability assessment is used to evaluate the sustainability performance of alternatives, which can be expressed as

$$LCSA=LCA+LCC+SLCA,$$

where LCA, LCC and SLCA address the performances on environmental, economic, and social aspect, respectively. According to the international standard (Ciroth et al., 2011), the three assessment tools all follow the same major steps, as shown in Figure 2.

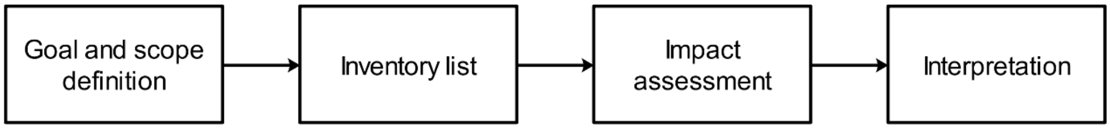

Figure 2 The flowchart of the basic steps for LCSA (Ciroth et al., 2011)

Table 1 Examples of the issues that should be addressed in the stage of scope definition

Addressed items	Description	Denotation
System boundary	The investigated life stages, such as production, treatment, and disposal.	-
Functional unit	A measure of the function of the target system which can provide a reference to the corresponding inputs and outputs(Cluzel et al., 2013; ECOIL, 2006).	-
Involved stakeholders	The considered stakeholders involve in the decision-making process.	$\{P_1, P_2, \cdots, P_k\}$, k is the number of stakeholders.
Strategies/options	The investigated alternatives in the study.	$S^i = \{s_1^i, s_2^i \cdots, s_{n_i}^i\}$, S^i is the strategy set of stakeholder i . n_i is the number of strategies of stakeholder i .
……	……	……

In this stage, the related preliminaries should be clearly identified, such as system boundaries for LCSA, stakeholders, and alternatives. Table 1 provides some examples on the issues that should be defined in this stage as well as their description and denotations. The functional unit is the basis of sustainability assessment. All the considered impacts are evaluated by the amount of functional unit (Soltani et al., 2016).

All in all, the scope definition should be clarified specifically according to the investigated system and decision-making problem.

3.2. Sustainability assessment

Criteria system should be established for sustainability evaluation and decision-making process. The criteria system $\{c_1, c_2, \cdots, c_m\}$ in sustainability assessment usually involves with three pillars of sustainability, that is environmental, economic, and social aspects (Kumar et al., 2017). Some studies may also consider the technical perspective (Ren et al., 2017). Eleven criteria covering environmental, economic, social, and technical aspects were covered in this work. Detailed information and description for each criterion are shown in Table 2.

Table 2 Criteria system for the sustainability assessment

Aspect	Criterion	Description
Environmental (AS1)	Climate change (C_1)	The impacts caused by greenhouse gases (Clary, 2013).
	Acidification (C_2)	The compounds which are precursors to acid rain (Dincer and Abu-Rayash, 2020).
	Eutrophication (C_3)	The potential to cause over-fertilization of water and soil, which can lead to the increased growth of aquatic plant (Čuček et al., 2015).
Economic (AS2)	Net costs (C_4)	The net expenses of various costs and benefits in the total treatment process. Negative value refers to earning.
Social (AS3)	Social acceptance (C_5)	The extend of acceptance and recognition for the technical route.
	Government support (C_6)	Government's tendency and policy support for sludge treatment technology.
	Education significance (C_7)	The education implications for similar businesses and other institutions (like schools).
Technical	Odors control (C_8)	The ability of controlling or eliminating odors.

(AS4)		
	Technical complexity (C_9)	The sophistication of the technology route.
	Maturity (C_{10})	The maturity and application scale of the technology.
	Technical accessibility (C_{11})	The accessibility to the technology from Domestic or overseas companies considering the regulations and limitations (Torkayesh et al., 2021).

The criteria selection should obey some general principles for reliable and scientific sustainability evaluation and decision-making, which have been introduced in the overview of Wang et al. (2009). The criteria system provided here is an example for the framework, which can be further adjusted according to the needs of stakeholders and actual situation.

Performance data of the criteria for different strategies can be collected either from literature review, field research, simulation, and experiments for sustainability assessment. Inventory list provides the necessary data on the energy, resources and materials inputs and outputs within the system boundary. LCC can also be analyzed in the similar way based on the costs and benefits in each life stage. Although there is limited research on SLCA, it still can be analyzed by the similar core thought, especially for the quantitative indicators (Ciroth et al., 2011). However, there are many indicators and data collected from the experts which cannot be directly described by qualitative variables, like acceptance, policy support, and technical maturity. Under such situation, linguistic terms and fuzzy theory are introduced to address the performance of the strategies on these indicators. In the research, triangular fuzzy numbers (TFNs) are applied to describe the performances of the qualitative indicators in social and technical aspects. Their corresponding relationship with the linguistic term is shown in Table 3.

Table 3 Corresponding triangular fuzzy numbers of linguistic description for the performance on the social and technical indicators (Chiou et al., 2005)

Linguistic terms	Denotation	Triangular fuzzy numbers
Very poor	VP/VL	(1,1,3)
Poor	P/L	(1,3,5)
Medium/Acceptable	M	(3,5,7)
Good	G/H	(5,7,9)
Very good	VG/VH	(7,9,9)

When multiple experts provide their opinions on the performances of social and technical indicators, evaluation results should be integrated together for the further calculation and data process. The integrated results can be obtained by Eqs. (1) - (3).

$$l_q = \sum_{t=1}^{T} l_q^t / T \tag{1}$$

$$m_q = \sum_{t=1}^{T} m_q^t / T \tag{2}$$

$$u_q = \sum_{t=1}^{T} u_q^t / T \tag{3}$$

where l_q, m_q, and u_q represent the lower bound, the most possible value and the upper bound of the integrated TFN addressing the performance on the qth criterion, respectively. T is the number of involved experts for the evaluation. l_q^t, m_q^t, and u_q^t refer to the evaluation data expressed by TFN of the tth expert. For example, if there are three experts participating the evaluation, then $T = 3$. If the evaluations of the three experts for a certain technology in terms of technology maturity are VH, M, and H, respectively, the corresponding triangular fuzzy numbers are (7,9,9), (3,5,7), and (5.7.9) according to Table 3. Then, based on Eqs. (1) - (3), the integrated evaluation results on the technological maturity according to the opinions of three experts is (5,7,8.33) ($l_q = (7+3+5)/3 = 5$, $m_q = (9+5+7)/3 = 7$, $u_q = (9+7+9)/3 \approx 8.33$).

Transforming the fuzzy numbers into crisp numbers is a necessary step for the calculation of overall sustainability index since the performance data for environmental and economic criteria are all crisp numbers. The defuzzied result can be calculated by Eq. (4) (Guo and Zhao, 2017).

$$a_q = \frac{l_q + 4m_q + u_q}{6} \tag{4}$$

where a_q is the defuzzied performance data of the qth criterion, which belongs to social or technical aspect. For instance, if a triangular fuzzy number is (3,5,7), then the defuzzied result of this TFN is $(3+4\times 5+7)/6 = 5$.

3.3. Decision-making process

Decision making and analysis can be carried based on the performance evaluation data provided by LCSA. Three major steps are conducted to get the recommended selection of strategies, including criteria weighting, calculation for the sustainability index, and two-player or multi-player game, which are introduced in Section 3.3.1, Section 3.3.2, and Section 3.3.3, respectively.

3.3.1. Criteria weighting

There are many different types of weighting methods, including subjective weighting methods, objective weighting methods, and the combination of both (Wang et al., 2009).

Equal weighting and AHP method are commonly applied methods for criteria weighting because of the simple operation and ease of understanding. However, traditional weighting methods may not process the fuzzy preference provided by the stakeholders. Hence, fuzzy theory was introduced to combine with weighting approaches and deal with the uncertain information, such as fuzzy AHP (Sun, 2010), and fuzzy BWM (Guo and Zhao, 2017; Hafezalkotob and Hafezalkotob, 2017). In this research, a fuzzy BWM proposed by Hafezalkotob and Hafezalkotob (2017) for individual and group decision-making (GI-fuzzy BWM) is applied to obtain the weight of each criterion according to the preferences of different groups of stakeholders. More detailed introduction about the related concepts and analysis for this fuzzy BWM can be found in the research of Hafezalkotob and Hafezalkotob (2017). A basic description for the calculation steps is illustrated in Figure 3. This fuzzy weighting method is selected because it can not only deal with the uncertain preferences, but also can help to solve the problem when there are many different experts with different levels of expertise. The weighting method can be applied to obtain the weights considering the preferences of different groups of stakeholders and final generate a set of fuzzy weights. It can also be used to integrate different opinions in the same group. In this study, the weighting method GI-FBWM is applied to integrate the opinions in the same party (i.e., with the same interests), which belongs to the latter situation.

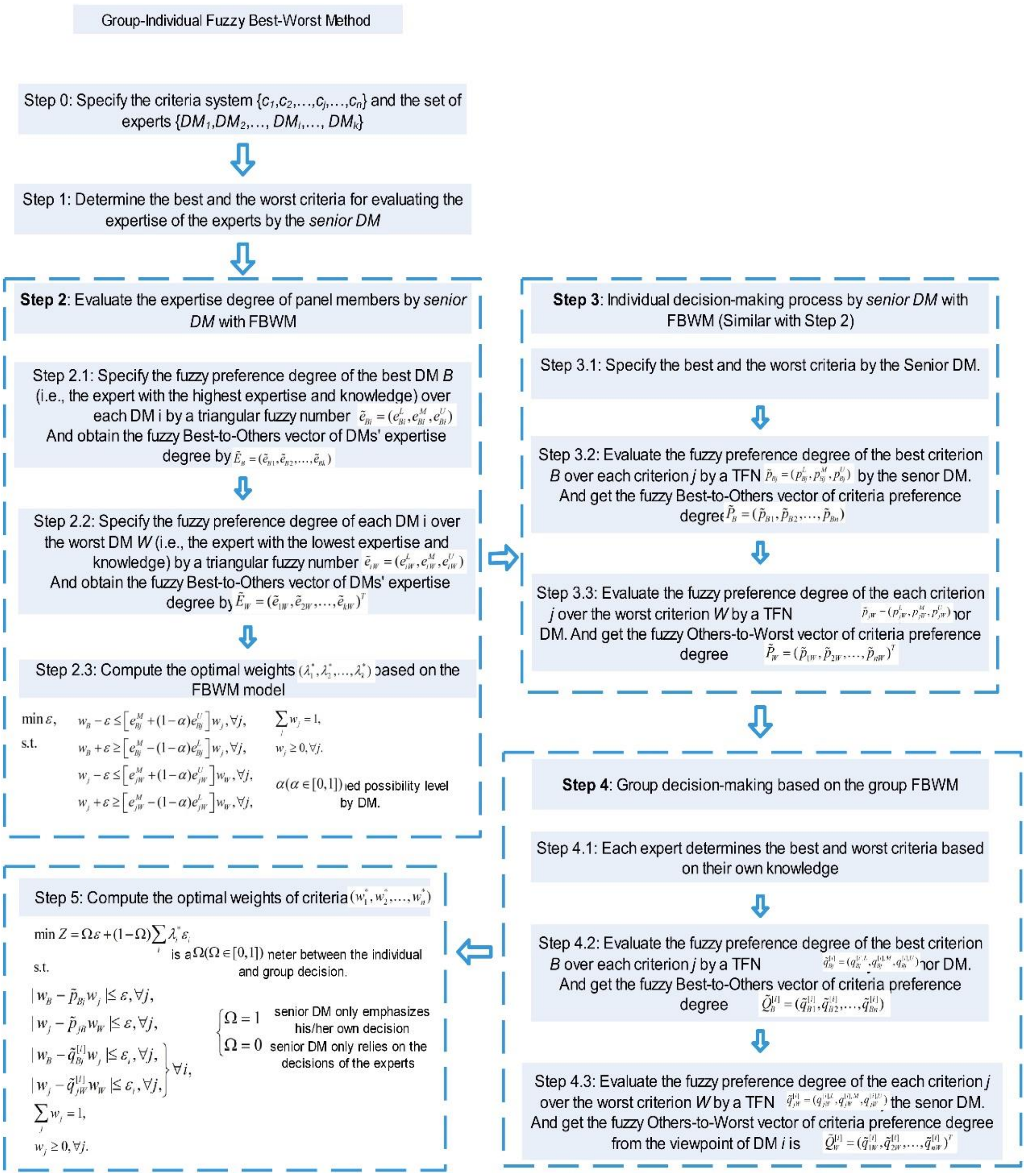

Figure 3 Basic step description of the GI-FBWM (Hafezalkotob and Hafezalkotob, 2017)

3.3.2. Calculation for the sustainability index

In this step, MCDA method is applied to generate an overall index to describe the entire sustainability performance of the strategy for specific player. Normalization is necessary for the further calculation because of the differences in the units and dimensions. Criteria can be classified into beneficial criteria and cost criteria. Beneficial criterion means the criterion that higher value is preferred, while cost criterion refers to the indicator that lower value is better. The category of each criterion is shown in Table 4. Normalization step can be conducted by Eq. (5) and Eq. (6) according to the category of the specific criterion.

$$\text{Beneficial criterion:}\quad a_q^j = \frac{b_q^j - b_{\min}^j}{b_{\max}^j - b_{\min}^j} \tag{5}$$

$$\text{Cost criterion:}\quad a_q^j = \frac{c'^j_{\max} - c'^j_q}{c'^j_{\max} - c'^j_{\min}} \tag{6}$$

where a_q^j is the normalized performance of impact of q th criterion for the j th player. $b_{\max}^j$ and $b_{\min}^j$ are the maximum and minimum values of the beneficial criterion for the j th player, respectively. b_q^j refers to the performance data of investigated strategy on the q th criterion for the j th player. The meanings of other symbols can be inferred in the similar way. $c'^j_{\max}$ and $c'^j_{\min}$ define the rang of the performance data of the cost criterion, and c'^j_q represents the performance value of the strategy of the studied cost indicator for the j th player.

Table 4 The illustration of the category of each criterion

Category	Beneficial criteria	Cost criteria
Criteria	C_5, C_6, C_7, C_8, C_{10}, C_{11}	C_1, C_2, C_3, C_4, C_9

Afterwards, the normalized performance data should be integrated together. Weighted sum method is used to directly generate the sustainability index of a strategy, as is shown in Eq. (7) (Soltani et al., 2016),

$$\mathrm{SI}_j^i = \sum_{q=1}^{m} w_q a_q^j,\ j = 1, 2, \ldots, k,\ i = 1, 2, \ldots, n_j.\ , \tag{7}$$

where w_q is the weight of the qth criterion. SI_j^i is sustainability index for strategy i from the perspective of player j, which is the basis for the generation of payoff matrix. According to the involved stakeholders, the SI_j^i of different stakeholder can form the array of sustainability index under the corresponding setting of strategies as the element of payoff matrix. The value of SI can address the overall sustainability performances of the strategy for the specific player, which can also be regarded as the overall benefits in terms of sustainability when applying the strategy.

By utilizing Eq. (7), the payoff matrix reflecting the outcomes of different pair of strategies can be obtained, which can be further applied in game theory in the next step.

3.3.3. Game theory

This research is conducted based on a two-player game. It can also be extended to multiple-player game by the same core thought (Soltani et al., 2016). A two-player non-constant sum game is considered in this study. Player $i\ (i = 1, 2)$ has n_i strategies, which can be denoted as strategy set S_i with finite n_i elements. Payoff generated from the previous assessment and analysis is denoted as the function $u_1(s_1, s_2)$ and $u_2(s_1, s_2)$ of the outcome $(s_1, s_2) \in S_1 \times S_2$. The objective of this step is to find out an optimal pair of outcomes $(s_1^*, s_2^*) \in S_1 \times S_2$ called a Nash equilibrium, which satisfies the following conditions:

$$u_1(s_1^*, s_2^*) \geq u_1(s, s_2^*),\ \forall s \in S_1 \tag{8}$$

$$u_2(s_1^*, s_2^*) \geq u_2(s_1^*, s), \forall s \in S_2 \quad (9)$$

Hence, the optimal solution (s_1^*, s_2^*) provides a theorical selection for the decision-making problem. However, different choices might occur due to their different preference and interests in the actual decision-making process, and there is only one final decision for the adapted sludge treatment technology. In this case, additional consultations are necessary and the solution is provided in the next step.

3.4. Mutual agreement

Although a pair of best strategies can be found based on game theory, it might be less attractive under some situations where the industries may not be willing to conduct such a strategy. Therefore, additional incentives or tipping measures are necessary to make the pair of strategies more acceptable to all the stakeholders. Usually, the incentives or tipping fee can be determined by the payoff matrix. According to the outcomes, a range of tipping fee can be found out to help the stakeholders reach a consensus. It should be noted that sometimes the tipping fee may not be available directly from the inequations defined by the payoff matrix. The inequations should satisfy some conditions to make the range of tipping fee not be an empty set. Under this situation, the weights of tipping fee for different stakeholders can be adjusted flexibly to make the inequations have solutions. Hence, the result of game theory suggests the possible direction for the final decision, and the mutual agreement provides a solving approach for the stakeholders to finally obtain a decision which is acceptable for both players.

4. Case study

In this research, the proposed MCDM and game theory framework was applied to assess and determine the most suitable strategy from four scenarios according to the needs of two stakeholders. One sludge treatment facility was constructed based on the final decision for the sludge management.

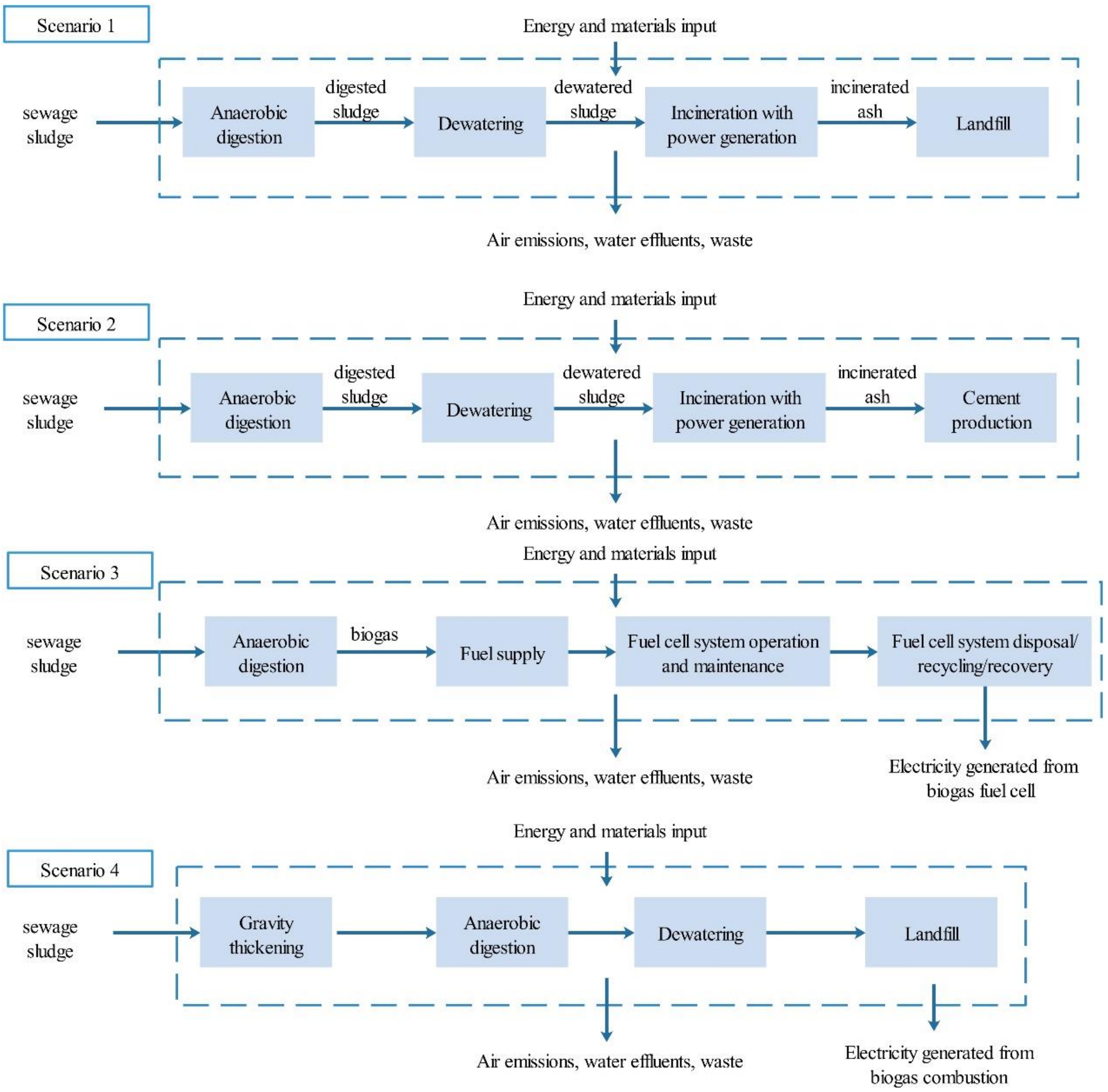

Figure 4 The scope of four sludge treatment scenarios considered for LCA in the case study (Lam et al., 2016)

System boundaries of the investigated four scenarios in this research are shown in

Figure 4. The system boundaries considered in the case study included the major treatment process, related transportation, post treatment, materials and energy inputs and outputs, and emissions. Impacts of sludge generation were excluded. The four sludge-to-energy scenarios can be described as follows:

(1) Scenario 1 – S1: Sludge incineration with power generation followed by landfill disposal (Lam et al., 2016).

(2) Scenario 2 – S2: Sludge incineration with power generation followed by cement production with the incinerated ash (Lam et al., 2016).

(3) Scenario 3 – S3: Sludge digestion for electricity production by fuel cells (Liu et al., 2020b).

(4) Scenario 4 – S4: Sludge digestion for electricity generation by combustion (Liu et al., 2020b).

These four sludge-to-energy technical routes were selected because the following reasons: i) all of the scenarios can be used for electricity generation, which is an indispensable form of energy for the daily life; ii) traditional incineration, i.e. S1, has been widely applied in many developed countries, but there is an improved technical route based on S1, that is S2. The performances of these two scenarios should be discussed according to the preferences and conditions of different regions; iii) biogas generated from sludge digestion for electricity production by fuel cells has been tested and supported by some developed countries, but the application cases are limited in China (Liu et al., 2020b; Su et al., 2009); iv) biogas combustion for electricity generation is a mature technology and has wide application in rural area. However, treating sludge in this way alone may be criticized for not treating it completely. Further discussion is still necessary to analyze the performances of these options especially with the considerations of different criteria and conflicting interests.

The functional unit was selected to be 1 kWh net electricity generation. The time horizon of life cycle assessment was defined as 20 years. It is assumed that 1058 t of dewatered sludge are treated by the STF per day and the operating days are 360 days/year (Drainage Services Department, 2017; Lam et al., 2016). Involved stakeholders are sludge treatment facility (STF) as the player 1, and the government (the Gov) as the player 2. These two players were selected because they usually have different or even conflicting interests on sludge management problem. STF may focus more on the economic and technical aspects while the government may emphasize the importance of environmental and social aspects. Meanwhile, these two stakeholders are obvious parties of interests for sludge management problem. Hence, these two roles were initially considered in the game. The two players have the same four strategies, including S1, S2, S3 and S4.

Criteria system has been constructed and shown by Table 2. The performance data of environmental and economic indicators were collected and estimated based on the previous papers (Lam et al., 2016; Liu et al., 2020b). The related performance data on social and technical aspects were evaluated by the experts from sewage sludge management industries. Questionnaires were used to collect their opinions for the corresponding performance on each criterion. Four experts with related background on sewage sludge treatment and environment management were required to use a 5-scale table to evaluate the performance of each scenario (see Table 3).

Based on the above assumptions and information collected, further calculation can be conducted and corresponding results can be obtained, which are presented in the next section.

5. Results and discussion

5.1. Sustainability assessment results

Environmental and economic impacts were estimated based on the results from previous studies (Lam et al., 2016; Liu et al., 2020b) and the corresponding impacts were processed according to the assumptions for the functional unit and system boundaries. The environmental life cycle impacts of each scenario are shown in Table S.1 in the Supplementary Information. According to the estimated results in Table S.1 and Eq. (5) and Eq. (6), normalized environmental impacts can be obtained and are presented in Table S.2. Negative value refers to the positive effect on the specific environmental impact category. Results showed that S1 and S2 shared the similar environmental impacts on the three investigated categories while the later performed a little bit better than the former one. S3 showed impressive performances on all the environmental indicators. Only in the last indicator was S3 slightly inferior to S4. The scenarios with process of combustion or incineration, including S1, S2, and S4, had significant impact on climate change, while the influences on the other two criteria were not so considerable.

In the case study, environmental, social, and technical impacts are considered to be shared by both players, and the outcomes of economic indicator can be influenced by the decision of each other. LCC was applied to analyze the outcomes of different pair of strategies. Landfill tipping was regarded as a type of expense of STF and a source of income for the Gov, which was estimated based on the costs for landfill, the total amount of sludge treatment and the corresponding amount of electricity generation (Soltani et al., 2016). Energy recovery can provide benefits for both players. In addition to the energy supply for its own processing system in STF, the generated electricity can also be sold to the users. Opportunity costs were considered as well. Estimation results for the net costs of each pair of strategies are shown in Table S.3 and the normalized results are presented in Table S.4. Negative value refers to the benefits that the player can obtain from the selection. The calculation results revealed that under above assumptions, S2 took a dominant position for STF, while S1 and S4 showed advantages over the other two options for the Government.

Performances on social and technical aspects were evaluated based on the feedbacks collected from four related practitioners. The linguistic descriptions and the corresponding TFNs of the performances for the investigated social and technical indicators of each strategy were shown in Table S.5 and Table S.6 in the Supplementary information. By Eqs. (1) - (3), the integrated evaluation results can be obtained and are listed in Table S.7. Afterwards, the TFNs were defuzzied by Eq. (4) to prepare for the next step and the corresponding results are shown in Table S.8. Normalized results can be subsequently obtained based on the above calculation (see Table S.9). The results presented by Table S.9 revealed that S2 performed relatively good in all the investigated social and technical and no zero value in the performance data of S2, while each of the other strategies performed poorly on at least one indicator. Scenario 3 showed pretty extreme performance, where it presented excellent results on C_6, C_7 and C_8 but the performances data on the other indicators were very unsatisfactory.

5.2. Criteria weighting: GI-fuzzy BWM

Previous literatures presented the attitudes and preferences of the facility and the government towards different sustainability dimensions and sub-indicators (Liu et al., 2020b; Ren et al., 2017; Soltani et al., 2016). The preferences were first collected from literatures and then two experts in sewage sludge treatment plant and department of environmental protection were interviewed to see whether the preference order obtained from literatures was too contradictory with the practice context in mainland China. The preference orders were accordingly adjusted based on the opinions and explanations of the experts. Then, according to the interviewed results the criteria weights were determined by GI-fuzzy BWM step by step (Hafezalkotob and Hafezalkotob, 2017). The detailed calculation steps are presented in the Supplementary Information. The weighting results from the perspective of STF manager are shown in

Table S.20 and Table S.22. The weighting results from the viewpoint of government manager are shown in Table S.30 and Table S.32. In the case study, we only consider the situation of senior decision-maker determining the final weights of all the criteria and the situation of group decision-making can be similarly calculated according to the description. Based on the content of these tables, although the specific data were not exactly the same, both players expressed their emphasis on the environment. The major difference between the preferences of the two stakeholders lie in the social and technical aspects. Sludge treatment facility attached more importance to the technical aspect while the government concerned more about the social indicators. Environmental aspect was emphasized by the STF due to the requirement and related regulations on sludge discharge management. According to the experience in the practice, sludge projects with normal operation are usually profitable. Hence, the preferences of the involved stakeholders presented the following results.

5.3. Sustainability index and game theory

According to the assessment results and calculated weights of the criteria, the payoff matrix addressed by the sustainability index can be obtained, which is shown in Table 5.

Table 5 Payoff matrix of the two-player game for sludge management

Player 1 - STF	Player 2 - Government			
Selection	S1	S2	S3	S4
S1	(0.21,0.26)	(0.21,0.25)	(0.21,0.62)	(0.21,0.65)

S2	(0.28,0.26)	(0.28.0.25)	(0.28,0.62)	(0.28,0.65)
S3	(0.73,0.26)	(0.73,0.25)	(0.73,0.62)	(0.73,0.65)
S4	(0.32,0.26)	(0.32,0.25)	(0.32,0.62)	(0.32,0.65)

Based on the payoff matrix presented in Table 5, Scenario 4 had obvious advantage over other scenarios in the sustainability index for the Government in spite of STF selecting any other alternative. Scenario 3 was also a dominate strategy for STF. Therefore, results of game theory suggest that S3 and S4 are the best selections for STF and for the Government, respectively. According to the analysis for the sustainability assessment results, S3 showed satisfactory performances on environmental and social aspects. It also performed acceptable on C_8. Considering the emphasis on environmental indicators, S3 can bring more benefits to the STF under this situation. S4 presented relatively good performances on environmental aspect as well. Meanwhile, the performance of S4 was mediocre in other criteria, but few were particularly bad. Due to the preference on environmental and social aspects, S4 is a suitable option for the government. A tipping fee should be paid to the government by the sludge treatment facility in order to convince the government to change their strategy.

5.4. Mutual agreement

The tipping fee refers to a suggested amount which can convince the government to select the same option with STF, that is prefer S3 to S4, and maintaining the STF still interested in S3 in the situation of case study. According to the above discussion and analysis results, if a tipping fee of $0.19-7.59 per kWh net electricity generation during the sludge treatment process can be paid to the government, both stakeholders will be more preferred to the selection on Scenarios 3. The range of tipping fee is calculated based on the considered assumptions.

$$0.73 - 0.054x > 0.32 \rightarrow x < 7.59 \quad (10)$$

$$0.62 + 0.16x > 0.65 \rightarrow x > 0.19 \quad (11)$$

where x represents a tipping fee with positive value. In this case, the weights of tipping fee are consistent with the weights of economic aspect for each player. It can be adjusted flexibly according to the conditions of reaching a final compromise.

5.5. Sensitivity analysis

Uncertainty is common in the actual decision-making process. Sensitivity analysis was conducted to explore the impact of weight changing of different aspect and criteria of different stakeholder on the final decision-making result. Without changing the preference of each criterion in each aspect, the local weight of each aspect is changed in order to study the effect of weight variation. Based on the above assumption, the local weights of all the sub-indicators were fixed, while the weight of the investigated perspective of the specific stakeholder is set to be 0.2, 0.4, 0.6, and 0.8, respectively. Meanwhile, the weights determined by the other stakeholder keep consistent with those in the original case, leading to the same sustainability index of corresponding selection. The weighting assignments from the perspective of STF include four different groups and each contains 4 pieces of data records. The weighting variations of environmental aspect and the corresponding global weights for the criteria from the perspective of STF are shown in Table S.33 and Table S.34, respectively. More detailed weighting assignment for the other three aspects with respect to STF can be similarly obtained and are presented in Table S.35 - Table S.40. As for the weighting variations of different aspects for the Government, the assigning approach are the same leading to the same weighting assignments on the local weights for different aspects. However, the global weights of the various weighting assignments are different due to the differences of preferences between STF and the Government. Specific weighting results can be similarly calculated for the perspective of Government and are shown in Table S.41 – Table S.44.

Based on the sustainability assessment results and the weighting assignment of each group, sensitivity analysis results can be obtained and are shown in Figure 5 and Table S.45 for STF, and Figure 6 and Table S.46 for the Government, respectively. The value variations of sustainability index from the perspective of STF under different groups of weighting assignments are presented in Figure 5. Since the weights of all the criteria for the Government were fixed, the outcome of payoff was consistent with the initial result in the case study (0.6491 for S4). Nevertheless, the sustainability index of STF varied with the weights changing. According to the calculation results, when the value of sustainability index exceeds that of the Government, the control of decision will belong to STF, and this party should pay a certain amount of tipping fee to convince the Government to change their selection. Figure 5 also reveals that although the final decisions frequently changed from the perspective of STF, the ratio of SI's variation is around 20% (absolute value), which is not a large amplitude compared with that of the Government.

From the perspective of STF, the following conclusions can be drawn.

- S3 is more preferred by the STF as the weight of environmental aspect rising.
- S2 shows advantage on the economic aspect over the other aspects and it will take the first place when the importance of net cost is emphasized.
- S2 also has acceptable performances on the social indicators and can be recommended as the weight of social dimension rising.
- S1 has the priority when the weight of technical aspect gradually increases. For the investigation of the fourth aspect, government plays the dominate role and only when the weight of technical dimension is 0.8 will the sustainability index of STF surpasses that of the Gov.
- There is an overall upward trend of SI for the STF as the weight of different aspect rising, especially for the economic and social aspects. The other two aspects showed a trend of rising volatility, that is first decrease and then goes up. The occurrence of such kind of change is related to the different growth rate of SI for the scenarios with the change of weight, which is not a major focus of this study and could be analyzed in detail in the future work.

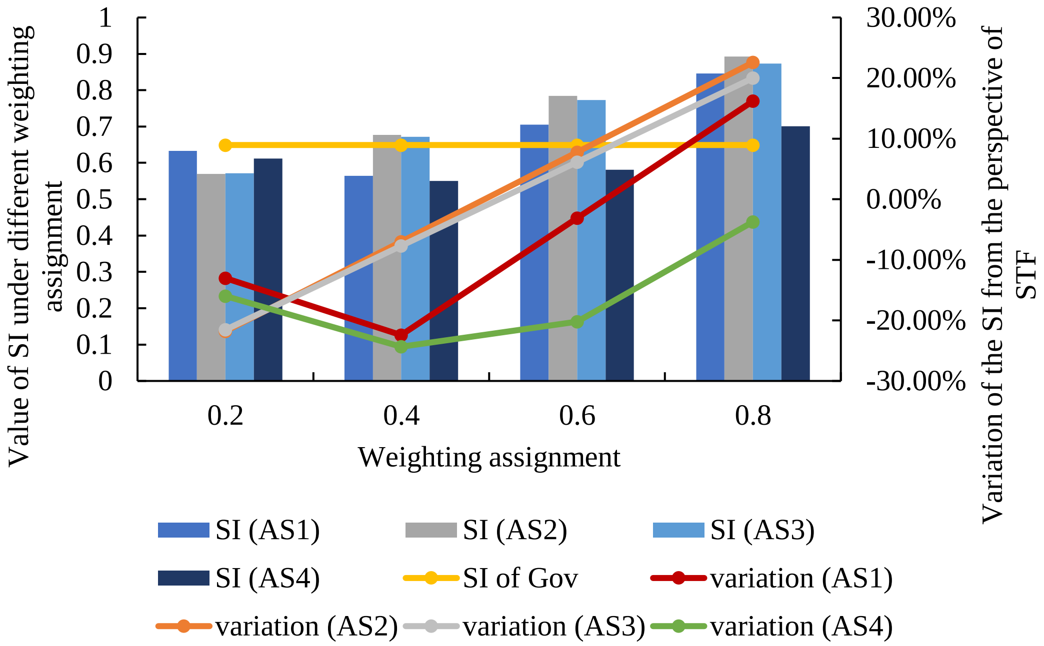

Figure 5 Variation of the sustainability index (SI) of STF under different weighting assignments from the perspective of STF. SI (AS1) refers to the value of sustainability index of the STF's choice when the weight of AS1 is assigned to be the specific value. The meaning of other aspects can be obtained in the similar way. Variation (AS1) is the variation ratio of the result compared with the original SI for the STF in the case study. Similar meanings can be obtained for the others.

For the Government, sustainability index of the choice for STF is a fixed value of 0.7280 for choosing S3 in the weighting variation. The final decisions under different weighting assignments presented by Table S.46 in the Supplementary Information are quite stable, although the SI of governmental changed with the variation of weighting. This is because the value of SI for STF is higher than that of the Gov in most presented cases. Hence, the former dominated the decision-making process mostly. Only S4 and S2 showed outstanding attractiveness on economic and social aspect, respectively.

Meanwhile, the SI's variation range for the Government is [-6.96%, 39.45%], which shows a more dramatic change compared with the situation of STF, in spite of the stable decision-making results.

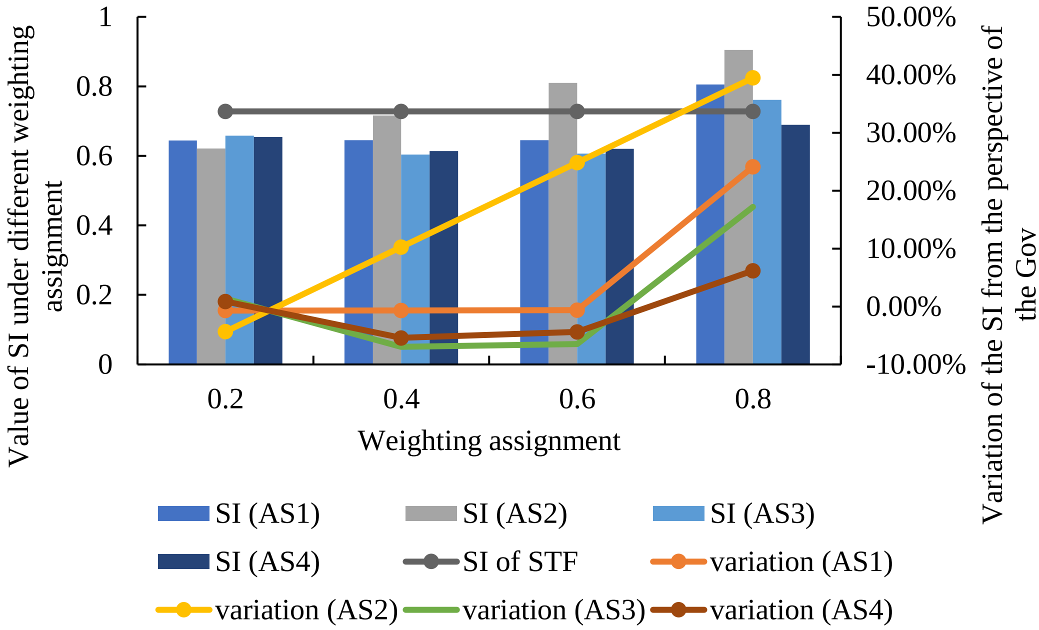

Figure 6 Variation of the sustainability index (SI) of the Government under different weighting assignments from the perspective of the Gov

The influence of weight variation for each criterion was investigated by setting the weight of focused criterion as 0.25 while the weight of others keeping the same. The situation when C_1 was selected as the major criterion was taken as an example and the weighting assignment is shown in Table S.47. The weighting assignments for the other criteria can be similarly obtained. Although the weighting assignments are the same for the two players, the net costs for them were different leading to the differences in the decision results. Meanwhile, the preferences of the player were fixed as the initial case study when the criterion was investigated from the perspective of the other player. Sustainability indices for the eleven groups of weighting assignments can be calculated based on the above assumptions. Variation of the sustainability index of the final strategy selected by each player under different situation is shown by Figure S.1 in the Supplementary information. Detailed results can be found in Table S.48 and Table S.49. The results revealed that the value of SI significantly decreased under the assumed weighting assignments compared with that of initial case study. Only increasing the weight of C_8 to 0.25 for STF will also increase the SI. In addition, the variation range of that of SI for the government is obviously wider than that of the STF, but the final decisions are relatively stable due to the dominate role of the party with a higher SI.

Different development status of the features of sludge may also lead to the uncertainty of assessment parameters. The influence of parameter uncertainty of quantitative variables (i.e., $C_1 – C_4$) for S3 from the perspective of the STF was explored by changing the value of investigated indicator within [-5%, 5%]. The variation of SI of S3 for STF was selected as an example since it is the final choice in the case study and some general trends can also be reflected from the results, which are shown in Figure S.2 in the Supplementary Information. Detailed results are provided in Table S.50. Analysis results indicated that the value of SI under the assumptions were still relatively stable and did not show dramatically change. Only the situations of C_3 and C_4 showed slightly change while the other two criteria kept consistent with the original results because S3 had excellent performances on these two criteria even under the assumed parameter variation. On the one hand, the step of normalization largely stabilized the changes in SI value. On the other hand, since the investigated four criteria are all cost criteria, the increasing on the performance data would decrease the sustainability performance evaluation results of S3, leading to the downtrend showed by SI. When the value of C4 increased by 3% or more, SI of S3 would not change anymore because the relative performance of S3 in this criterion has fallen to the lowest. The uncertainty situations of social and technical indicators were not investigated in detail, which can be a working direction for the future work.

The influence of weighting method selection is also investigated. In this framework, GI-FBWM is applied to flexibly solve the group and individual decision-making problem and obtain the fuzzy weights based on the preferences of stakeholders. Two other fuzzy weighting methods, i.e. fuzzy BWM (Guo and Zhao, 2017) and fuzzy AHP (Wang et al., 2006) were applied for criteria weighting and further decision-making analysis to validate the decision-making results under the situation where only the opinions of senior managers are considered. Detailed results are provided in Table S.55 – Table S.59 in the Supplementary information. The final recommendations can be obtained based on the weights and performance data in the initial case study (see Table S.59). Both approaches recommend (S3, S4) for the two players, which is the same as the results obtained by GI-FBWM, but S4 is more preferred by the two methods. This difference may result from the variance between the fuzzy weights obtained by GI-

FBWM. And the results also show the advantages of the two strategies, that is S3 and S4. Future research may consider extending the traditional fuzzy MCDM method in the proposed framework to further explore the influence of weighting methods selection on the combination with game theory.

According to the above analysis and discussion, it is safe to draw the conclusion that the proposed methodology framework has feasibility to solve the decision-making problem with the consideration of conflicting interests of different stakeholders as well as multiple criteria. Results obtained from the case study under the assumptions and conditions indicated the rationality and reliability of the methodology. In the case study, S3 or S4 was suggested by the final decision-making result. Although S3 was the final choice after the step of mutual agreement, S4 is also can be selected by the two players through the similar process. In this situation, government should pay a certain amount of tipping fee to the STF to convince them and reach a consensus. Similar results were also suggested by previous studies (Liu et al., 2020b; Ren et al., 2017). These two studies analyzed the sustainability performances of several sludge-to-electricity technologies and both results indicated the priority of biogas from sludge digestion for electricity generation, that is S3 and S4 in this research, leading to the belief of the reliability of the strategy result obtained from the proposed method. Sensitivity analysis results revealed that the final decision-making result is relatively stable because of the balance of multiple stakeholders. Hence, the proposed methodology framework can be regarded to be robust.

5.6. Implications

Based on the discussion for the results, some useful suggestions can be provided for the stakeholders on the sludge management and the applicability of the constructed method. Detailed recommendations are listed as follows.

- Biogas from sludge digestion for electricity production by fuel cell (S3) is preferred when the environmental aspect is emphasized. However, for the technical reasons, biogas combustion for electricity generation (S4) is more secure under certain conditions since it has a wider application base.
- Incineration followed by cement production (S2) presented acceptable performance on all the aspects except for the environmental perspective. Hence, it shows advantages when these three aspects are stressed. Compared with S2, S1 shows some advantages in terms of technical aspect. Therefore, if it is necessary to further promote the application of S2, some technical problems should be solved first. S3 faces the similar situation. Future research may consider improving the maturity and technical performance as a target to further promote the application of these technologies.
- “Tipping fee” is actually a mean of persuasion to convince the other stakeholder choose the same strategy as the choice of dominate stakeholder, since only one technical route can be selected and conducted in the STF. It can be any helpful measure which contributes to improve the sustainability index of the other player and makes the concession acceptable to the dominate side simultaneously, and

finally assists the stakeholders achieve a consensus for the final strategy.

- Based on a two-player game theory and MCDM methods, the methodology framework can be applied to solve the sludge management problem considering the interests of two different groups and multiple criteria. Different from the traditional decision-making process, the proposed framework emphasizes the interactions and participation of stakeholders in criteria weighting and mutual agreement. The interplay of economic behaviors of different stakeholders is also reflected in the analysis, which is usually not included in the traditional decision-making process. More complicated situation, like multiple-player game, may be a working direction for the future research.

Besides the suggestions for sludge management strategies, some implications regarding the applicability, advantages and weaknesses of the proposed framework can also be obtained based on the analysis results, which are summarized in Table 6. Considering the ability of addressing fuzzy information and flexibility of dealing with the conflict interests, it is suitable to solve the decision-making problem with uncertain preferences and multiple stakeholders with different focuses, even conflicting interests. It can provide insightful reference and advice for the strategy selection and promote the total decision-making process to reach a consensus.

Table 6 The strengths and the weaknesses of the proposed methodology framework

Strengths	Weaknesses
● Conflicting criteria and interests of different stakeholders can be considered. ● Impact of the interactions between	● Social impact is considered as the third sustainability pillar not as a stakeholder involved in the decision-making process.

stakeholders can be addressed. ● Fuzzy information from the experts' judgement can be processed. ● Performances on the four sustainability pillars can be evaluated. ● Final decision-making result is stable and can be accepted by both players.	● Weighting and the evaluation for social and technical indicators rely on the preferences, experience and knowledge of the stakeholders.

6. Conclusions

In this paper, a decision-making framework was constructed based on game theory and MCDM methods for sludge management. Eleven criteria covered environmental, economic, social, and technical aspects were considered to address the sustainability performances for the investigated strategies. An individual and group fuzzy BWM was applied to integrate the opinions of different experts for criteria weighting. Two-player game was established to address the decision-making problem and a mutual agreement step was added to help the stakeholders to finally reach a consensus. A case study was carried out to demonstrate the proposed framework. Four sludge valorization technical routes were investigated as the sludge treatment strategies. Sludge treatment facility and the government were involved as two players in the game for decision-making. According to the analysis results, the Nash equilibrium was provided by the strategy pair (S3, S4) for STF and the government with value (0.73, 0.65), respectively. A final agreement on selecting S3 for both players can be reached by STF paying a tipping fee within the range of $0.19-7.59 per kWh net electricity generation to the government. The results indicated that biogas for electricity generation by fuel cells can be competitive when the environmental aspect was important. Sensitivity analysis was also conducted to explore the influence of weighting variation on the different aspect for the two stakeholders and results revealed that the final strategy was usually determined by the dominant party, that is the stakeholder with higher sustainability index. S3 and S4 were recommended when the weights of social and technical aspects increased while S2 was more preferred if the importance of economic indicator was emphasized. Technical challenges still restrict the further promotion of sludge-to-energy technologies. Hence, improvement on the operating conditions and technical performance is still necessary for the sustainable management of sewage sludge.

The major contributions of this work are reflected by the following aspects. Firstly, this work theoretically proposed a decision-analysis framework based on an individual and group fuzzy BWM and game theory for sustainable sludge management industry considering social and technical impacts, which is the first attempt to use game theory together with MCDA methods for sludge-to-energy technologies decision making and analysis as the authors' aware. Secondly, a case study was applied to demonstrate the model. Results verified the applicability of the framework and useful suggestions were also provided according to the analysis results which can promote the decision-making process with conflict interests in the practice. Finally, sensitivity analysis results showed the flexibility for processing the fuzzy preferences of different groups of stakeholders and the stability of decision-making results with the variations of fuzzy weights, which may also indicate the possibility of promoting to other fields for application.

There are some limitations in the current study. Firstly, the framework initially considered two-player game without the discussion from the perspective of residents. The influence of social aspect was taken into account by the sustainability assessment, but the impact could be different with the interactions with residents as the third stakeholder. Secondly, the performance data on social and technical aspects were collected based on the experts' experience and opinions, which could be subjective and vague. More quantitative data are expected for the objective assessment of the different strategies. Future research can consider these points to conduct different scale of experiment for data collection, explore the feasibility and solution for multi-player game to further improve the completeness of the methodology framework.

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References

Aplak, H.S., Sogut, M.Z., 2013. Game theory approach in decisional process of energy management for industrial sector. Energy Convers. Manag. 74, 70–80. https://doi.org/10.1016/j.enconman.2013.03.027

Asian Development Bank, 2012. Promoting Beneficial Sewage Sludge Utilization in the People's Republic of China.

Chiou, H.K., Tzeng, G.H., Cheng, D.C., 2005. Evaluating sustainable fishing development strategies using fuzzy MCDM approach. Omega 33, 223–234. https://doi.org/10.1016/j.omega.2004.04.011

Ciroth, A., Finkbeiner, M., Hildenbrand, J., Klöpffer, W., Mazijn, B., Prakash, S., Sonnemann, G., Traverso, M., Ugaya, C.M.L., Valdivia, S., Vickery-Niederman, G., 2011. Towards a Life Cycle Sustainability Assessment.

Clary, J.J., 2013. Life cycle impact assessment definition study: background document III. Toxicol. Methanol 47–72. https://doi.org/10.1002/9781118353110.ch3

Cluzel, F., Leroy, Y., Yannou, B., 2013. Toward a structured functional unit definition framework to limit LCA results variability. Proc. 6th Int. Conf. Life Cycle Manag. Gothenbg. 2013 6–9.

Čuček, L., Klemeš, J.J., Kravanja, Z., 2015. Overview of environmental footprints. Assess. Meas. Environ. Impact Sustain. 131–193. https://doi.org/10.1016/B978-0-12-799968-5.00005-1

Dincer, I., Abu-Rayash, A., 2020. Sustainability modeling, Energy Sustainability. https://doi.org/10.1016/b978-0-12-819556-7.00006-1

Ding, M., 2017. In-depth industry research on sludge treatment industry.

Ding, X.F., Liu, H.C., 2019. A new approach for emergency decision-making based on zero-sum game with Pythagorean fuzzy uncertain linguistic variables. Int. J. Intell. Syst. 34, 1667–1684. https://doi.org/10.1002/int.22113

Drainage Services Department, 2017. Hong Kong Monthly Digest of Statistics - Stastics on sludge disposal and treatment in Hong Kong.

ECOIL, 2006. Life Cycle Assessment (Lca).

Grimes-Casey, H.G., Seager, T.P., Theis, T.L., Powers, S.E., 2007. A game theory framework for cooperative management of refillable and disposable bottle lifecycles. J. Clean. Prod. 15, 1618–1627. https://doi.org/10.1016/j.jclepro.2006.08.007

Guo, S., Zhao, H., 2017. Fuzzy best-worst multi-criteria decision-making method and its applications. Knowledge-Based Syst. 121, 23–31. https://doi.org/10.1016/j.knosys.2017.01.010

Hafezalkotob, Ashkan, Hafezalkotob, Arian, 2017. A novel approach for combination of individual and group decisions based on fuzzy best-worst method. Appl. Soft Comput. J. 59, 316–325. https://doi.org/10.1016/j.asoc.2017.05.036

Hashemkhani Zolfani, S., Banihashemi, S.S.A., 2014. Personnel Selection Based on a Novel Model of Game Theory and Mcdm Approaches. https://doi.org/10.3846/bm.2014.024

Kumar, A., Sah, B., Singh, A.R., Deng, Y., He, X., Kumar, P., Bansal, R.C., 2017. A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.11.191

Lam, C.M., Lee, P.H., Hsu, S.C., 2016. Eco-efficiency analysis of sludge treatment scenarios in urban cities: The case of Hong Kong. J. Clean. Prod. 112, 3028–3039. https://doi.org/10.1016/j.jclepro.2015.10.125

Liu, Y., Man, Y., Ren, J., 2020a. Waste-to-wealth by sludge-to-energy: a comprehensive literature reviews, Waste-to-Energy. INC. https://doi.org/10.1016/b978-0-12-816394-8.00003-3

Liu, Y., Ren, J., Man, Y., Lin, R., Lee, C.K.M., Ji, P., 2020b. Prioritization of sludge-to-energy technologies under multi-data condition based on multi-criteria decision-making analysis. J. Clean. Prod. 273, 123082. https://doi.org/10.1016/j.jclepro.2020.123082

Medineckiene, M., Zavadskas, E.K., Turskis, Z., 2011. Dwelling selection by applying fuzzy game theory. Arch. Civ. Mech. Eng. 11, 681–697. https://doi.org/10.1016/s1644-9665(12)60109-5

Ren, J., Liang, H., Dong, L., Gao, Z., He, C., Pan, M., Sun, L., 2017. Sustainable development of sewage sludge-to-energy in China: Barriers identification and technologies prioritization. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.09.024

Rulkens, W., 2008. Sewage sludge as a biomass resource for the production of energy: Overview and assessment of the various options. Energy and Fuels 22, 9–15. https://doi.org/10.1021/ef700267m

Soltani, A., Sadiq, R., Hewage, K., 2016. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making. J. Clean. Prod. 113, 388–399. https://doi.org/10.1016/j.jclepro.2015.12.041

Su, D., Wang, X., Liu, Y., 2009. Three Typical Processes of Electricity Generation by Sewage Sludge. Environ. Prot. Sci. 35, 54–57.

Sun, C.C., 2010. A performance evaluation model by integrating fuzzy AHP and fuzzy TOPSIS methods. Expert Syst. Appl. 37, 7745–7754. https://doi.org/10.1016/j.eswa.2010.04.066

Syed-Hassan, S.S.A., Wang, Y., Hu, S., Su, S., Xiang, J., 2017. Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2017.05.262

Torkayesh, A.E., Malmir, B., Rajabi Asadabadi, M., 2021. Sustainable waste disposal technology selection: The stratified best-worst multi-criteria decision-making method. Waste Manag. 122, 100–112. https://doi.org/10.1016/j.wasman.2020.12.040

Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew. Sustain.

Energy Rev. https://doi.org/10.1016/j.rser.2009.06.021

Wang, Y.M., Elhag, T.M.S., Hua, Z., 2006. A modified fuzzy logarithmic least squares method for fuzzy analytic hierarchy process. Fuzzy Sets Syst. 157, 3055–3071. https://doi.org/10.1016/j.fss.2006.08.010

Wei, L., Zhu, F., Li, Q., Xue, C., Xia, X., Yu, H., Zhao, Q., Jiang, J., Bai, S., 2020. Development, current state and future trends of sludge management in China: Based on exploratory data and CO2-equivaient emissions analysis. Environ. Int. 144. https://doi.org/10.1016/j.envint.2020.106093

Yang, G., Zhang, G., Wang, H., 2015. Current state of sludge production, management, treatment and disposal in China. Water Res. https://doi.org/10.1177/0954406216646137

Zhao, J., 2018. Several Kinds of Sludge Incineration Treatment Technology (in Chinese). Ind. Furn. 40, 1–6.