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TOWARDS SUSTAINABLE VALORIZATION OF SLUDGE: A COMPREHENSIVE DECISION-SUPPORT FRAMEWORK

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PhD

The Hong Kong Polytechnic University

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Towards Sustainable Valorization of Sludge: A Comprehensive Decision-Support Framework

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

May 2022

Certificate of Originality

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_______________(Signed)

___Yue Liu___(Name of student)

Abstract

The generation of sewage sludge increases year by year with the population growth. Under the current situation of environment and resources and the requirement of sustainable development, it is necessary to conduct effective sludge treatment processes to reduce the negative environmental impacts. During the decade, sludge valorization technologies have attracted wide attention since they can process harmful matters, recover valuable components, and realize energy regeneration simultaneously. There are various sludge treatment technologies which can be applied for value-added products production and these technologies usually have different merits and shortcomings in different aspects. It would be challenging to directly judge their performance and make a suitable choice among all the options, especially when considering multi-criteria. However, analyzing the performance on different perspectives of the technologies is important and necessary under current concerns on sustainable development. Therefore, a comprehensive decision-support framework covering life cycle sustainability assessment and multi-criteria decision-making is needed to guide the decision-making process of sewage sludge.

Although some studies have explored different sludge management technologies, there are still many issues that have not been discussed in-depth or even touched upon, such as the solution for sustainability evaluation under lacking data conditions, sustainability-oriented decision-making considering social and technical aspects, and sustainable supply chain design. Hence, this project aims at constructing a comprehensive decision-support framework to provide insightful reference information

and suggestions for related managers, including life cycle sustainability assessment for sludge valorization technologies, sustainability prioritization under different conditions and sustainable supply chain design and optimization. The major results and contributions are presented as follows.

Firstly, in terms of sustainability evaluation, a composite sustainability index is proposed to evaluate the performance of sludge-to-energy technologies from the perspective of energy recovery, carbon emissions and water consumption. The index can also be extended to analyze the footprints of other concerned elements, which can promote the understanding of the features of different sludge management technologies. Results indicate the priority of gasification and melting for sludge treatment and energy recovery. Current challenges and barriers to sustainable sludge management are also figured out by the results.

Secondly, different multi-criteria decision-analysis frameworks are developed to solve decision-making problems under complicated conditions, including performance evaluation and decision-making with insufficient performance data, decision-making problems under multi-data conditions, and group decision-making problems. To deal with the problem of lacking data for sustainability evaluation and prioritization of emerging technologies, process simulation and fuzzy PROMETHEE II approach are applied to analyze sustainability ranking and provide recommendations for stakeholders. Decision-making problems under multi-data conditions are discussed and addressed by Dempster–Shafer theory combined with the fuzzy best-worst method (DS-FBWM), which can effectively process the decision-making problems with crisp numbers, interval numbers, linguistic descriptions, and incomplete information. Afterward, a game theoretical-based multi-criteria decision-analysis method is established to deal with the group decision-making problems considering the conflicting interests and interactions between stakeholders. With the guidance of the decision-making frameworks, stakeholders can find out the effective and suitable alternative for sustainable sludge management under complex situations.

Finally, how to design and optimize the supply chain in the urban area for sewage sludge is discussed by constructing a mix-integer programming model, which can help to decide the proper location of sludge treatment facilities and the technical routes for sludge management. A case study in the context of Hong Kong is conducted and results show relatively good consistency with the practice. Results suggest that centralized management of sewage sludge with proper daily capability and cost-effective technical route adaption can effectively reduce the total costs for sludge treatment.

This research provides useful information on the state-of-arts of current sludge management technologies and analyzes the existing difficulties and challenges of sustainability-oriented evaluation and decision-making under complicated situations. To address these problems, innovative sustainability evaluation approaches and MCDA methods are developed, which can provide effective solutions for practical application as well as reference information to guide future research theoretically. Practical cases are analyzed to demonstrate the feasibility of the proposed methodology frameworks and the results indicate the applicability and reliability of these models, which can also provide insightful suggestions and implications for the experts and policymakers.

Publications

Journal papers

Yue Liu, Jingzheng Ren*, Yi Man, Ruojue Lin, Carman K.M. Lee, Ping Ji, 2020. Prioritization of sludge-to-energy technologies under multi-data condition based on multi-criteria decision-making analysis. Journal of Cleaner Production 273, 123082. https://doi.org/10.1016/j.jclepro.2020.123082. **Impact Factor: 9.297**. [This article is presented as part of Chapter 6]

Yue Liu, Tao Shi, Ao Yang, Jingzheng Ren*, Weifeng Shen, Chang He, Sara Toniolo, 2022. Sludge valorization process for waste-to-value-added products: process simulation, sustainability assessment and fuzzy multi-criteria decision making. ACS Sustainable Chemistry & Engineering 10, 34, 11428-11440. **Impact Factor: 9.224.** [This article is presented as part of Chapter 5]

Yue Liu, Jingzheng Ren*, Liang Dong, Yuanzhi Jin, Yi Man, 2022. Urban Sludge to Value-added products for promoting the development of circular economy: Supply network design and optimization. Resources, Conservation & Recycling 182, 106317. **Impact Factor: 10.204**. [This article is presented as part of Chapter 8]

Yue Liu, Ruojue Lin, Jingzheng Ren*, 2020. Developing a life cycle composite footprint index for sustainability prioritization of sludge-to-energy alternatives. Journal of Cleaner Production 281, 124885. https://doi.org/10.1016/j.jclepro.2020.124885. **Impact Factor: 9.297**. [This article is presented as part of Chapter 4]

Yue Liu, Ruojue Lin, Yi Man, Jingzheng Ren*, 2019. Recent developments of hydrogen production from sewage sludge by biological and thermochemical process.

International Journal of Hydrogen Energy 44, 36, 19676-19697. https://doi.org/10.1016/j.ijhydene.2019.06.044. **Impact Factor: 4.939**.

Yue Liu, Jingzheng Ren.*, 2021. Developing a sustainability-oriented multi-criteria game theoretical decision analysis framework: A case study of sludge management. Journal of Cleaner Production 354, 131807. **Impact Factor: 9.297**. [This article is presented as part of Chapter 7]

Book chapter

Yue Liu, Jingzheng Ren, 2021. Overview of Sustainability, Sustainable Development and Sustainability Assessment: Concepts and Methods. In book: Energy Systems Evaluation 1, 1-29. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-030-67529-5_1. [This chapter is presented as part of Chapter 2]

Yue Liu, Yi Man, Jingzheng Ren, 2020. Waste-to-wealth by sludge-to-energy: a comprehensive literature reviews. In book: Waste-to-Energy, 45-74. https://doi.org/10.1016/B978-0-12-816394-8.00003-3. [This book chapter is presented as part of Chapter 2]

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Chapter 1 Introduction

This chapter starts with the research background and provides a brief review for the relevant research problems. Then, the research scope, objectives and significance are introduced to emphasize the major focus and contribution of this project. Finally, the structure of the thesis and outline of each chapter are presented.

1.1. Research background

With the development of economy and society, the living standard of human beings is improving continuously, but the situation of resources and environment is increasingly serious due to the huge demands and the impact of daily activities. Sustainable development has attracted more and more attention as a way of development to seek the balance between human beings and environment. Many efforts have been conducted to gradually realize sustainable development by different people in different fields. More and more attempts have been carried out to explore renewable energy sources in order to reduce the dependence on fossil fuels, including solar energy, wind, biomass, nuclear, and tidal energy. Biomass as a kind of renewable energy with a wide range of sources has also drawn wide attention because of the wide availability and easy accessibility, such as biofuels made from growing plants and biodegradable waste.

Sewage sludge as a byproduct generated from wastewater treatment plants can also be regarded as biomass. The improving requirement on the quality of wastewater leads to the rising in the generation of sewage sludge year by year (Tarpani and Azapagic, 2018; Yang et al., 2015). According to the specific source area and plant types, sewage sludge can be classified into municipal sludge, intertidal zone sludge and industrial sewage sludge (Wong et al., 2014). Nevertheless, the most typical classification is by the degree of treatment, such as treated sludge (digested sludge, composted sludge, dried sludge, etc.), and untreated sludge (raw sludge, primary sludge, secondary sludge, etc.) (Fränzle et al., 2012; Syed-Hassan et al., 2017; Verlicchi and Zambello, 2015). Despite the various types of sewage sludge, the basic compositions are similar, including non-toxic organic carbon matters, N- and P-containing matters, toxic pollutants, pathogens and other microbiological pollutants, inorganic components and water (Rulkens, 2008). On the one hand, if the sludge is discharged directly into the environment without proper treatment, severe secondary contamination may be caused by hazardous substances. On the other hand, many valuable matters are contained in sludge which can be reused or recycled, like N- and P-containing components. In addition, the relatively high carbon-content in sludge provides the possibility of energy recovery from sewage sludge. Hence, suitable treatment and disposal methods which can effectively process the waste and realize value-added products recovery are necessary and important. Sludge-to-energy technologies are therefore proposed and developed to achieve the goal of harmless and resource utilization treatment of sewage sludge (Rulkens, 2008).

In recent decades, many different sludge management technologies which can convert waste into diverse kinds of useful energy are under studied and developed. Some typical technologies include anaerobic digestion, co-digestion, incineration and co-incineration with energy recovery, wet oxidation, pyrolysis and gasification (Fytili and Zabaniotou, 2008; Rulkens, 2008). The rise of new technologies has also attracted more attention in recent years, mainly referring to anaerobic fermentation (Liu et al., 2019), microbial fuel cells (MFCs) (Gude, 2016), and supercritical water gasification (SCWG) (Syed-Hassan et al., 2017). Different technologies show different characteristics in the recovery of valuable products from sewage sludge. For example, incineration has been widely applied as a thorough treatment of sludge in many developed countries (Li et al., 2005). Sanitary landfill was once a popular method to dispose treated sludge in many countries, but the considerations of possible pollution on the soil and underground water and the increasing stringent sludge management regulations, it may not be suitable anymore (Fytili and Zabaniotou, 2008; Yang et al., 2015). All the environmental and resource conditions and requirements of sustainable development drive stakeholders and decision-makers to seek suitable and sustainable sludge-to-energy technical routes to promote sustainable management of the sludge industry.

It is important to investigate the sustainability performance of the different sludge-to-energy scenarios to provide more reliable decision-making references. Various aspects should be considered in the sustainable decision-making process of sludge management, like the three classical dimensions of sustainability (environment, economy, and society). Life cycle sustainability assessment (LCSA) method is a powerful tool to study the overall sustainability performance of target systems with the considerations of the environmental, economic, social impacts alongside the entire life cycle stages (Ciroth et al., 2011). Previous studies have verified the feasibility and applicability of sustainability evaluation of LCSA for sewage sludge management (Yoshida et al., 2013). Environmental and economic impacts were frequently discussed and analyzed by previous research within the range of several common sludge treatment technologies, like anaerobic digestion, incineration (Hong et al., 2009; Xu et al., 2014), pyrolysis (Kim and Parker, 2008; Li and Feng, 2018), and wet air oxidation (Svanström et al., 2004; Tarpani and Azapagic, 2018). The discussion on the footprints of significant components in sewage sludge as well as the performances of some newly developed sludge treatment technologies are still limited. All these facts reveal that there is still much room for the improvement in the research of sustainability assessment for sludge management technologies.

Some basic knowledge and understanding of sustainability performances of different sludge treatment techniques can be developed according to the sustainability evaluation results. However, more complex situations may occur in the actual decision-making process of sludge management, including the handle of hybrid data conditions, uncertain information process, conflicting interests, and the interactions between stakeholders. Multi-criteria decision-making methods are then applied to deal with these problems and help to prioritize and further select the most suitable sludge-to-energy scenario among all the options. They have a relatively flexible framework to combine with many different theories and methods to solve more complicated problems like fuzzy set theory and game theory. Fuzzy theory can help with the process of uncertain information, and game theory can deal with the interactions between stakeholders. Nevertheless, the analysis of MCDM methods or the improved decision-making frameworks on sludge-to-energy technologies are still limited, leading to the expectation on the further improvement for related research.

According to the above analysis, it is still necessary to develop a comprehensive decision support framework for sludge management. Since energy or other valuable products are usually expected to be recycled during the treatment of sewage sludge, the technologies which can achieve this goal are focused more in this project. Hence, a sustainability-oriented decision-making framework based on MCDA methods for sludge-to-value-added products technologies is proposed and applied in this domain to promote the sustainable development and management of sewage sludge and further help to realize circular economy.

1.2 Research scope, objectives and significances

This project aims at developing a sustainability-oriented decision-support framework for sludge management from life cycle perspective, where the technologies with energy or value-added products recovery are the focus. To start with, it is necessary to figure out the following questions:

(1) What are the development states of different sludge-to-energy technologies? What about the major features, merits, and shortcomings of these technologies?

(2) How the energy flow and footprints of major elements in sludge treatment technologies can be analyzed?

(3) How the sustainability performance of sludge management technologies can be

addressed especially for the emerging technologies which usually lack of data? How can a suitable selection be made among the alternatives considering uncertain preferences of stakeholders?

(4) How the decision-making problems of sludge management with multi-type data or incomplete information due to the limited data sources can be solved?

(5) How the decision-making problems with conflicting interests can be processed especially when the interactions between decision-makers cannot be neglected?

(6) How the supply chain for sludge-to-energy technologies can be designed and optimized with the consideration of multiple sustainability indices?

Based on the above questions, the major research objectives of this project are presented as follows.

(1) To conduct a literature review on the development status of different sludge-to-energy technologies in order to provide a comprehensive perception on the basic features of the various techniques.

(2) To develop a composite footprint index with the consideration of energy flow and significant elements from life cycle perspective for the sustainability evaluation of sludge-to-energy technologies based on fuzzy best-worst method (fuzzy BWM) and fuzzy analytic hierarchy process (fuzzy AHP) method.

(3) To establish a fuzzy MCDA framework based on process simulation and fuzzy PROMETHEE II approach to make up for the problem of insufficient data of emerging technologies and address the uncertain preferences from decision-makers.

(4) To develop a MCDA framework with the ability of processing multi-data conditions, including crisp numbers, interval numbers, linguistic descriptions and incomplete information for sludge-to-electricity technologies based on Dempster–Shafer theory (DS theory).
(5) To develop a MCDA framework based on game theory and a novel individual and group fuzzy BWM to deal with the decision-making problems with conflicting interests of different groups of stakeholders under uncertain preferences.
(6) To develop a supply chain optimization model based on mixed-integer programming model for urban sludge management.

Thus, this study can contribute to the following points:

(1) This research provides a relatively comprehensive literature review on the sludge-to-energy technologies which can help related managers and researchers to have a better understanding on the state-of-art of the sludge management technologies.
(2) This research constructs a comprehensive decision support framework for sludge valorization utilization including sustainability assessment, sustainability-oriented prioritization and selection under different uncertain situations (such as insufficient performance data, multi-data conditions, and group decision-making with conflicting interests), and supply chain design and optimization. The entire decision-making flow can provide useful reference information for stakeholders to find out the suitable alternative in complex scenarios.
(3) This study analyzes many actual cases to demonstrate the effectiveness of the proposed model in different situations. The results can not only suggest the

feasibility of the model, but also provides constructive advice which can put forward insights for the practices and have positive influence on the construction and sustainable development of sludge management industry.

1.3 Organization of the thesis

Besides the Introduction chapter, the reminder parts of the thesis are organized as follows.

Chapter 2 provides a comprehensive literature review on the status-of-arts of various sludge valorization technologies, sustainability evaluation, ranking and selection under multi-data conditions and group decision-making with conflicting interests, as well as supply chain design for urban sludge management. Research gaps were pointed out according to the literatures. Hence, the research focus of the rest studies can be correspondingly decided.

Chapter 3 presents the entire research methodology framework for this project to show the logic of the studies. A brief introduction for the involved methods in each chapter is also provided.

Chapter 4 constructs a composite sustainability index to energy the sustainability performance considering energy efficiency and material flows alongside the investigated life cycle stages. Fuzzy BWM and fuzzy AHP were applied to generate the fuzzy weights for each indicator and then integrate the performance data into an overall index. Six scenarios were studied in the case study and the results revealed the feasibility and flexibility of the proposed model.

Chapter 5 establishes a decision-making framework to evaluate the sustainability performances of sludge management technologies and conduct alternative selection based on process simulation and fuzzy PROMOTHEE II approach to handle the problem of lack data for the emerging technologies and the vagueness generated from decision-makers. Process simulation provides the basic data for the sustainability evaluation. Fuzzy BWM was applied to generate the fuzzy weights based on the preferences of decision-makers and fuzzy PROMETHEE (Preference ranking organization method for enrichment evaluation) II approach was utilized to obtain the final ranking for all the alternatives. A case study for four sludge valorization technologies were investigated to illustrate the feasibility and applicability of the proposed methodology framework.

Chapter 6 generates a decision-making framework for sludge-to-energy technologies based on DS-theory and fuzzy BWM to deal with the decision-making problems with hybrid information, including crisp numbers, interval numbers, linguistic descriptions, and incomplete information. DS-theory was employed to process the situation with incomplete information and fuzzy BWM was applied to help with the calculation of fuzzy preferences of stakeholders. An extended VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje in Serbian) method for interval numbers was utilized as the validation method. A case study of four different sludge-to-electricity technologies with different data conditions were analyzed to demonstrate the applicability of the constructed model.

Chapter 7 introduces game theory to MCDA method in order to handle the decision-making problem considering different preferences and even conflicting interests of the involved stakeholders. Life cycle assessment tool was first applied to obtain the evaluation results of different strategies and then a novel individual and group fuzzy BWM was applied to analyze the preferences of different groups of decision makers. Subsequently, game theory was utilized to find out the most suitable pair of strategy among all the selections based on the payoff matrix. A two-player game was discussed as the case study to explore the feasibility and robustness of the model.

Chapter 8 proposes a supply chain design and optimization model for sludge valorization utilization in urban area based on a mixed-integer programming model with the consideration of economic benefits, mass constraints, as well as the environmental impacts. A case study based on the conditions in Hong Kong was analyzed to demonstrate the proposed model and the influence of parameter variation were also discussed.

Chapter 9 summarizes the preliminary conclusions and major contributions of current work. Limitations and possible future working directions are also proposed correspondingly to promote the sustainable development of sludge management.

Chapter 2 Literature Review

In this chapter, current studies on the development status of sludge-to-energy technologies, sustainability assessment methods, sustainable decision-making for sludge management under different conditions, and supply chain design and optimization for biomass-to-energy are reviewed. Current development statue of common sludge treatment technologies with energy and valuable materials recovery are reviewed in the Section 2.1 to provide a basic knowledge and cognition. Life cycle-based sustainability assessment is a powerful tool to analyze the sustainability performance of investigated systems. Besides the typical LCSA tool, some other sustainability evaluation approaches which are also helpful for sustainability assessment are reviewed in Section 2.2, especially the application in sludge management field. The application of process simulation in sludge management and decision-making process is introduced in Section 2.3. To deal with the sustainability-oriented decision-making problem for sludge-to-energy technologies under hybrid data conditions, LCSA-based MCDA methods are reviewed in Section 2.4. In Section 2.5, the MCDA methods to handle the situation under different groups of stakeholders with different or even conflicting interests are discussed. An overview on the urban supply chain design and optimization models for waste or biomass to energy are presented in the Section 2.6. Based on the literature review, the existing research gaps are emphasized at the end of each section.

Literature review was conducted by searching the focused keywords in different databases, including Scopus, Google Scholar, and Web of Science. Related papers were found out through keywords in title and abstract. For the papers which may possibly provide useful information after reading the title and abstract, more detailed content will be checked to collect relevant information. More exact description for the methodology toward literature review is provided in the corresponding section if it is necessary to supplement.

2.1 Development of sludge-to-energy technologies

2.1.1 Problem statement

The increasing demand of water usage and rising population lead to the growing production of sewage sludge, which is a by-product generated from the wastewater treatment (Fytili and Zabaniotou, 2008; Yang et al., 2015). Proper treatment for sewage sludge is necessary to conduct aiming to decrease or eliminate the contamination caused by harmful components contained in the waste, including toxic materials, and pathogen (Rulkens, 2008). Hence, conventional simple treatment for sewage sludge like direct landfilling and agricultural use is no longer suitable for present situation due to the obvious negative effect on the environment and human health (Yang et al., 2015). Meanwhile, the increasing severe resource and environmental issues have gradually driven the public to aware the importance of seeking for renewable and clean energy. Nontoxic organic compositions and valuable products generated from sludge treatment remind the academics to combine energy production and resource reuse with harmless process for sewage sludge. It is regarded as a promising way for energy recovery and valuable products generation from sewage sludge because it keeps high consistency with the sustainable development requirement (Fytili and Zabaniotou, 2008).

The major methods for sludge treatment can be basically divided into two categories – biological and thermochemical treatment. Biological processes mainly refer to anaerobic digestion (AD), co-digestion and fermentation. Microbial fuel cells (MFCs) for electricity production by using sewage sludge with specific microorganisms have become a hot topic during recent years. Thermochemical processes primarily include incineration and co-incineration, pyrolysis, gasification, supercritical water oxidation (SCWO) and supercritical water gasification (SCWG). Heat, electricity and biofuels are the major products generated from the treatment process, where the biofuels contain biogas, biodiesel, and bio-hydrogen or hydrogen-rich gas. Phosphorous recovery is also a research focus because of the considerable amount of organic matters by accumulation from the large quantity of daily processed effluent (Manara and Zabaniotou, 2012; Rulkens, 2008; Syed-Hassan et al., 2017).

There already exist plenty of alternatives for energy and resource recovery from sewage sludge. However, the maturity of technologies and inapplicable equipment lead to the high cost of the total operation (Rulkens, 2008) and limit the further promotion and application of the energy recovery methods (He et al., 2014). These basic facts indicate that various efforts are still needed to improve the energy efficiency and reduce the total cost so that the entire process can reach the cost-efficient status and contribute to the sustainable development.

This section aims to provide a brief introduction of several types of sewage sludge treatment technologies for energy and resource recovery based on literature review and discuss the present challenges and future development prospect of these techniques. A comparison alongside the environmental, technical and economic aspects is presented to provide some suggestions for the government support and further research. In this section, the reviewed articles were identified by using the database of the Scopus and Google Scholar by the keywords in their title, abstract, and keywords. Specifically, the keywords selected for literature review in this section include “sewage sludge”, “sludge treatment”, “sludge-to-energy”, “energy recovery” and “reviews”. After preliminary selection of keywords, the articles which are judged to be more relevant will be further reviewed to collect and summarize the useful information.

2.1.2 Biological processes

Biological treatment is the process with the activity of microorganism in sewage sludge to degrade and stabilize the materials. Common methods of this category include photolysis, anaerobic digestion, anaerobic fermentation, microbial fuel cells and composting. Research on photolysis for sludge treatment is limited which is omitted here. Composting as a conventional approach for agricultural application may cause soil pollution due to the existence of heavy metals (Amir et al., 2005) is also not discussed in this chapter. Pretreatment is usually required for biological process to promote the process of disintegration and heating is the most frequently used method (Appels et al., 2008). Other pretreatment approaches are discussed in detail in the study of Zhen et al. (2017).

2.1.2.1 Anaerobic digestion

There are four procedures involved in anaerobic digestion which consist of hydrolysis, fermentation, acidification, and methane formation. With the function of extracellular enzyme, hydrolytic bacterium degrades the organic matters into organic components in simple small molecule. Then hydrogen, acetic acid, and volatile fatty acids are generated from the hydrolysis products by specific bacteria during the acidification stage. Methanogens convert the H_2 and organic acids into CH_4 and CO_2, where macromolecular acids are first converted into H_2, formate and acetate, then further converted into CH_4 and CO_2 (Rulkens, 2008). The reaction process for the anaerobic digestion was shown in Figure 2.1.

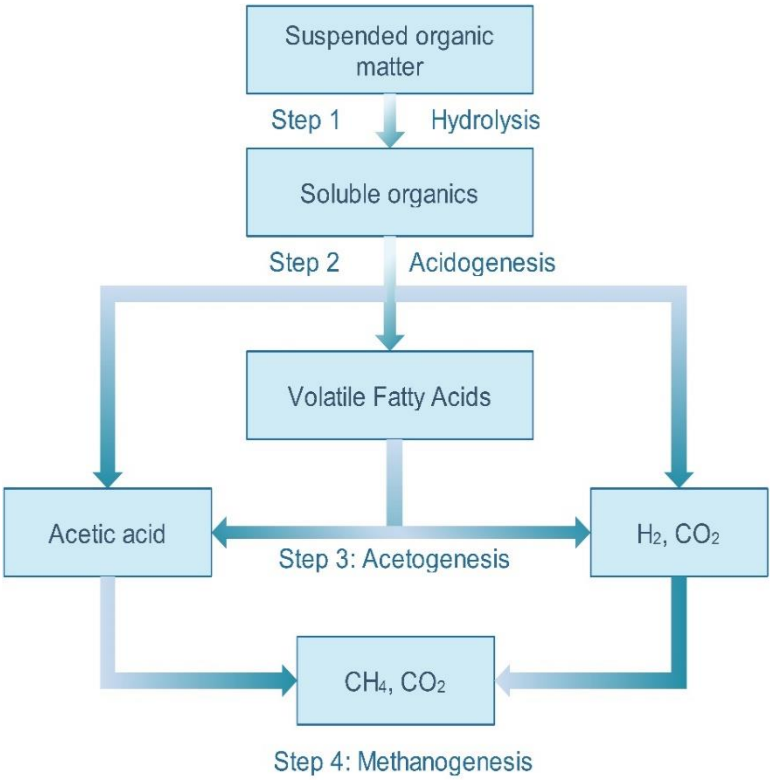


Figure 2.1 Flow chart of the reaction steps in anaerobic digestion (modified from Appels et al., (2008))

Strictly anaerobic environment is the first condition for anaerobic digestion. The process is also influenced by temperature, pH value and duration for solids and hydraulic. Increasing temperature is in favor of improving the dissolution efficiency of organic matters and promoting the reaction rates as well as the elimination of pathogens. However, it is also a trade-off due to the rising formation of free ammonia which can inhibit the activity of useful bacteria. It is necessary to control the pH within a suitable range because of the different features of various microorganisms in each specific stage of anaerobic digestion. More particular analysis for the impact of different factors on anaerobic digestion can refer to the research of Appels et al. (2008). As for the equipment set, two reactors are enough for the total process, where one is for the former three steps and the other for the methane generation (Rulkens, 2008).

Anaerobic digestion is a widespread method for sewage sludge stabilization and biogas production with the methane composition of approximately 63 vol% (Appels et al., 2008), which can be converted into electricity or heat. Co-digestion with other types of waste including municipal solid waste and food waste is also a common method to promote the process of decomposition and improve the biogas production (Fernández-Nava et al., 2012; Mehariya et al., 2018; Sosnowski et al., 2003). It should be noted that only part of the toxic substances are removed during the process which means that further treatment is still necessary (Rulkens, 2008). Meanwhile, the energy contained in biogas is dissatisfactory due to the relatively low heating value leading to possible upgrading process before the biogas application (Appels et al., 2008). Hence, future work may consider how to optimize the operation conditions and obtain a higher content of methane to improve the energy recovery rate and reduce the total production costs. Life-cycle costs estimation for anaerobic digestion was conducted by Tarpani and Azapagic (2018) with several specific assumptions and the cost was evaluated to be -

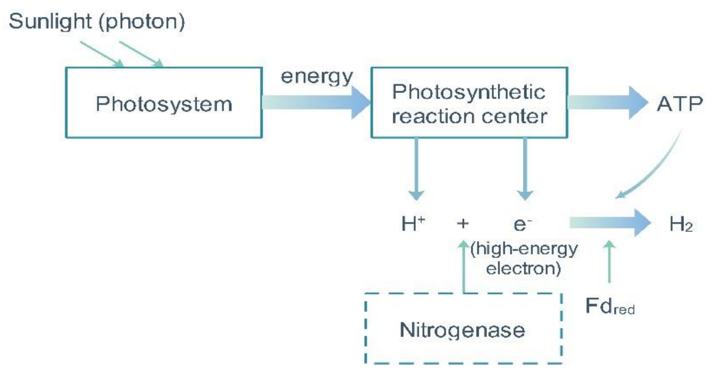
17.6 GBP per 1000 kg dry matters of sludge which means a profit obtained from the AD process. However, this estimation was sensitive to many factors especially the energy sales prices and recovery rate.

2.1.2.2 Anaerobic fermentation

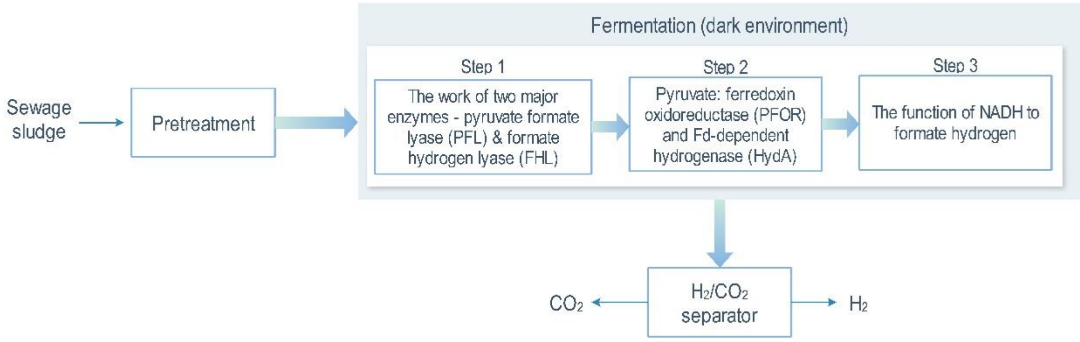
According to the differences in operation conditions, anaerobic fermentation can be classified into photo-fermentation and dark-fermentation. Both occur in the strictly anaerobic environment and the former requires enough light source while the latter can conduct under dark environment.

Photosynthetic bacteria, such as Rhodobacter sphaeroides O.U001, and Rhodobacter capsulatus R, using the solar energy with the function of nitrogenase enzyme converts organic acids and alcohols into hydrogen and carbon dioxide. Reaction principle of acetic acid as substrate for photo-fermentation is described in Eq. (2.1) (Argun and Kargi, 2011) and basic process was shown in Figure 2.2 (a).

$$CH_3COOH+2H_2O \rightarrow 4H_2+2CO_2 \tag{2.1}$$



(a) Photo fermentation (modified from (Guo et al., 2007))



(b) Dark-fermentation (modified from Hay et al. (2013) and Nikolaidis and Poullikkas (2017))

Figure 2.2 Anaerobic fermentation process for sewage sludge

Dark-fermentation refers to the process that heterotrophic bacteria transform the carbohydrates like glucose into hydrogen, carbon dioxide, and volatile fatty acids (VFAs) with the impact of hydrogenases under the dark oxygen-free condition. Typical microorganisms for hydrogen generation by dark-fermentation include Clostridium species, Bacillus sp., and several specific thermophilic bacteria. Current studies focused on hydrogen production from anaerobic acidogenic sludge with monosaccharides as the major substrates. Taking the glucose as an example, Eq. (2.2) showed the reaction mode of this process (Argun and Kargi, 2011). Figure 2.2 (b) illustrated the reaction steps of dark-fermentation.

$$C_6H_{12}O_6+2H_2O \rightarrow 2CH_3COOH+4H_2+2CO_2 \qquad (2.2)$$

Besides the inherent requirement regarding light source, photo- and dark-fermentation are also influenced by pH value, temperature, and the contents of specific metal elements. More detailed information on the effect of different factor toward fermentation to produce hydrogen can be found in the study of Argun and Kargi (2011) and Wang and Wan (2009).

Photo-fermentation possesses the advantages on hydrogen yield and reduced cost for heat pretreatment under certain conditions (Ike et al., 1997a, 1997b), but the slow reaction rate, low light conversion efficiency and strict demand on light source limit its application (Argun and Kargi, 2011). Dark-fermentation shows better performance on the ability of strain's growth and hydrogen formation, hydrogen generation efficiency and reaction rate. Meanwhile, no requirement for light and wide range of sources of the raw materials (e.g., organic wastes, and sludge) also lead to wider applicability of dark-fermentation (Guo et al., 2007).

The products of dark-fermentation can be applied as the substrates for photo-fermentation. Therefore, many researchers explored the combination or multi-step of fermentation for hydrogen production aiming to increase the total yield. The theoretical amount of sequential dark- and photo-fermentation is 12 mol H_2 with 1 mol glucose as the substrate, as indicated by Eq. (2.3). The highest hydrogen yield from sequential dark-and photo-fermentation was recorded to be 7.2 mol/mol glucose (Argun and Kargi, 2011).

$$C_6H_{12}O_6+2H_2O \rightarrow 12H_2+6CO_2 \tag{2.3}$$

Research on the biological process for hydrogen production from sludge remains in preliminary experimental stage and studies on photo-fermentation are even scarcer. It was reported that almost 80% of the theoretical yields (the ratio of hydrogen generated amount to the consumed amount of substrate) was obtained from photo-fermentation with low light intensity and unsatisfactory hydrogen formation speed (Argun and Kargi, 2011). Available data of H_2 yield from wastewater was recorded to be 1.267 mol H_2/mol substrate (Eroğlu et al., 2009) and the H_2 content varies within the range of 47-98%

(Hay et al., 2013). As for dark-fermentation, the total yield of H_2 was obtained as 3.0 mol/mol glucose through the experiments for heat pretreated anaerobic sludge and corn stover (Datar et al., 2007). High reaction rate could be achieved by continuous operation mode while the highest hydrogen yield was provided by batch fermentation with low density of initial materials. Few studies involved with the costs for hydrogen production from wastewater and sludge and the analysis usually depended on many specific conditions and assumptions (Hay et al., 2013). Hence, more investigations and experiments are necessary to be conducted to have a better understanding of each step and further to improve the total performance of hydrogen generation by biological approaches.

2.1.2.3 Microbial fuel cells (MFCs) for electricity production

Microbial fuel cells combined with wastewater and sludge treatment has become a hotspot during recent years due to the ability to convert the waste to clean electivity directly (Gude, 2016). With the existence of microorganism at anode as the catalyst, a series of electrochemical reactions happen under mild conditions (e.g., normal pressure and temperature) accompanied with energy release (Gude, 2016; Jiang et al., 2009). Common equipment for MFC includes single-chambered reactor and two-chambered reactor. The related reactions on anode, cathode, and the total were shown in Eq. (2.4) – (2.6) respectively (exampled by acetic acid as the substrate for electricity production) (Gude, 2016). Reaction principle is illustrated in Figure 2.3.

Anode: $CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^-$ (2.4)

Cathode: $2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$ (2.5)

Total: $CH_3COO^- + 2O_2 \rightarrow 2HCO_3^- + H^+$ (2.6)

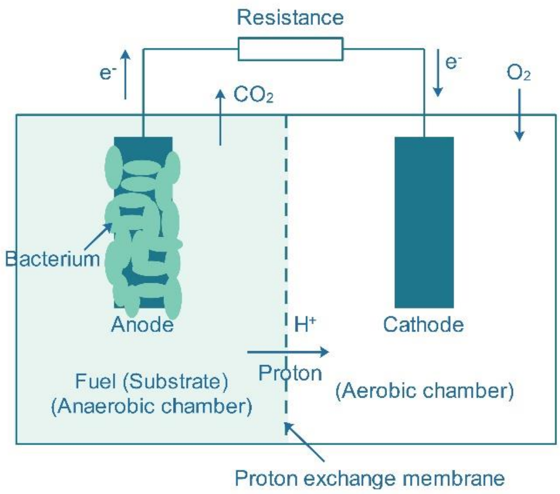


Figure 2.3 Mechanism description of a two-chamber MFC (modified from Du et al. (2007))

Generally, pretreatment is needed to improve the solubility of organic matters for the subsequent electricity production by MFCs. It is reported that sludge pretreated by low ultrasonic density in a long operation time could reach a similar effect on the decomposition of sludge under ultrasonic wave in high density for a short time-length (Zhao et al., 2010). The performance of MFCs is characterized by the ratio of substrate conversion, which is influenced by the parameters of equipment, the features of applied bacteria, and the physicochemical properties of input sewage sludge, such as the electrode surface, the microorganism ability of utilizing substrate, and organic loading rate (Gude, 2016; Rabaey et al., 2003). Specific influence of several different factors on the performance of MFCs has been overviewed by Gude (2016).

There exists a quantity of studies on treating sewage sludge by MFCs toward energy recovery, however, it is still in the initial experimental stage without widespread application in large-scale (Gude, 2016). A comparison of energy production performance of MFCs from different types of sludge was conducted by Ma et al. (2013)

The optimal current intensity was recorded as 38.1 W/m^3, which was obtained by a particular kind of sewage sludge named recovered organic matter owing to low internal resistance caused by a relatively high content of soluble chemical oxygen demand (SCOD) (Ma et al., 2013). Experiment results revealed that MFCs possess application potential on processing anaerobic digested sludge compared with treating primary sludge directly (Ge et al., 2013). A stable current was obtained in the 250-hour duration with the total chemical oxygen demand (TCOD) reducing by 46.4% in a two-chambered MFC to process excess sewage sludge and produce electricity (Jiang et al., 2009). In addition, MFCs have the ability to generate electricity directly from the organic components in sewage sludge without other operations to separate, purify, and convert the produced energy forms compared with the biogas generated from anaerobic digestion. Extra cost for electricity generation during the process consumes only 0.024 kW or 0.076 kWh/kg-COD on the average which is one order of magnitude lower than that of aerobic treatment for activated sludge (around 0.3 kW or 0.6 kWh/kg-COD) (Gude, 2016; Zhang et al., 2013a, 2013b). All the results show that the utilization of MFCs for organic matters in wastewater and sludge degradation and electricity generation owns huge development and application value in the term of “waste-to-wealth”.

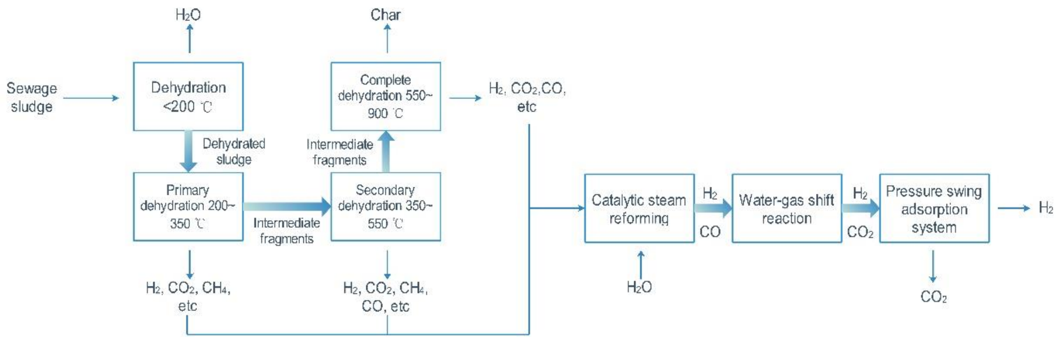
However, it is acknowledged that there is still a long-distance from normalization and industrialization for the application of MFCs due to the existence of the following challenges. Taking the cost into account, the chemical oxygen demand (COD) removal rates are unsatisfactory which were recorded in the range of 0.0053-5.57 g COD/(L·d) from various substrates (Clauwaert et al., 2008). Nevertheless, the range of cost-effective goal in MFCs for wastewater treatment was supposed to be 5-10 kg COD/m^3, that is approximately 0.5 USD/m^3 (0.39 GBP/m^3) (Janicek et al., 2014). Power outputs vary with the specific operating conditions and experimental scale, from 0.0018 to 2 W/m^2, i.e., 0.2-200 W/m^3 (Janicek et al., 2014). The system of air cathode and biocathode, which has higher sustainability due to the outstanding ability on pH balancing, is still under development as well as the integration process with other advanced technologies aiming to obtain more energy and remove the organic matters. Hence, more investigations are expected to improve the energy production efficiency and reduce the production cost to make this treatment method competitive.

2.1.3 Thermochemical processes

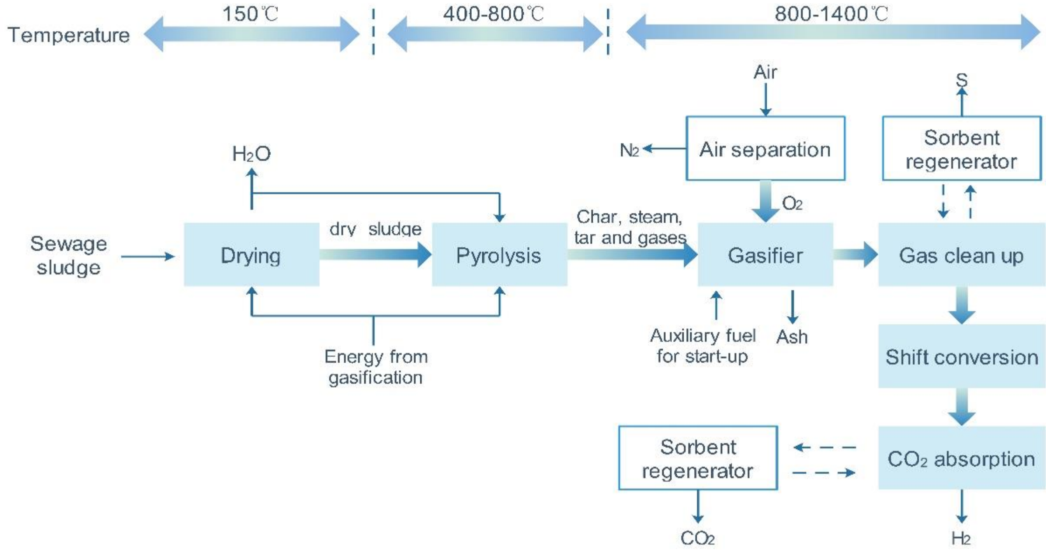
Thermochemical treatment is a sort of widespread methods for sewage sludge disposal since it can effectively reduce the volume of sludge and recover energy simultaneously. After pretreated by drying or other dehydration steps, sewage sludge can be transported for further thermochemical methods including combustion, incineration, pyrolysis, and gasification. Then various forms of biofuels (solid, liquid, and gaseous products) can be obtained from sewage sludge during the process (He et al., 2014; Syed-Hassan et al., 2017). Supercritical water gasification is an innovative way for sewage sludge process and hydrogen production. The principles of SCWO are similar to those of SCWG. Nevertheless, SCWO technique with a developing history for over thirty years, has been applied in defense industry to eliminate the influence of obsolete biochemical weapon (Crooker et al., 2000; Kamler and Andres, 2012), while the SCWG is an emerging technology which still remains in research stage (He et al., 2014).

2.1.3.1 Pyrolysis and gasification

Pyrolysis is a thermochemical process which operates the sewage sludge majorly between 350 and 500 °C with the pressure of 0.1-0.5 MPa under oxygen-free environment (Hosseini and Wahid, 2016; Rulkens, 2008).There also exist pyrolysis experiments for sludge degradation and energy production at high temperature (nearly 1000 °C) (Domínguez et al., 2006; Xiong et al., 2009). The main process called primary pyrolysis occurs from approximately 200 °C when the organic components of sludge begin to convert into volatile matters and char, which is a significant procedure covered the evaporation of internal water to mark the initial steps for all the thermochemical transformation. Previous researchers have investigated the characteristics of primary pyrolysis by applying the thermogravimetric analysis (Alvarez et al., 2015; Magdziarz and Werle, 2014). Three phases for sewage sludge decomposition were summarized by Fonts et al. (2001) and it was pointed out that the main degradation for organic polymers occurs from 300 to 450 °C (Syed-Hassan et al., 2017). The existence of discrepancies is natural because of the differences in inherent features of sludge and the operation situation. The process of pyrolysis was described in Figure 2.4 (a).



(a) Pyrolysis



(b) Gasification

Figure 2.4 Process description of pyrolysis and gasification for sewage sludge (modified from Manara and Zabaniotou (2012) and Nikolaidis and Poullikkas (2017))

Products generated from pyrolysis categorized by temperature were studied by Xiong et al. (2009). The corresponding summarization on the content of the products was provided by Syed-Hassan et al. (2017) which revealed that liquid takes up 20.4-52.1 wt% (on feed basis), char in charge of 35.6-61.9 wt%, and gaseous products occupies 3-28.9 wt% varying with the specific experimental conditions. Liquid tar from pyrolysis is regarded as a mixture consisting of complex organic compounds and the ideal utilization can be realized if the straight chain hydrocarbons with high heating value are contained in the tar (Sato et al., 2003). Solid products made up by carbonaceous matters are characterized by low heating value and high metals content which leads to the unfeasibility for further energy supply application (Werther and Ogada, 1999). However, it is suitable for landfilling and function as absorption for acid matters due to the favorable surface structure (Radovic et al., 1997). Gaseous products formed from pyrolysis include a relatively high content of hydrogen (20-40 vol%), carbon dioxide (around 10-20 vol%), carbon monoxide (about 20-40 vol%), methane (about 10-15 vol%), and several light hydrocarbons (Manara and Zabaniotou, 2012; Xiong et al., 2009). Hence, pyrolysis is supposed to be a potential way to obtain hydrogen from sludge.

Temperature, operation duration and pressure, turbulence, the properties of materials, and catalyst are inclusive in the group of important factors for the pyrolysis products yields, where the temperature not only puts influence on the production but also effects the quality of the products (Manara and Zabaniotou, 2012; Syed-Hassan et al., 2017). Xiong et al. (2009) studied the effect of sludge's moisture, heating rate, and temperature on the products generation and found that gases yields increased as all the three factors rising and they were all in favor of the generation of hydrogen. A comparison of the effect of traditional and microwave pretreatment methods on the yield of each component was carried out by previous researchers (Domínguez et al., 2006) and specific influence of different factors have been overviewed by Manara and Zabaniotou (2012) and Syed-Hassan et al. (2017).

Costs estimation for pyrolysis depends on the specific assumptions for the prices of materials and energy, target products, and local legislation. Currently, the cost evaluation was mainly conducted from the life cycle perspective. Under the pre-conditions in the research of Tarpani and Azapagic (2018), pyrolysis was regarded as the most optimal alternative for sludge treatment due to relatively ideal energy recovery and mean sales of the products. The only sewage sludge pyrolysis plant in the world was claimed to close (Fonts et al., 2012). This fact leads the researchers and stakeholders to reflect how to overcome the technical difficulties, improve the economic benefits and adjust the management strategies to make it a feasible way for future sludge treatment.

Gasification provides a production pathway for gaseous products and solid char under high temperature (Hosseini and Wahid, 2016). It is regarded as an extension treatment for pyrolysis since gasification is generally operated at a higher temperature around 800-1400 °C with the air, or steam as the gasification agent (Manara and Zabaniotou, 2012; Syed-Hassan et al., 2017). Combustible gases include CH_4, H_2, and CO together with vapor, hydrocarbon, and tar are formed during the gasification process. The process is usually divided into four phases consisting of drying, pyrolysis, oxidizing stage, and reduction reaction. Detailed reaction principles were referred to the study of Manara adnd Zabaniotou (2012) and classification for different reactions occurring in gasification was reviewed by Syed-Hassan et al. (2017). Basic process of gasification was shown in Figure 2.4 (b).

Operation parameters which can put influence on the products yields and composition are considered to be gasifying agent, the applied gasifier, temperature, equivalence rate, the ratio of steam to material, and operation duration (Syed-Hassan et al., 2017). Steam gasification and higher temperature are in favor of the gas products yields and reducing the generation of tar. More specific analysis on the influences of the factors can be found in previous studies (Manara and Zabaniotou, 2012; Syed-Hassan et al., 2017). Carbon monoxide and hydrogen as the major gaseous products in the syngas have a typical content range as 6.28-10.27 vol% and 8.89-11.17 vol% (Fytili and Zabaniotou, 2008; Manara and Zabaniotou, 2012). A higher hydrogen content of syngas was obtained at 35-40 vol% by using steam as the gasifying medium from the sludge with hydro-char under the increased presence of alkali and alkaline earth metals (Gai et al., 2016). Since the relatively considerable hydrogen content in the generated gaseous products, gasification could be a feasible way to produce hydrogen with a further process which converts carbon monoxide into hydrogen to improve the total yield of this clean energy, i.e., steam reformation (Nikolaidis and Poullikkas, 2017).

However, some existing challenges impede the further application of the products and the promotion of this technology, such as the presence of impurities (tar) in the gas, high moisture content, and N, S composition in the raw material (Syed-Hassan et al., 2017). Additional investment for the purification and separation of the valuable products might be needed before the application of products for energy supply. Nevertheless, the investigation for economic estimation of gasification treating sewage sludge is rare, with an evaluation from the perspective of biomass at 1.77-2.05 USD/kg (1.39-1.61 GBP/kg), which had a high dependency on the assumptions of raw materials and plants operation status (Bartels et al., 2010; Nikolaidis and Poullikkas, 2017). Both the pyrolysis and gasification for sludge treatment are undeveloped technologies with a relatively low technology maturity compared to that of incineration (Samolada and Zabaniotou, 2014), which are introduced in Section 2.1.3.2.

2.1.3.2 Incineration

The moisture content of dewatered sludge can considerably reduced, which could be further processed by incineration or other post-treatment approaches (Fränzle et al., 2012). The organic substances in sludge are fully combusted with abundant oxygen and converted into CO_2, H_2O, and some other gaseous products during the incineration process (Wang et al., 2016). This operation involves with a series of complex changes and reactions, including evaporation, volatilization, degradation, sintering, melting, oxidation-reduction reactions accompanied by the corresponding comprehensive physical and chemical reaction process of mass transfer and heat transfer (Hirose et al., 2009; H. Li et al., 2013). Energy recovery through incineration majorly refers to the electricity and heat recovery system (Hong et al., 2009; Xu et al., 2014). Post-treatment for the residues consists of the process for ash which contains non-volatile heavy metal ions and exhaust gas disposal (Wang et al., 2016). Taking the technique of the fluidized-bed incineration as an example, the process was illustrated in Figure 2.5.

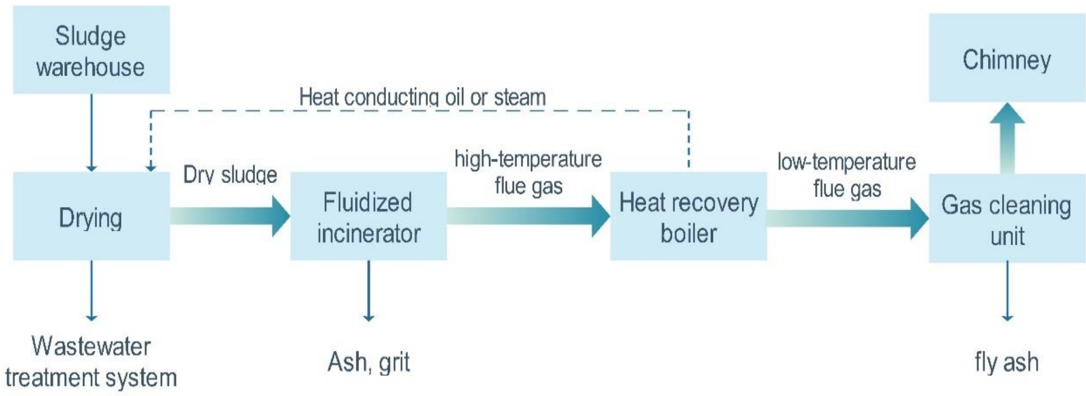


Figure 2.5 Flow sheet of fluidized-bed incineration system for sewage sludge (modified from Zhao (2018))

There exist two kinds of operation mode for incineration, direct-incineration and mixed-incineration. Based on the premise of moisture content and heating value, direct-incineration can be applied with or without auxiliary fuels. Several requirements for direct-incineration were listed in Table 2.1 which help to maintain the fuel consumption and costs in an acceptable range. Mixed-incineration means to burn the sludge with other combustible materials, which omits the step for drying with a relatively simple and convenient operation process compared with direct-incineration. More detailed characteristics for these two technologies were summarized by Li et al. (2013) and Zhou et al. (2008).

Table 2.1 Requirements on characteristics of sludge for incineration (H. Li et al., 2013)

Category	pH	Moisture content (%)	Low heating value (kJ/kg)	Organic matters content (%)
Self-sustaining incineration	5 – 10	<50	>5000	>50
Fuel incineration		<80	>3500	
Drying incineration				

Note: moisture content for drying incineration means the moisture content of input sludge to the drying system. Sand content is an important aspect to consider when choosing the type of incinerator.

Sludge retention time, operation temperature, air excess coefficient and the features of sludge are the major factors that can influence sludge incineration process. Burning is a process which required enough time to ensure the reactants have fully reacted. Retention time is associated with the particle size of sludge and smaller particle contributing to the effectively burning with quicker speed and less detention time (Yao and Naruse, 2005). In general case, increasing temperature could promote the incineration process to take place thoroughly within a very short duration. However, incineration with too high temperature may cause higher investments for fuels and secondary pollution resulted from increasing oxynitride in the exhaust gas. The reaction rate was sensitive to temperature during the low temperature phase but could not be increased significantly when the temperature was high (Li et al., 2005). Air excess coefficient can be expressed in Eq. (2.7),

$$\alpha = \frac{V}{V_0} \tag{2.7}$$

where α represents the air excess coefficient. V and V_0 mean the amount of actual air supply and theory air supply, respectively.

Enough oxygen supply is a necessary condition to guarantee the full combustion of organic matters in sludge which also contributes a lot to the drying and burning process. However, if the coefficient exceeds the suitable range, it could also cause a reduction in temperature and increase the emissions of exhaust gas (Wang et al., 2016).

Equipment applied in incineration majorly include the fluidized bed, multiple grate furnace, belt furnace, melting furnace, and rotary kiln. The fluidized bed as the most widespread facility for sludge incineration takes a major charge of the market with over 90%. Li et al. (2013) summarized the main characteristics of the fluidized bed and provided a brief introduction of multiple grate furnace and rotary kiln. Zhao (2018) gave a detailed description for rotary kiln incineration, fluidized bed incineration, and grate incineration technology.

Incineration is a traditional sludge treatment method with obvious advantages over landfilling and agricultural usage which leads it to be accepted as a widespread disposal option in Europe. The merits mainly manifest in the following aspects: (i) remarkable volume reduction which has been reported as about 10% to that of dewatered sludge; (ii) effective disposal for the toxic matters contained in sludge; (iii) possessing a comparable heating value with that of brown coal which provides a feasible way to conduct energy recovery simultaneously; and (iv) little odor generation (Fytili and Zabaniotou, 2008). Sludge treatment centered by incineration can achieve the most thorough degree of sewage sludge process from the perspectives of quantity reduction, stabilization, harmless treatment, and reutilization.

Although incineration has been regarded as one of the most promising methods for sludge treatment, the existence of several problems limits the development of it, including high operation costs, secondary contamination from the exhaust gas (Li et al., 2005), limited energy recovery rate, and unsatisfactory combustion stability of sludge (H. Li et al., 2013). The estimation for incineration costs varied with selected regions, which also showed a high dependency on the applied technologies and assumptions for the sales prices of the recovered energy (Qin et al., 2011; Tarpani and Azapagic, 2018). Future research for sewage sludge incineration should consider more about the optimization for operating conditions in order to realize the goal of low energy consumption, cost-efficient, high energy recovery rate, and low emissions to match the requirement of sustainable development.

2.1.3.3 Combustion

Generally, plenty of thermochemical treatment methods for sewage sludge are associated with the sludge combustion process. A detailed study conducted by Werther and Ogada (1999) provided comprehensive information regarding sludge combustion, covering the mechanism, influencing factors, mono- and co-combustion, equipment and other alternatives for sewage sludge treatment. The principle of sludge combustion is consistent with that of incineration. Gaseous products from combustion process are similar to those from pyrolysis which consist of H_2, CH_4, H_2O, and CO_2 (Magdziarz and Werle, 2014). Since the similarity of the characteristics of sludge combustion with other thermochemical processes (pyrolysis, gasification, and incineration), more specific information about combustion is omitted here which can be found in the previous studies (Font et al., 2001; Magdziarz and Wilk, 2013; Werther and Ogada, 1999).

2.1.3.4 Supercritical water oxidation and supercritical water gasification

Treated in supercritical water (SCW) with temperature higher than 374 °C and pressure higher than 22.1 MPa (Savage, 2002), the pre-drying step for sludge can be omitted which lead to a decrease on the sludge process expenditure. Three major technologies belonging to SCW treatment for sewage sludge consist of SCWG, SCWO, and supercritical water partial oxidation (SCWPO) (Qian et al., 2016).

Supercritical water oxidation is supposed to be a promising method to efficiently and completely decompose the organic matters in sludge with excess oxidants (Qian et al., 2016; Stendahl and Jäfverström, 2003). Some specific reactors equipped in research institutions and universities were summarized by Qian et al. (2016). 316L stainless steel batch reactor was found to be the most frequently used one. Reaction principles involving in SCWO are quite similar to those of SCWG, which was shown in Figure 2.6.

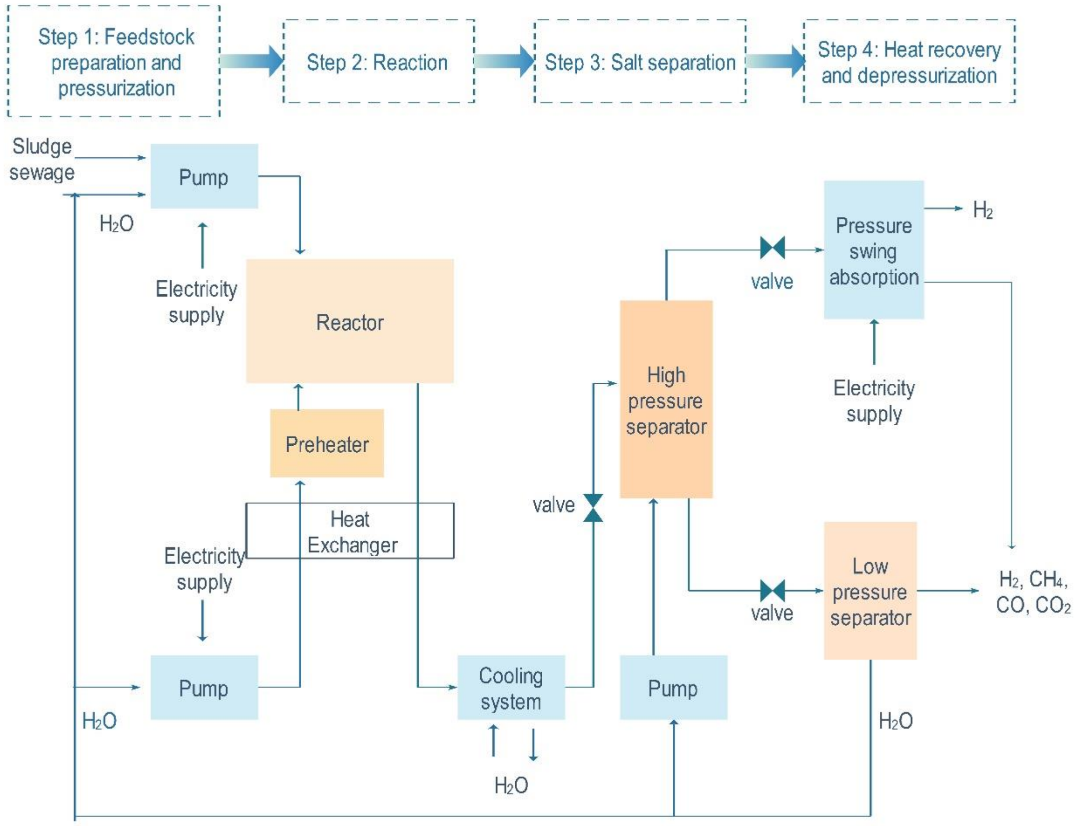


Figure 2.6 Technological process of hydrogen production from SCWG by sewage sludge (modified from Bermejo and Cocero (2006) and Hosseini and Wahid (2016))

The main propose of applying SCWO is to remove the total organic carbon (TOC), chemical oxygen demand (COD), and ammonia nitrogen (NH_3-N), and obtain treated effluents which meet discharge standards. Removal rates influenced by several operation conditions include operation duration, temperature, pressure, and properties of sludge (Qian et al., 2016). Energy recovery is not the primary consideration, but inorganic matters left in the residual ash, especially phosphate, can be recovered for further application, which has been investigated by groups of researchers (Acelas et al., 2014; Stendahl and Jäfverström, 2003). Except for the aforementioned factors, applied acid type also puts an impact on phosphorus release from the ash, which was recorded that the application of oxalic acid can result in a higher phosphate yield (more than 95% phosphate was recovered) compared with using sulfuric acid (Acelas et al., 2014). Other detailed information regarding the mechanisms of SCWO and the functional principles of different factors can be found in the previous studies (Bermejo and Cocero, 2006; Qian et al., 2016; Schmieder and Abeln, 1999; Stendahl and Jäfverström, 2003).

High content of hydrogen can be generated from sewage sludge by using SCWG or SCWPO. The following part focuses on SCWG technology and relevant information regarding SCWPO technique was referred to the research of Qian et al. (2016). The mechanism of relevant reactions in SCWG is similar to that of SCWO, which usually involves with three kinds of reactions (Eq. (2.8) - Eq. (2.10)) (Hosseini and Wahid, 2016). Apart from hydrogen (15-40 vol.%), methane (10-40 vol.%), carbon dioxide (20-50 vol.%), carbon monoxide and other kinds of hydrocarbons are also formed during the process (Amrullah and Matsumura, 2018). Research has shown that methane is preferred to generate with lower temperature and higher concentrations of dry solids in sludge (Rodriguez Correa and Kruse, 2018; Yan et al., 2006). Hence, maintaining a suitable combination of operation conditions for SCWG is necessary to obtain hydrogen-rich gas.

$$\text{Biomass+H}_2\text{O} \rightarrow \text{CO+H}_2 \tag{2.8}$$

$$\text{CO+H}_2\text{O} \rightarrow \text{CO}_2\text{+H}_2 \tag{2.9}$$

$$\text{CO+3H}_2 \rightarrow \text{CH}_4\text{+H}_2\text{O} \tag{2.10}$$

The performances of SCWG are primarily influenced by the characteristics of raw materials, substrates concentration, operating temperature, pressure, the oxidant coefficient, and catalysts (Qian et al., 2016; Reddy et al., 2014). Residence time also puts an impact on the liquid and gaseous products generation. Experiment results indicated that the generation of gases was favor with increasing temperature and duration, but it was also accompanied by a growing production of char when residence time exceeded 50 s at 600 °C. However, there was no significant increase in hydrogen production as the reaction progressed while the volume ratio of CO_2 raised remarkably (Amrullah and Matsumura, 2018). Char formation and energy released during the reaction were studied and results showed that total process was weakly exothermic when the temperature below 680 °C (Catello and Fiori, 2011). A series of experiments was conducted to study the influence of NaOH and Ni toward H_2 generation by SCWG. The highest hydrogen production as 4.8 mol/kg organic substrate was obtained with the presence of 3.33 wt% Ni and 1.67 wt% NaOH (Gong et al., 2014). Further introduction and analysis for the effect of different factors were summarized by previous studies (Y. Chen et al., 2013; Fan et al., 2016; Qian et al., 2016).

Technologies regarding SCW share similar advantages and shortcomings. Raw materials applied in SCWG and SCWO are allowed to be moist which directly lead to a decrease in the drying investment (Calzavara et al., 2005). Besides, less energy is required for hydrogen storage due to the high pressure during the operation. High efficiency at relatively low temperature also distinguishes SCWG from the other gasification technologies (Hosseini and Wahid, 2016). All these facts reveal that SCWG is a promising technique to obtain clean hydrogen from sewage sludge. However, it is the particularity of SCW that brings certain challenges to the promotion and development of this technology, which refer to corrosion, high operation cost, and plugging (Bermejo and Cocero, 2006; Catello and Fiori, 2011; He et al., 2014).

Improved equipment and optimized facility design are required to adapt to the changes in characteristics of water under specific operating conditions. The application of catalysts may contribute to the reduction of operation cost. Suitable process design may also be helpful to make SCWG a more cost-efficient technology compared with other methods. Nevertheless, it should be noted that the subdued solubility of inorganic catalysts may cause the plugging in the continuous reactor and the lifetime of catalysts would also be influenced under the unsuitable conditions. Relative solutions to these problems were provided by He et al. (2014) in detail. A design for the first SCWO plant of China was proposed which addressed the three technical problems in SCWO with description and experimental results (Xu et al., 2011). They also conducted a comparison of SCWO and incineration with the respect to the running costs. Results showed that facility investment for SCWO was higher than that of incineration at the same process capacity condition, but SCWO would show more superiority as the scale increasing. Future work could focus more on the process design, equipment improvement, and optimization to realize the reduction on investment and improvement on the total profits so that the techniques in SCW can be more competitive with others.

Environmental impacts assessment of SCWO for sewage sludge treatment was conducted with aspect to three environmental indicators, which showed that SCWO for undigested sludge is an environmental benign method especially with heat recovery from the process (Svanström et al., 2004). Economic analysis for hydrogen production by SCWG was estimated to be 2.3 EUR/GJ (2.01 GBP/GJ), which might be competitive with the production costs by natural gas reforming and electrolysis when meeting certain conditions (Gasafi et al., 2008).

2.1.4 Resources recovery from post-treatment

Sewage sludge ash (SSA) is usually generated after the incineration treatment, which could be a source of pollutant if without suitable process due to the potential high content of heavy metals. However, the possible application of SSA in the construction industry has gradually been recognized and drawn wide attention recently. Research has proved the feasibility of utilizing SSA for road construction and building materials production, including cement, bricks, ceramic and glass (Smol et al., 2015).

Although the composition of SSA has a high similarity with that of cement leading to the alike properties, some characteristics of SSA, like large particle size and higher content of SiO_2, may result in the unfeasibility of direct application of SSA for specific materials production (Chen et al., 2013). Important properties usually refer to moisture content, organic fraction, particle size distribution and chemical composition which can be detected by different kinds of technologies and measuring methods (Chakraborty et al., 2017; Chen et al., 2013). The analytic results obtained by the research of Chen et al. (2013) indicated that a remarkable decrease occurred in flexural and compressive strengths of the cement with high substitution ratio of SSA. However, if the substation ratio could be adjusted in a suitable range, the cement mixed with SSA could show a similar strength as the blank samples. Chakraborty et al. (2017) explored the appropriate mixing ratio of SSA with quicklime and blast furnace slag for a cementitious material production and results showed that 7:2:1 was an applicable ratio for both sustainable construction material production and waste management. More particular description about the industrial application of SSA can be found in the studies of Świerczek et al. (2018) and Smol at al. (2015). They both illustrated that SSA possesses a huge potential in industrial application and can promote the development of circular economy and help to achieve a sustainable society.

2.1.5 Discussion and analysis

2.1.5.1 Summarization of energy and resource recovery from sludge treatment

According to the above introduction of various sludge-to-energy technologies, there are generally three major kinds of energy forms which can be recovered from sewage sludge, including biofuels (bio-oil, and combustible gases), electricity and heat, with direct or indirect (needs upgrading or post disposal) application in transportation and electricity supply. Phosphorus recovery can be conducted by SCWG simultaneously which can be further applied to fertilizer production. Sewage sludge ash generated from thermochemical process such as incineration has high potential application value on construction materials production. Valuable products recovered from sewage sludge through a series of the process are summarized in Figure 2.7. The major features, including the merits and shortcomings, of different sludge treatment technologies are presented in Table 2.2.

Table 2.2 Major features of the reviewed sludge treatment technologies

Category	Technology	Major products	Merits	Shortcomings
Biological processes	Anaerobic digestion	Biogas (high CH_4 content)	Mild operation conditions. High technology maturity. Relatively low energy input.	Long period for reaction. Odors generation. Follow-up process is required.
	Anaerobic fermentation	Hydrogen (CO_2 mixed)	Mild operation conditions. Low energy input.	Long period for reaction. Requirement on light. Requirement on the area for the sunshine. Low energy efficiency. Low technology maturity.
	MFCs for electricity generation	Electricity	Direct electricity generation without energy form conversion. Mild operation conditions. Low additional energy input.	Low energy efficiency. Low technology maturity. Long period for reaction.
Thermochemical processes	Pyrolysis	Bio-oil, char, tar, hydrogen-rich gas (H_2, CH_4, CO, etc.)	Relatively high economic viability (Tarpani and Azapagic, 2018). Abundant additional products generation. The combustible gases can be efficiently converted into electrical power.	Complicated treatment process for the gases due to the existing of toxic pollutants in sewage sludge.
	Gasification	Char, tar, hydrogen-rich gas (H_2, CH_4, CO, etc.)		Under development.
	Incineration	Heat, electricity	Regarded as the most thorough way for sludge treatment.	High energy input. Emissions of pollutants and ashes. High requirement on the moisture content of sludge.
	Supercritical water oxidation & supercritical water gasification	Hydrogen-rich gas (H_2, CH_4, CO, etc.), phosphorus	No requirement on the moisture content of substrate. High efficiency at relatively low temperature (Liu et al., 2020a).	High requirements on the operating conditions and equipment. Possible corrosion, high operation costs and plugging (Liu et al., 2020a). Low technology maturity.

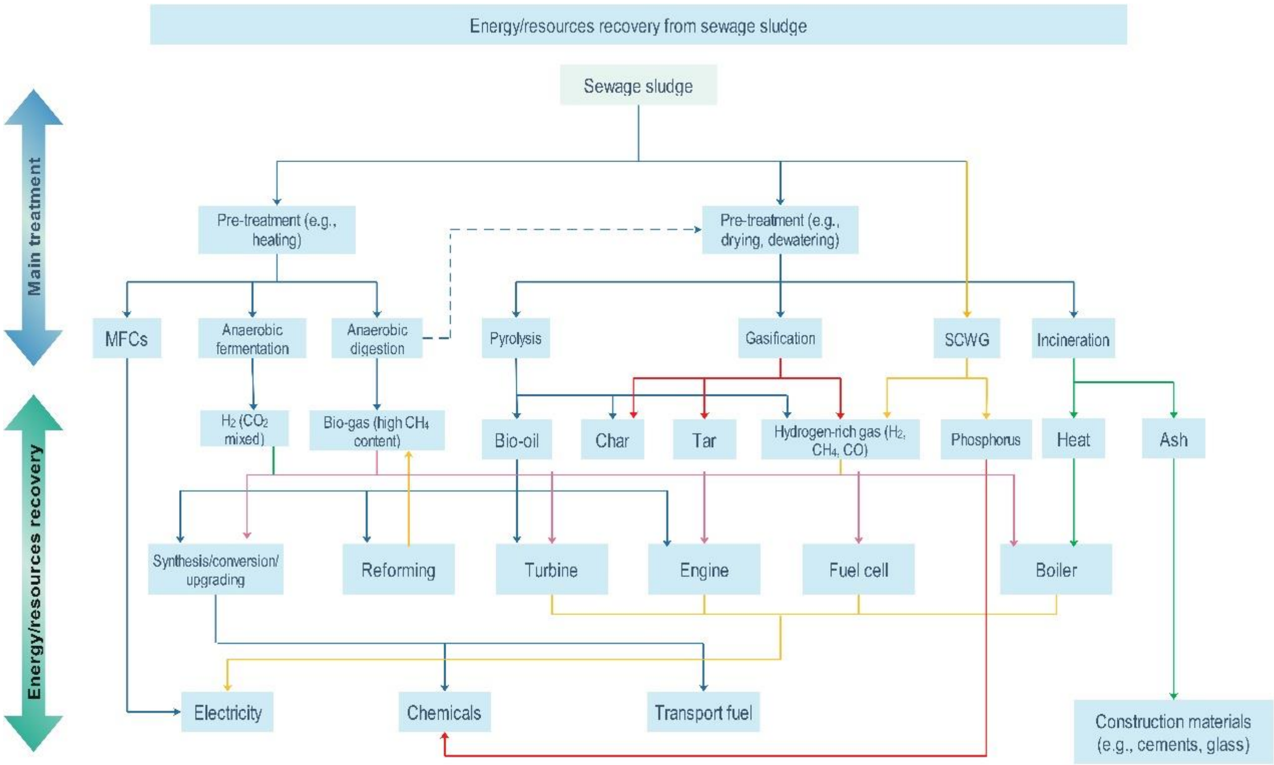


Figure 2.7 Products recovery from different treatment of sewage sludge (modified from Syed-Hassan et al. (2017))

Generally, simple process for sewage sludge may not bring it up to the discharge standards. Therefore, it is important to determine how to combine several treatment methods together in order to achieve the most complete treatment of sewage sludge and recycle energy and resources as much as possible. For instance, anaerobic digestion can be applied as a stabilization step followed by incineration or other thermochemical conversion with biogas and heat recovery from the process. Sewage sludge ash from incineration can be transported to construction industry for materials production (Hong et al., 2009).

2.1.5.2 Comparison and assessment

The treatment methods discussed in this work involve various forms of energy and resources recovery. It is necessary to investigate the performances of these disposal approaches on different aspects, such as technical, environmental, and economic perspective, to guide the future improvement of technologies and better sustainable development of waste management industry. Technical features for the selected technologies were summarized in Table 2.3.

Table 2.3 Technical performances of the sludge-to-energy technologies

Technology	Operation conditions	Maturity[a]	Reaction rate[b]	Recovered products: Major products	Recovered products: Yield or content
AD	Oxygen-free; suitable temperature and pH	***	*	CH_4	63 vol%
Anaerobic fermentation	Oxygen-free, suitable temperature and pH; light	*	*	H_2	1.267–3 mol H_2/mol substrate
MFCs	NPT	*	*	Electricity	0.2-200 W/m^3
Pyrolysis	Major in 350-500 °C, 0.1-0.5 MPa; oxygen-free	**	**	H_2	11-38 vol%[c]
Gasification	800-1400 °C; air or steam as gasifier agent	**	**	H_2	11-32.5 vol%[d]
Incineration	High temperature; dewatered sludge or co-incineration with other fuels	***	**	Heat; electricity	1024.5 kWh/t dry sludge[e]
SCWG	Wet environment; SCW	*	***	H_2	31-40 vol%[f]

a: Technical maturity was compared based on the work of Samolada and Zabaniotou (2014). Lab scale is represented by "*"; trial stage is for "**" and large pilot scale is for "***".

b: Similar with maturity, the increasing number of "*" means the faster reaction rate. Biological processes usually have low reaction speeds and long duration.

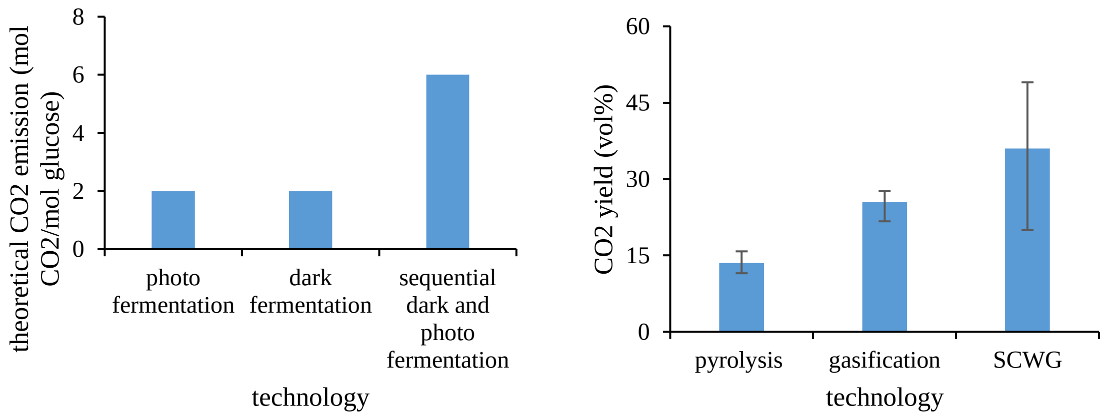
c: Data was summarized from the work of Xiong et al. (2009).

d: Summarized from Gai et al. (2016).

e: Data source (Xu et al., 2014).

f: Summarized from Amrullah and Matsumura (2018).

With the respect to energy recovery, hydrogen or hydrogen-rich gas can be obtained from anaerobic fermentation, pyrolysis, gasification, and SCWG. Biological process to produce hydrogen is relatively low investment requirement, but it is obviously limited by the plenty of operation conditions due to the features of microorganisms, as it is shown in Table 2.3. Long reaction duration is another drawback of biological methods and the total hydrogen yields are still unsatisfactory. Therefore, although biological method for clean hydrogen production is attractive because of the low costs and environmental benefit effect resulting from few fuel consumptions, it is still far from large scale industrial application. Compared with biological processes, thermochemical methods for hydrogen production possess certain technical foundation. Meanwhile, the reaction rates are superior to those of biological processes. The generated CO and CH_4 could be further reformed to improve the hydrogen production to some extent. However, the high operation and maintenance costs with relatively low energy recovery rates may lead to the financial loss of sludge treatment plant. Moreover, the increasing H_2 yields also companies with the increasing emission of CO_2, which may lead to the additional costs for CO_2 capture (see Figure 2.8). Technical maturity of these technologies is still limited compared with that of incineration. Hence, more efforts are expected to improve the technical pathway and optimize the total yields of hydrogen.



(a) biological methods (b) thermochemical methods

Figure 2.8 CO_2 emissions from sludge treatment technologies for hydrogen recovery (data sources for (b) are Amrullah and Matsumura (2018), Gai et al. (2016), and Xiong et al. (2009))

Electricity is another major energy form recovered from sludge treatment, which can be generated directly from MFCs or indirectly from other disposal approaches.

Electricity generation from MFCs seems to be more effective in terms of access because there is no conversion process, such as converting H_2 to electricity. Applying other methods to conduct electricity recovery always involves electricity conversion efficiency, which means that energy loss during the process is inevitable. Hence, MFCs has unique advantages for electricity production. Nevertheless, it is still limited by the poor current density and wide variation of COD removal rate. Improving the comprehensive performance of MFCs for sewage sludge treatment combined with electricity production is necessary for future development and application of MFCs technology. Further disposal for the raffinate is also worthy to explore aiming to choose a more suitable method for energy recovery and waste treatment.

Life cycle assessment (LCA) is a powerful tool to evaluate the environmental and economic impacts of sewage sludge technologies. There exists a certain amount of assessment work for several sludge-to-energy technologies using LCA to assess the environmental and economic impacts. Six scenarios with or without anaerobic digestion for sludge treatment were analyzed with the respect to environment and economy by Hong et al. (2009). Results revealed that the alternative with gasification and melting was more environmental beneficial and economically affordable. Investigation conducted by Xu et al. (2014) identified that the option with anaerobic digestion and incineration with energy recovery performed well on both environmental and economic aspect comparing with other options. Many studies indicated that incineration for dewatered digested sludge with energy recovery was more superior than other methods over the environmental and financial aspect (Lombardi et al., 2017;

Yoshida et al., 2018). A detailed life cycle analysis for sludge treatment with energy and resources recovery was investigated by Tarpani and Azapagic (2018). Their results showed that pyrolysis and anaerobic digestion could bring more profits considering the average amount of recovered products. A wider variety of life cycle cost (LCC), however, occurred in the pyrolysis process which was resulted from the changes of quality and quantity of products recovered. This fact led to anaerobic digestion becoming a more suitable method due to the well-established markets and wide application of recovered electricity from biogas. This study also reflected that estimation for LCC has a high dependency on the assumptions on the sales prices and products recovery rates. Hence, it is necessary to consider the specific conditions of the different regions. Current research spent fewer efforts on the evaluation of other aspects, such as technical and social perspective to take more indicators into account. Therefore, besides the optimization work on various sludge treatment technologies to improve the energy recovery rates, future research should also focus more on the assessment for specific energy forms recovery. Taking more comprehensive indicators into considerations is expected so that the analysis results can reflect all-sided performances of the alternatives and help stakeholders make the most suitable determination.

Based on the analysis and literature review above, anaerobic digestion followed by incineration can be regarded as a competitive scenario for converting sludge to energy. The technical maturity of these two technologies is acceptable and the complete degree of sludge treatment is acknowledged satisfactory. Meanwhile, the resources and energy generated in the process can offset parts of the investment and even bring profits if the technology can be well-developed.

2.1.6 Summary

This study reviewed the current main treatment technologies of sewage sludge combined with energy recovery, including anaerobic digestion and fermentation, MFCs, pyrolysis, gasification, incineration, and SCWG. Major mechanisms, effect factors, and major products generated during the progress and their yields were summarized and presented. The main forms of energy recovery from the treatment process include electricity and different kinds of biofuels. Clean electricity can be directly produced from MFCs for sludge treatment, or indirectly obtained by the conversion from the combustion of biofuels and heat from sludge incineration. Biofuels consisting of hydrogen, methane, and carbon monoxide can be got both biologically and thermochemically, which can be further converted into a purer energy form for application. Chemicals mainly refer to phosphorus and other byproducts recycled from the thermochemical process. Char generated from pyrolysis and gasification has the potential for absorbent production due to the surface structure. Sewage sludge ash left by the incineration process can be applied for construction materials like cement and glass. Hence, sewage sludge as a kind of waste initially can be converted into various valuable energy and materials by sludge-to-energy technologies, which can contribute a lot to the sustainable development of the society.

As an emerging branch of waste treatment, the maturity of most of the treatment approaches is limited. Based on the current assessment work, anaerobic digestion followed by incineration has the most beneficial effects both environmentally and economically owing to the considerable energy recovery and thorough treatment. Microbial fuel cells for electricity production is superior to other methods because of the omitted step for conversion. Hydrogen generation from SCWG is attractive distinguished by the fast reaction rate and unique characteristics of SCW which allows sludge to be treated without drying. However, the common drawbacks of all these technologies are the high operating costs and low energy generation yield and some of them may still face several technical problems, especially the technologies associated with SCW. Necessary external incentives are needed, and the government should manage to provide technical and financial support to promote the progress of relevant research. Since sludge-to-energy technologies can bring remarkable positive influence on society, more efforts on the improvement and optimization for the technical process and facility are still necessary, aiming to increase the energy recovery rates, reduce the total investment and make the technologies more affordable and even cost-efficient enough to be comparable with normal energy generation technologies.

2.2 Life cycle sustainability assessment and the application for different sludge-to-energy technologies

2.2.1 Background of sustainability and sustainable development

With the development of science and technology and the continuous growth of population, the total demand for resources is also increasing significantly. Nevertheless, considerable resources that are indispensable for people's daily life are non-renewable resources. Meanwhile, the environmental problems caused by the incontinence of development accumulated and eventually led to the gradually deterioration on the environment in many regions. Under current pressure and challenges faced in resources and environment, the concept of sustainability and sustainable development were proposed for the long-term development of the mankind (Ciroth et al., 2011; Keeble, 1988). It is an important concept as well as a principle of action which can even influence the development direction of a country and even the whole world.

Sustainable development can be a goal for better development which can balance the relationship between the development of human society and environment. It can also be regarded as an indicator to evaluate the extent to which it meets the requirement of sustainable development. Sustainability performance evaluation is an important branch in the domain of sustainability research. Reference data can be provided by sustainability assessment results, which can work as the basis for sustainable management of sewage sludge. Diverse approaches have been constructed and applied for sustainability assessment in different fields (Angelakoglou and Gaidajis, 2015). Although plenty of literatures were published on sustainability evaluation methods or the evolution of sustainable development goals (Griggs et al., 2013; Lu et al., 2015), the focus of these methods limited in some specific fields, including industrial water utilization (Willet et al., 2019), industrial systems (Angelakoglou and Gaidajis, 2015), transport infrastructure projects (Bueno et al., 2015). Hence, it is necessary to discuss the research on sustainability from a general point of view.

In this section, a comprehensive literature review on the related concept of sustainability and sustainable development is provided. Sustainability evaluation methods are roughly classified into six categories for brief introduction and qualitative comparison. Suggestion are put forward based on the analysis results to further improve and promote the development and application of these methods.

2.2.2 Methodology

The Scopus database (Scopus, 2020) was applied to identify the articles characterized by the terms, such as ”sustainability review” and ”sustainability assessment/evaluation”, in their title, abstract, and keywords. According to the database on Scopus (2020), over 28,000 pieces of work regarding the topic of ”sustainability” and ”review” or ”overview”. Environmental science took the dominant part in the related topics with around 17% of the total records. Social science and engineering also concerned a lot on the sustainability, which contribute about 14% and 11%, respectively. Energy field contributed about 8% in the topic of sustainability study (see Figure 2.9). The growing trend of publications related to sustainability reviews shown by Figure 2.10 reveals the raising concerns on sustainable development. More investigations were conducted on “sustainability assessment/evaluation”, nearly 50,000 records in the database on Scopus. The concerns on the research relevant to “sustainability assessment/evaluation” also increases as is shown by Figure 2.11. Hence, it can be found that research problems related to sustainability and sustainability evaluation has attracted more and more attention during recent decades. Among the publications, research papers occupy takes the majority, while the reviews only occupy about 7%. The publication structure is similar to the reviews on sustainability, with environmental science, social science and engineering occupying the major part (all over 10,000). 8,800 pieces of sustainability evaluation work were published on energy field. According to the above statistics records, there is a growing concern on research problems related to sustainability in many disciplines, especially in engineering and energy fields.

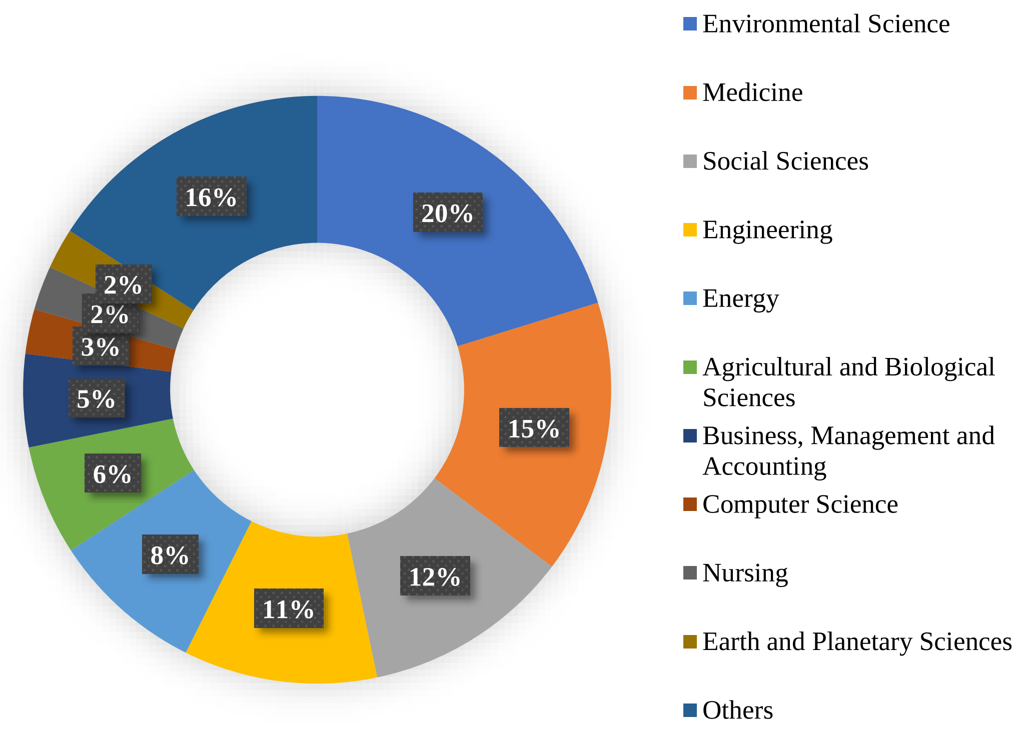


Figure 2.9 Percentage contribution of reviews in different disciplines on “sustainability” and “review” or “overview”

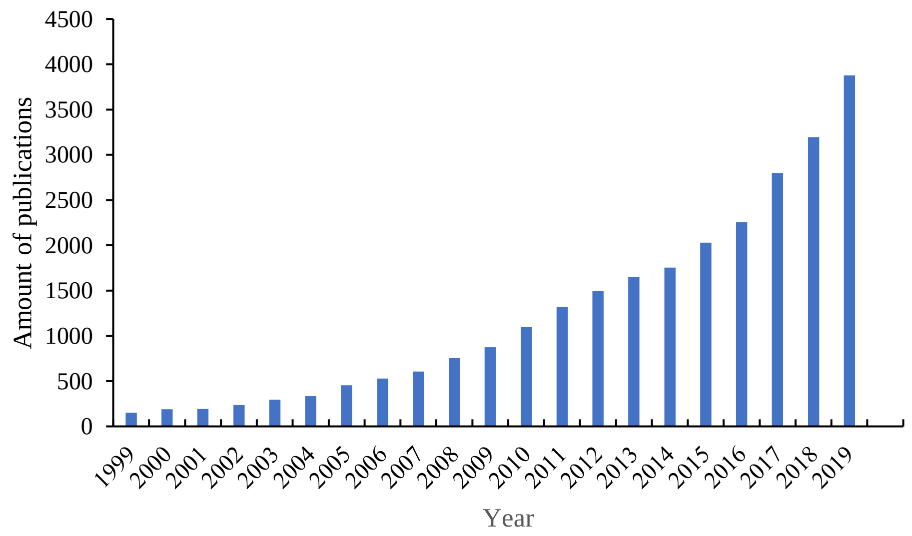


Figure 2.10 Publications on ”sustainability” and ”review/overview” from 1999 to 2019 (Scopus, 2020)

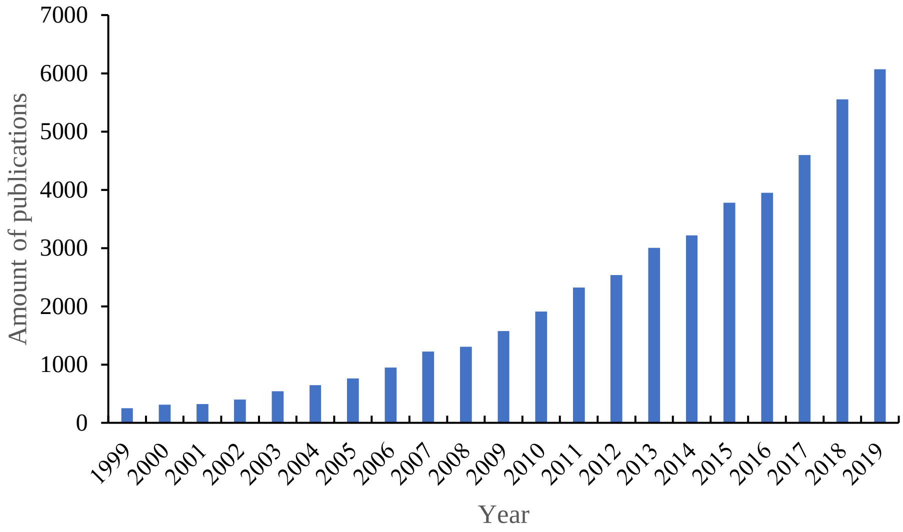


Figure 2.11 Publications on ”sustainability evaluation/assessment” from 1999 to 2019 (Scopus, 2020)

Since life cycle sustainability assessment (LCSA) is a powerful tool which is frequently applied in different fields for sustainability assessment, keywords “life cycle sustainability assessment” and “life cycle assessment (LCA)” were also investigated to analyze the research trend (see Figure 2.12). More than 7,000 pieces of papers published with the topic related to LCA over the past two decades. Research articles contributed to over 60% in the total records while overviews only occupied around 7%. Environmental science, engineering and energy take the top three among the total related publications on LCSA or LCA, which indicates the close relationship between these disciplines and sustainability and the growing concerns on sustainability performances.

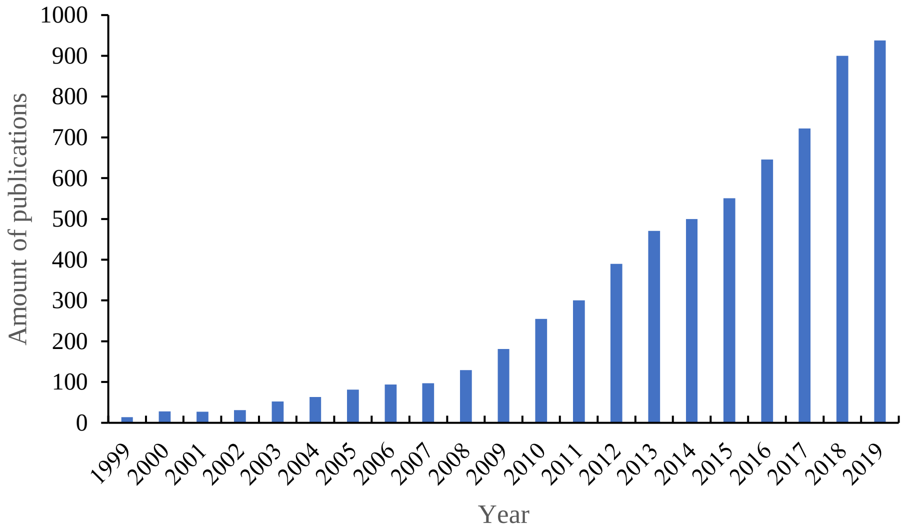


Figure 2.12 Publications on ”life cycle sustainability assessment” or ”life cycle assessment” (Scopus, 2020)

The importance attached to sustainability and sustainable development gradually increases according to the above data and discussion. Although there are considerable studies on sustainability and sustainable development, related reviews are still limited with only about 5% of the total records. Therefore, it is believed that a review on related concepts and methods on these topics is necessary for better understanding of sustainability.

In this chapter, the reviewed articles were collected by Google Scholar, majorly from the database of Scopus. By using the keywords of “sustainability”, “sustainable development”, and “sustainability evaluation or assessment”, related studies were searched and filtered out. The title, keywords, and abstract were checked to verify whether the investigation can provide significant information on sustainability. Articles will be checked in detailed to collect helpful information if the summary in the abstract is found to be useful.

2.2.3 Overview

2.2.3.1 Sustainability and sustainable development

The term ”sustainability” is derived from a Latin word ”sustinere” which means to hold up (Onions and Charles, 1964). Sustainability refers to the process of maintaining the environmental balance and harmony in resource development, investment direction, technological development and institutional change when the human being seek for the social progress. The concept of sustainability became to attract attention and gradually developed from the 1980s. The most widely accepted definition of sustainability is the one proposed by the World Commission on Environment and Development (WCED). The definition points out that sustainable development refers to the development form which can satisfy the needs of current society without compromising the requirement of development for future generation (Ciroth et al., 2011; Keeble, 1988). Environment, economy, and society are three perspectives that are commonly discussed in sustainability problems (Capra and Luisi, 2012). Cultural, technological and political aspects are also considered as the sub-domains of sustainable development, which are presented in Figure 2.13 (James, 2014; Magee et al., 2013). More recently, a new systematic domain model consisting of economic, ecological, political and cultural four dimensions was proposed which accords with the United Nations, Unesco, and Agenda 21, especially the culture as the fourth dimension of sustainable development (James, 2014).

Economics Production & resourcing Exchange & transfer Accounting & regulation Consumption & use Labour & welfare Technology & infrastructure Wealth & distribution	**Ecology** Materials & energy Water & air Flora & fauna Habitat & land Place & space Constructions & settlements Emission & waste
Politics Organization & governance Law & justice Communication & movement Representation & negotiation Security & accord Dialogue & reconciliation Ethics & Accountability	**Culture** Engagement & identity Performance & creativity memory & projection Belief & meaning Gender & generations Enquiry & learning Health & wellbeing

Figure 2.13 Four domains of sustainability adopted by the UN and Metropolis Association (James, 2014)

Sustainability can be simply understood as improving the quality of human life within the capacity of eco-system (IUCN/UNEP/WWF, 1991). Responsibility and proactive decision-making and innovation are usually required to reduce and minimize the negative influence and maintain the balance between ecology, economy, policy and culture (Magee et al., 2013). Different specific types of sustainability are included in sustainable development which can be reflected by different fields, such as sustainable agriculture, sustainable architecture, and sustainable supply chain (Costanza and Patten, 1995; Mota et al., 2015). Researchers in different fields have conducted many efforts to explore related problems on sustainability for better development of the whole society. A critical review on sustainable development was presented and the existing problems were also discussed in the early 1990s (Lélé, 1991). The challenges and opportunities for sustainable development of current society were analyzed and summarized in the previous book (Elliott, 2008). Specific goals were set and explained in the document of the United Nations to promote the understanding of the tasks for sustainable development aiming at the achievement of better development mode by 2030 (Ferri, 2010). Five priorities of the UN sustainable development goals were proposed and the importance of measurement and evaluation methods were emphasized since they have significant influence on reflecting the sustainability performance (Lu et al., 2015), which indicates the significance of sustainability evaluation methods in sustainability related research, which are introduced in the next section.

2.2.3.2 Sustainability assessment methods

Many attempts have been conducted by scholars for developing new sustainability evaluation methods or improving the exisiting approaches. Table 2.4 provides a brief summarization for previous studies and reviews on sustainability evaluation methods.

Table 2.4 Major information about related reviews and studies on sustainability evaluation methods

Reference	Major information on reviewed/research content	Number of review methods
(Angelakoglou and Gaidajis, 2015)	Sustainability assessment methods which can be applied for environmental performance evaluation by industries.	48
(Sala et al., 2015)	Provide a innovative and systemic framework for sustainability assessment to support the decision-making process.	N.A. (analysis)
(Poveda and Lipsett, 2011)	Fundamental methods, specific and integrated strategies as well as credit weighting tools for sustainability evaluation in large industrial projects.	66
(Singh et al., 2009)	Sustainability indicators applied in decision and policy making according to the classification.	61
(Cinelli et al., 2014)	Evaluate the potential of MCDM approaches on sustainability assessment.	5 (MAUT, AHP, PROMETHEE, ELECTRE, and DRSA)
(Gibassier and Alcouffe, 2018)	Review and analyze the relationahip of EMA and environmental management controls (EMCS) with sustainability.	2
(Campos-Guzmán et al., 2019)	Sustainability assessment tools which can be applied for renewable energy systems (focused on LCA and MCDM)	N.A.
(Sala et al., 2013a)	Analyze the main characteristics of sustainability assessment methods and discuss the major aspects for	N.A.

	improving the robustness and comprehensiveness of sustainability evaluation.	
(Székely and Knirsch, 2005)	Review the best available indices applied by twenty German companies for sustainability evaluation.	13
(Willet et al., 2019)	Sustainability assessment methods applied in industrial water systems belonging to five categories were reviewed.	82
(Turkson et al., 2020)	Provide a systemetic review on the framework of sustainability assessment for energy production regarding the methods, measurement, and issues.	N.A.
(Bueno et al., 2015)	Provide an overview for the sustainability evaluation tools applied in transport infrastructure projects.	12
(Luthra et al., 2015)	Apply fuzzy AHP method to identify and rank the influencing factors to construct a sustainability assessment framework for energy management in India.	N.A.
(Gil and Duarte, 2013)	Provide a review for the state-of-ar of sustainability evaluation tools which can be applied in urban design and management.	11
(Gbededo et al., 2018)	Present a systemetic review on the sustainabille manufacturing methods (focused on LCA)	N.A.

According to the above literature review and Table 2.4, LCA and MCDM are powerful tools for sustainability assessment. Considerable studies were conducted to apply LCA and MCDM based approaches in sustainability evaluation. The discussion on ingrated framework of LCA and MCDM for sustainability evaluation of renewable energy systems was carried out to analyze the application potential in this field by reviewing 154 relevant cases (Campos-Guzmán et al., 2019). The analysis results showed that individually using LCA or MCDM could not realize a comprehensive sustainability assessment while hybrid framework of these two tools could work as a satisfied approach for sustainability evaluation. A review on social sustainability was carried out to discuss the research state-of-art on social sustainability especially for the classical and emerging themes and assessment methods (Colantonio, 2009). Through analyzing the progress in sustainability science and existing sustainability evaluation methods, Sala et al. (2013a) pointed out that life cycle-based methods and LCSA make significant contribution to sustainability evaluation. The strengths and weaknesses of utilizing LCSA were investigated from the ontological, epistemological and methodological aspects (Sala et al., 2013b). The state-of-art of LCSA for products was analyzed by Kloepffer (2008) and the research revealed that environmental LCA and life cycle cost (LCC) have a relatively complete reserach foundation while social life cycle sustainability assessment (SLCA) is still under development. By reviewing 340 papers on sustainability assessment for industrial water application, 82 methods were identified which were further classified into five major cate categories, including key performance indicators, composite indices, environmental acconting, material and energy flow analysis and life cycle analysis (Willet et al., 2019). The authors found that material and energy flow analysis presents a satisfactory performance combined with sustainable systems indicators (SSIs). Bond et al. (2012) also conducted an analysis for the development state-of-art of sustainability evaluation methods and assessed the basic performance of these approaches from six crtieria. Except for MCDM and LCA, exergy analysis and other optimizaition-based methods, like multi-objectice optimization model, can also be applied for sustainability assessment (Turkson et al., 2020).

In order to provide clearer summary and facilitate the related analysis on the assessment approaches, it is necessary to figure out the categories of the methods. There is no unified classification standard for sustainability assessment methods. The researchers usually classfied the evaluation approaches according to their research purpose and focused field. Several classification approaches for the evaluation methods are summarized in previous reviews (Angelakoglou and Gaidajis, 2015; Singh et al., 2009; Willet et al., 2019) and shown in Table 2.5.

Table 2.5 Classification of sustainability assessment methods in different references

Reference	Classification	Standard of classification
(Ness et al., 2007)	i) Indicators (integrated and non-integrated) ii) Methods which are product-oriented; iii) Methods which are project- and policy-oriented.	According to the applied inticators and objectives.
(Poveda and Lipsett, 2011)	i) Generic methods; ii) Strategic methods; and iii) Integrated approaches.	According to the function and objective.
(Gasparatos, 2010)	i) Reductionist methods; and ii) Non-reductionist methods.	Whether the method is reductionist or not (broad general categories).
(Székely and Knirsch, 2005)	i) Surveys; ii) Criteria of stakeholders; iii) Reward projects; iv) Benchmarking; v) Sustainability indices/indicators; vi) External communication approaches; vii) Accreditation procedures; viii) Sustainability performances metrics; and ix) Non-quantifiable alternatives.	According to the conducting core thought.
(Angelakoglou and Gaidajis, 2015; Willet et al., 2019)	i) Indicators set; ii) Composite indices; iii) Socially responsible investment indicators; iv) Energy and matters flow analysis; v) LCA; and vi) Environmental acconting.	According to the focus and research purpose.
(Singh et al., 2009)	i) Economic approaches; ii) Physicial indicators.	Whether the method is economiy-oriented.
(Turkson et al., 2020)	i) MCDM methods; ii) Exergy analysis; iii) LCA; iv) Optimization-vased methods.	According to the core thought.
(Bueno et al., 2015)	i) Conventional decision-making methods (CBA, MCDA, LCA, SCLA, etc.); ii) Sustainability rating systems; iii) Other approaches which can address the sustainability appraisal (e.g., framework, guidlines, models).	N.A.

Since the major forcus of this chapter is on environmental sustainability and sustainable development of energy industries, the sustainability evaluation methods are classsified into the following six categories based on the previous reviews (Angelakoglou and Gaidajis, 2015; Willet et al., 2019), where MCDM is combined with the category of LCA since they are frequently applied together especially in the research related to sustainable energy development. The basic introduction, such as definition, features, advantages and disadvantages, of each category is summarized and shown in Table A1.1 in Appendix Part I. Some typical examples of sustainability assessment methods belonging to different categories according to the classification and corresponding information of each method are presented in Table A1.2. More detailed introduction can be found in the related references and previous reviews (Angelakoglou and Gaidajis, 2015; Poveda and Lipsett, 2011).

In order to have a better understanding of potential and ability of the different sustainability evaluation methods in sustainability assessment, an analysis and comparison alongside several importance criteria is conducted in the next section to investigate the performance of different sustainability evaluation methods.

2.2.4 Methods comparison and discussion

Due to the existence of a large number of sustainability assessment methods, it would be difficult to conduct comparison and evaluation by methods because it could require plenty of data, time and efforts. Meanwhile, evaluating by methods may only be applicable to a limited number of methods and lose the generality to the other approaches. Therefore, evaluation for the sustainability assessment approaches conducting by categories is suggested to keep the generality and cover a wider range of methods, which can also contribute to the improvement of the assessment methods (Angelakoglou and Gaidajis, 2015). Evaluation criteria are important reference to assess the ability of various sustainability assessment approaches. Different resaerch may build up the assessment system by considering different criteria due to the diverse focus and research objectives. Some criteria considered in previous studies have been summaried in Table 2.6. More detailed description can be found in the corresponding references.

Table 2.6 Considered indicators for the sustainability evaluation methods in different literatures

Reference	Criteria
(Angelakoglou and Gaidajis, 2015)	1. Potential of promoting actions for improvement. 2. Potential of helping with the decision-making process. 3. Potential for benchmarking. 4. Applicability and convenience of application. 5. Integration of wider spatial and temporal features.
(Sala et al., 2015)	1. Boundary-orientatedness. 2. Comprehensiveness. 3. Integratedness. 4. Involvement of stakeholders. 5. Expansibility. 6. Transparency. 7. Core thought of the evaluation method.
(Cinelli et al., 2014)	1. Applicability of qualitative or quantitative data. 2. Whether the method can be applied to analyze the influence throughout all the considered life stages. 3. Weighting approach. 4. Application of thresholds values. 5. Conpensation extent. 6. Uncertainty and sensitivity analysis. 7. Robustness. 8. Software support and graphical illustration. 9. Convenience of application. 10. Educating dimension.
(Sala et al., 2013b, 2013a)	1. Core thought of the assessment method (value choices, scopr's completenss, strategicity,). 2. Features of the method (integratedness, applicability and comparability, robustness, involvement of stakeholders)
(Bond et al., 2012)	1. Effectiveness on the procedures. 2. Effectiveness on the factual outcomes. 3. Transactive effectiveness; 4. Effectiveness on normalization. 5. Satisfactory of the related parties. 6. Potential of promoting the related knowledge and information.
(Bueno et al., 2015)	1. Full approach (can evaluate the three sustainability dimensions). 2. Life cycle thinking (investigate the entire life cycle). 3. Reliablt methodologies for the comparison of all trade-offs. 4. Flexibility and adatability to the aplied context. 5. Transparency.

According to the Table 2.6, some common criteria can be found in different references as the key points for the evaluation toward sustainability assessment methods, such as the effectiveness of indication on sustainability performance, potential of further improvement on sustainability performance, and applicability. In this section, a criteria system for the evaluation of sustainability assessment methods is built up based on the above literature review. The classification of the criteria applied in this work follows the categories proposed by Bockstaller et al. (2009), including scientific soundness, feasibility, and utility. Detailed criteria framework and corresponding description are shown in Table 2.7.

These criteria are selected to evaluate the potential of sustainability assessment methods from the perspective of the features of methology, application and learning dimension. The indicators of methodology perspective can address the inherent characteristics of the corresponding methods, such as the comprehensiveness (the number of addressed pillars), the ability of treating uncertainty and involvement of stakeholders. Sustainability assessmenr problems can be complex in the practice especially which plenty of conflicting factors and interests are considered in the evaluation. Therefore, it is expected that the sustainability assessment methods could be widely applicable with acceptable stability. Indices in applicaiton aspect reveal the convenience level in practical applications. Software support and ease of use can help to describe the convenience of applying the assessment methods. Graphic representation can provide more intuitive information and assessment results which may contribute to the understanding of the final evaluation results for stakeholders, especially those without professional background knowledge. Learning dimension is also an essential aspect for the sustainability evaluation approaches since it indicates the evaluation ability and impilication for better sustainable development and management in the related field in the future, which is a major forcus of this kind of research. Stakeholders also expect to learn more information from the assessment result in order to guide the future development of related industry. According to the criteria system and corresponding checklist, the number of asterisk (*) indicate the potential and ability for sustainability evaluation of the investigated methods categories. More asterisks mean higher potential and ability on sustainability assessment.

Table 2.7 Criteria system for evaluation of the sustainability assessment methods

Aspect	Criterion/issue	Checklist
Scientific soundness	C1: Can methods indicate the sustainability performance on the three pillars (environment, economy, society)[1]	Only one of the three pillars (*), two of the three pillars can be address (**), three pillars (or more) can be addressed (***).
	C2: Can methods be conducted with life cycle thinking?[2]	No (*), Yes (**).
	C3: Can methods be applied at small or medium scale and address the sustainability performance across time?[3]	Neither of them is satisfied (*), only one of the conditions can be satisfied (**), both conditions can be satisfied (***)[4].
	C4: Ability and effectiveness of treating uncertainty[2]	Can be combined with other methods for uncertainty analysis (*), inherent properties of the methods allow them handle the uncertainty (**).
	C5: Involvement of stakeholders[1,3].	Basic communication (*), and basic interactionsi in serveral specific stage (**), and close interactions along all stages (***)[1,3].
Feasibility	C6: Can methods easily be applied by non-professionals?[4].	No (*), Yes (**).
	C7: Whether methods have software support?[2]	No (*), Yes (**).
Utility	C8: To what extent can methods promote the further improvement and sustainable development of the investigated systems?[4]	No promotion or low promotion (*), can offer useful suggestions for the promotion (**), can provide effective suggestions for better sustainable development (***)[4].
	C9: To what extent does the sustainability assessment methods promote the conceptual learning?[5]	Relatively low (*), medium (**), relatively high (***).

[1] (Sala et al., 2013a); [2] (Cinelli et al., 2014); [3] (Sala et al., 2015); [4] (Angelakoglou and Gaidajis, 2015); [5] (Bond et al., 2012)

After the establishment of the criteria system, qualitative analysis and comparison for the sustainability assessment methods categories can be conducted accordingly. The detailed results are shown in Table 2.8.

2.2.4.1 Assessment results on scientific soundness

The ability of revelation on the sustainability performance on the three sustainability pillars (i.e., environment, economy, and society), is regarded as the comprehensiveness of the sustainability assessment method category. Except energy and matters flow analysis and environmental accounting, the other sustainability assessment method categories possess the potential of providing a comprehensive sustainability assessment on the three aspects. The former three method categories can reflect the performance on the three pillars by selecting indicators related to the corresponding aspect (Angelakoglou and Gaidajis, 2015). The inherent framework of LCSA has provided the assessment for the three aspects, that is LCA (environment), LCC (economy), and SLCA (society) (Ciroth et al., 2011). MCDM can also assess the investigated system from the three sustainability dimensions through constructing a criteria system covering all the aspects (Wang et al., 2009). Although energy and material flow analysis can promote the development on the socioeconomic and environmental aspect through investigating the material and energy flow efficiency (Huang et al., 2012), the category of assessment methods focuses more on environmental and economic perspectives. Similarly, environmental accounting methods are more inclined to address the sustainability performance on environmental and economic perspectives (Angelakoglou and Gaidajis, 2015), which makes it less prior in the criterion of comprehensiveness.

As for the life cycle thinking aspect, all the categories can be conducted alongside life cycle thinking to analyze the sustainability performance in the whole life stages. It is an inherent requirement for LCSA to conduct the sustainability analysis with life cycle thinking while others may not necessarily proceed with life cycle approach.

The scalability of sustainability assessment methods can influence their flexibility and applicability. Those with higher scalability can usually be applied on a wider scale and more flexible manners. However, some methods may have requirement on the data scale which would limit the applicability to small or medium scale industries. Individual or set of indicators and environmental accounting can be applied in small or medium scale, while the others without the applicability in such range (Angelakoglou and Gaidajis, 2015). LCSA usually can be applied in a relatively large scale such as urban or national context, but generally it is not applied into a larger scale like global range due to the specific features in different regions. The assessment results obtained by LCSA still significantly influenced by the features of the investigated region and assumptions on the examined systems (Tarpani and Azapagic, 2018).

Uncertainty and sensitivity analysis are important sections in the sustainability assessment due to the uncertainty introduced by imported data and subjective description. All the methods categories have the potential of treating the uncertainty in the evaluation by combined with interdisciplinary theory, such as probability theory (Guo and Murphy, 2012), stochastic process and Monte-Carlo method (Pereira et al., 2014). Reversely, some MCDM methods are supposed to have the potential to deal with the uncertainty by inherent features (Buchholz et al., 2009; Cinelli et al., 2014). Fuzzy theory combined with MCDM, which is so called fuzzy MCDM, can also help with uncertainty treatment (Hsieh et al., 2004; Mardani et al., 2015a). Most of the methods can be adequate for uncertainty treatment although varying with extent.

Both sustainability assessment and decision-making process have close relationship with stakeholders. Timely feedback and full interaction contribute to better acquisition of information and understanding the demands of stakeholders (Sala et al., 2013a). However, the involvement of stakeholders is still unsatisfactory in many approaches (Sala et al., 2015, 2013a). The involvement of stakeholders in current sustainability assessment methods is mainly limited in the criteria system constructing stage and weighting stage. This disadvantage is obviously reflected in life cycle-based methods since the development of the methods for the involvement with stakeholders remains in the early stage (Sala et al., 2013a).

2.2.4.2 Assessment results on feasibility

Ease of use reflects the complexity, acceptance, and the applicability degree to non-professionals of the sustainability methods. Some methods can be easy to understand and convenience to operate even without professional training, like AHP approach (Saaty, 1987) and best-worst method (Rezaei, 2015), while some could be difficult for non-experts to get started. The former three evaluation method categories share the similar complexity level and are frequently applied by industries, especially the individual or set of indicators (Angelakoglou and Gaidajis, 2015). LCSA and energy and material flow analysis require reliable data analysis which may increase the time and effort spending on sustainability evaluation by these two types of categories. The challenge that environmental accounting facing with is to converting diverse environmental parameters into monetary costs, which can be difficult to employ without clear guidance (Angelakoglou and Gaidajis, 2015).

Although the latter three method categories are inferior in the complexity, the software support and graphic representation can counteract the negative effects generating from the complexity to some extent, such as the database (GaBi, and Ecoinvent) for LCA, Sankey diagram for energy and material flow analysis, and some available tools for environmental accounting (Greenbase, Botkeeper, and Sphera).

2.2.4.3 Assessment results on utility

It is critical for the sustainability evaluation method to clearly indicate the sustainability performance of the investigated system and promote the management and development of related industry. This issue is evaluated by the ability and potential of promoting actions of improvement of the sustainability assessment methods category (Angelakoglou and Gaidajis, 2015). It is recognized that both LCSA and MCDM can provide relatively reliable sustainability evaluation (Angelakoglou and Gaidajis, 2015; Campos-Guzmán et al., 2019). LCA with ISO 14040 framework can provide with a partially sustainability evaluation while LCSA can provide a complete evaluation because the three sustainability dimensions are all covered. Similarly, MCDM can also be reliable complete sustainability evaluation tool since the consideration on the three pillars. The combination of LCA (or LCSA) with MCDM can achieve a relatively satisfactory evaluation effect with the completeness on considered aspects and the objectivity provided by LCA (Campos-Guzmán et al., 2019). Hence, more implications and targeted measures can be proposed according to the assessment results obtained by LCSA and MCDM. Energy and material flow analysis can offer useful suggestions for improving conversion efficiency. Other categories are also possible to provide valuable help for sustainable development through their specific feature, which can be referred to the review of Angelakoglou and Gaidajis (2015).

The learning dimension of sustainability evaluation method mainly reflected by the ability of revelation on the information and conducting cross-comparison among different industries. Cross-comparison is an important aspect for sustainability research especially for finding out better sustainable strategy. Life cycle-based methods show the advantages on cross-comparison since all the influence in the entire life stages are considered, which make the comparison between different systems be possible. Relatively speaking, methods included in individual or set of indicators are inferior in this aspect (Angelakoglou and Gaidajis, 2015). Bond et al.(2012) analyzed the merits and shortcomings on knowledge and learning aspect of current sustainability practice. Their analysis pointed out that although the methods can promote the implement of sustainable policy and planning in related industries, the follow-up investigation on the system is limited, which means that more efforts are still needed for further practice and reflection.

2.2.5 Discussion and implications

Evaluation result shows that LCSA combined MCDM can perform as reliable sustainability evaluation tool, followed by composite indices and energy and materials flow analysis. Individual/set of indicators and environmental accounting are not preferred in the evaluation results in the context of this section due to the unsatisfactory performance on scientific soundness and utility. The qualitative evaluation results in this section is similar to the analysis of previous study (Angelakoglou and Gaidajis, 2015), which also indicated the advantage of LCA. The difference between the evaluation results may be resulted from the difference between evaluation system and inspection criteria. The sustainability evaluation ability of LCA and MCDM has also be recognized by Campos-Guzmán et al (2019) through detailed analysis and comparison. Hence, it can be found that the potential of LCSA and MCDM for sustainability assessment has been gradually recognized and accepted.

Some limits and shortcomings can be found based on the above analysis and discussion. Suggestions are accordingly proposed to promote the improvement and development of the sustainability evaluation methods to achieve better sustainable development (Figure 2.14).

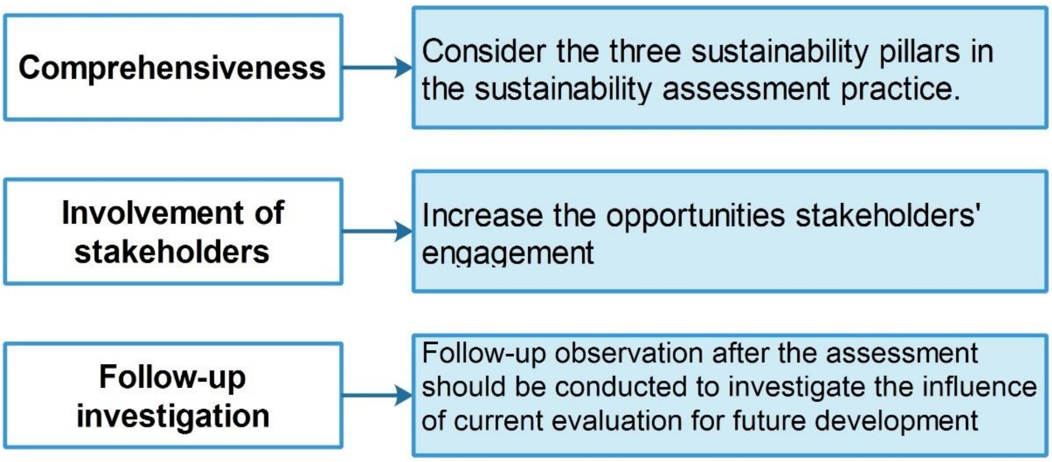


Figure 2.14 Development advice for sustainability assessment approaches (modified from (Bond et al., 2012))

Table 2.8 Qualitative assessment for the sustainability evaluation approaches based on classification

Perspective	Criteria	Indicators sets	Composite indices	SRI indicators	EMFA	LCSA and MCDM	Environmental accounting
Scientific soundness	C1	∗∗∗[1, 2]	∗∗∗[1, 3]	∗∗∗[1]	∗∗	∗∗∗[5]	∗∗[1]
	C2	∗∗[1, 6]	∗∗[1, 7]	∗∗[5]	∗∗[8]	∗∗[5]	∗∗[6]
	C3	∗∗[1]	∗∗∗[1]	∗∗[1]	∗∗∗[1]	∗∗∗[1, 7]	∗∗[10]
	C4	∗	∗	∗[9]	∗	∗∗[11]	∗[12]
	C5	∗	∗	∗	∗	∗[13]	∗
	Total	9	10	9	9	11	8
Feasibility	C6	∗∗[1]	∗∗[1]	∗∗[1]	∗[1]	∗[1]	∗[1]
	C7	∗[1]	∗[1]	∗[1]	∗∗[1]	∗∗[1]	∗∗[1]
	Total	3	3	3	3	3	3
Utility	C8	∗∗[1]	∗∗[1]	∗∗[4]	∗∗∗[1]	∗∗∗[1]	∗∗[1, 4]
	C9	∗[1]	∗∗∗[1]	∗∗[1]	∗∗	∗∗∗[4]	∗∗
	Total	3	5	4	5	6	4
Overall score		15	18	16	17	20	15

1 (Angelakoglou and Gaidajis, 2015). 2 (ALwaer and Clements-Croome, 2010). 3 (Talukder et al., 2017). 4 (Willet et al., 2019). 5 (Campos-Guzmán et al., 2019; Ciroth et al., 2011). 6 (Azapagic and Perdan, 2000). 7 (Hermann et al., 2007). 8 (Rincón et al., 2013).

9 (Koellner et al., 2007). 10 (Bueno et al., 2015). 11 (Geisler et al., 2005; Guo and Murphy, 2012)

12 (Ludwig et al., 2005) 13 (Sala et al., 2015).

SRI: Socially responsible investment; EMFA: Energy and matters flow analysis

Three are three major points for developing reliable sustainability evaluation methods and conducting more convincing sustainability assessment research. On the one hand, comprehensiveness of the sustainability evaluation should be further improved (Bond et al., 2012). Although many methods are possible to provide the framework to assess the performance on the three sustainability pillars, the majority studies still focused more on environmental and economic dimensions while the social impact is relatively less investigated. Some approaches may even not cover the others aspects beyond environmental and economic perspectives. The study of Gbededo et al. also revealed that less than 30% of the reviewed 54 papers conducted the sustinability assessment on the three sustainability demensions (Gbededo et al., 2018). It reflects that the consideration on integrated susstainability index is still limited in the current work. Therefore, comprehensiveness is necessary to improve in the future development of sustainablility evaluation. On the other hand, the involvement of stakeholders is still limited in the principle of assessment methodology, especially the life cycle-based approaches (Sala et al., 2013a). MCDM is possible to offer more chance for stakeholders and experts to participate in the assessment and decision-making process (Wang et al., 2009). However, other methodology categories show disadvantage on this aspect to different extent (Sala et al., 2015). Hence, increasing the opportunities for stakeholders' involvement for better negotiation and understanding is also one of the future tasks. In addition, follow-up investigation to observe the process of examined system and the long-term sustainability performance is scarce in the current evaluation practice. Some evaluation methods can only provide immediate sustainability consequences other than long-term impact analysis. Sustainability is a concept which has a close relationship with time. Thus, the ability of evaluating sustainability over time and long-term investigation for the examined alternatives are essential to contribute a more reliable sustainability evaluation results. According to the above discussion, more efforts are still epected to further improve the effectiveness and reliability of sustainability evaluation methods.

2.2.6 Life cycle sustainability assessment

According to the definition acknowledged by the World Commission on Environment and Development (WCED, Brundtland Commission), the concept of sustainable development refers to the development which meets the needs of current society without compromising the interest of future development (Ciroth et al., 2011). Hence, having an effective sustainability evaluation method for the target product and service is essential for better sustainable development of the entire society. To address the impacts of three sustainability dimensions, i.e., environmental, economic and social, LCSA was proposed based on the ISO 14040 (ISO 14040, 2006) which includes life cycle assessment (LCA), life cycle cost (LCC) and social life cycle assessment (SLCA) for the three pillars, respectively. Life cycle sustainability assessment is a powerful tool to evaluate all the environmental, economic, and social benefits and negative influences during the entire life cycle. It can benefit the potential decision-makers and stakeholders by the major following ways: i) helping to organize the mass and complex environmental, economic, and social data in a structured form; ii) providing a comprehensive picture of the positive and negative impacts aiming to identify the trade-offs between the three sustainable aspects and life cycle stages; iii) guiding the enterprises how to be more responsible for their business through considering all the impacts related to their products and services and improving the awareness of sustainability in value chain actors; iv) helping with choosing sustainable technologies and products and direct the business practices of enterprises by selecting the option with more positive impacts and avoiding the choice with negative influences (Ciroth et al., 2011). More detailed introduction about the befits of LCSA can be found in the reference (Ciroth et al., 2011).

As it has been mentioned before, LCSA can be described as

LCSA=LCA+LCC+SLCA

Hence, clearly addressing each subsection, i.e., LCA, LCC, and SLCA, is the guarantee to provide a comprehensive picture of LCSA for a targeted system. There are some common techniques and principles when practicing these methods. The evolution process and details of these methods were referred to the reference (Ciroth et al., 2011). The basic principles and steps are summarized in Table 2.9

Table 2.9 Major phases of three assessment techniques according to ISO 14040 and 14044

(Environmental) LCA	LCC	SLCA
Goal and scope	Define the goal, scope and functional unit	Goal and scope
Inventory of resources utilize and emissions	Inventory costs	Inventory
Impact assessment	Aggregate costs by cost classifications	Impact assessment
Interpretation	Interpretation	Interpretation

Although there exist slight differences in the phases of the three techniques, the major objectives and content of each phase are similar. The first stage is to state goal and scope of the research. This phase provides the context of the assessment, states the aim of this study and explains what the assessment results can be used for. This step usually involves some important and specific definitions of the research, including the functional unit, the system boundaries, assumptions, and limitations. The second phase should provide all the necessary input and emissions data related to the resources and energy from or regenerate output to the environment and society along the whole life cycle. The related impacts are illustrated in the third phase. The life cycle impacts results or indicators can be obtained by calculation or database. As for the environmental assessment, environmental interventions flow into midpoint impact categories and the into the endpoint (damage categories) (Jolliet et al., 2003). Interpretation is the last step which presents some explanations, conclusions and recommendations according to the impacts assessment results. Ciroth et al. (2011) provided the detailed introduction, explanation and case studies of these three techniques. Currently, LCA and LCC are commonly combined to discuss the sustainability performances of a specific product or service while SLCA is less discussed due to the difficulty in indicators assignment and related data collection.

Life cycle sustainability assessment has wide application in various fields, such as climate science (Levasseur et al., 2016), construction industry (Ortiz et al., 2009; Singh et al., 2011), and waste management(Laurent et al., 2014). Most of these studies focused on the analysis of environmental impacts. Anand and Amor reviewed the developments and summarized the challenges to guide the research directions for the future work of the application of LCA in buildings (Anand and Amor, 2017). A review on LCA studies regarding agricultural and industrial products was provided by Roy et al. (2009) which revealed that agricultural production received more attention in the field of life cycle of food products. Laurent et al. (2014) discussed considerable amount of LCA research of solid waste management systems and found that European countries were the commonly discussed regions and the types of assessed wastes were limited. All the research showed the reliability and application value of LCSA in different domains, especial the LCA for environmental engineering. Hence, there also exist certain amount of LCA studies of sewage sludge management (Yoshida et al., 2013), which are reviewed in the following subsections.

2.2.7 Life cycle sustainability assessment for the resource utilization of sludge

Scopus (“Scopus: Scopus Preview,” 2020) was applied to identify the articles characterized by LCA and sewage sludge in their title, abstract and keywords, which is shown in Figure 2.15. During the two decades in the records, there were totally 281 related papers published on this topic. If changing the searching keywords to “life cycle costs” and “sewage sludge”, results showed that there were 94 articles related to these tags. The number of published papers associated with “sustainability assessment” or “sustainability evaluation” and “sewage sludge” are 144 and 68, respectively. These data revealed that LCA as a reliable sustainability evaluation tool is frequently applied in sludge management field. The increasing trend of the publications on this topic also indicated the huge potential and market existing in this domain, which has caused more widespread attention simultaneously. Among all the original papers, 42 provided reviews for LCA and sludge management, which occupied approximately 15% in the total related papers (“Scopus: Scopus Preview,” 2020). Nevertheless, the review work is still limited towards LCSA of sludge management, especially for LCC and SLCA. Therefore, it is necessary to provide a literature review with the considerations of LCC and SLCA, not solely taking account of environmental impacts. The following sections summarize and review the 29 studies regarding to different kinds of evaluation (majorly LCA) of sludge management and resource utilization according to the four conducting phases of LCSA.

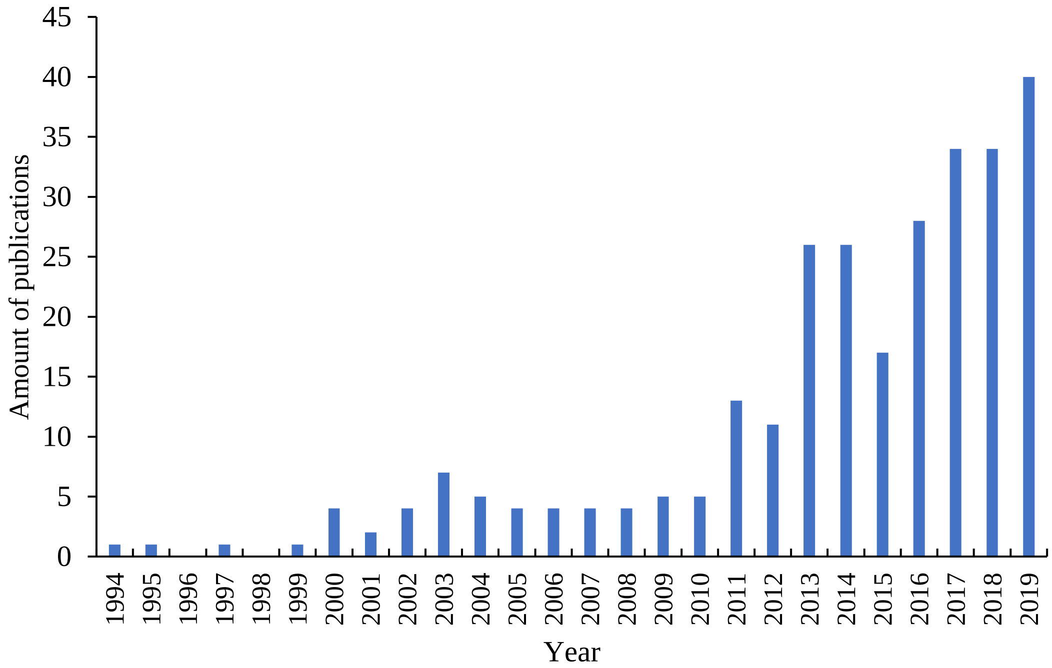


Figure 2.15 Publications on LCSA of sewage sludge since 1994 to 2019 on Scopus ("Scopus: Scopus Preview," 2020)

Goal and scope

In this phase, the objective and involving scale of the specific study are provided. According to the literature review, most of the related research were conducted to provide reliable decision-making reference for sludge management industry. Among the reviewed 30 pieces of evaluation work and reports, 21 include environmental life cycle assessment for various sludge treatment scenarios, 11 for economic evaluation or

LCC assessment, and 2 for LCA review. Only two single papers presented the LCC analysis for selected sludge management systems (Gasafi et al., 2008; Tarpani and Azapagic, 2018). However, no studies on SLCA were discussed in the reviewed 29 publications. Only 6 papers involve with technical analysis or related indicators, such as energy efficiency, materials flows and 2 reports indicated the social and practice situation of sludge management industry in China (Asian Development Bank, 2012; Ding, 2017).

Functional unit and system boundaries are defined in this stage. The majority of the studies selected 1 ton of sewage sludge on a dry basis with a few differences of the details (11 of the total 22 LCA studies). The amount of net energy generation (e.g., 1 GJ of electricity and steam generation) is also convenient for the analysis with energy flows (Hong et al., 2013). As for system boundaries, "gate-to-gate" and "cradle-to-grave" are two common types of scope description. The majority of the LCA studies covered the treatment, disposal and transportation stages. The construction and the end-of-life of infrastructures and equipment are usually out of the considerations due to the negligible influence compared with operating phases. For the study involving with environmental LCA and LCC, the definition of system boundaries for LCC may be a little different from those of LCA (Lundin et al., 2004). Some specific assumptions were also provided in this part, which usually put great impact to the assessment results of the study. A brief summarization of the reviewed evaluation work is listed in Table 2.10.

Table 2.10 Related information of reviewed LCA studies

No.	Reviewed work	Evaluation method	Functional unit	Study area	LCIA databases	Model applied
1	(Yoshida et al., 2018)	LCA	1 t of mixed sludge	the Greater Copenhagen area, Denmark	WWTP, Ecoinvent	EASETECH
2	(Li and Feng, 2018)	LCA	1 t TS of thickened sludge	-	Ecoinvent	-
3	(Liu et al., 2013)	LCA	1 dry ton of sludge	Tai lake watershed, China	IPCC, literature	-
4	(Uggetti et al., 2011)	LCA, LCC	1 ton of sewage sludge (wet weight)	Catalonia, Spain	Collected in full-scale facilities from Spain.	SimaPro 7.1
5	(Xiao et al., 2018)	LCA, LCC	1 dry ton of sludge	Xiamen, China	Collected from Xiamen's WWTPs	GaBi 6.0
6	(Suh and Rousseaux, 2002)	LCA	1 ton of the mixed sludge in dry basis	France	-	-
7	(Hong et al., 2009)	LCA, LCC	1 ton of DS	Japan	Collected from references	-
8	(Xu et al., 2014)	LCA, LCC	1 tone of DS	China	Collected from references	-
9	(Lederer and Rechberger, 2010)	LCA	1 ton of raw sludge	15 European countries	Collected from reference	-
10	(Hong et al., 2013)	LCA	1 GJ of net energy for electricity and steam production in a sludge co-incineration plant	Zhejiang, China	Company monitoring data	-
11	(Abuşoğlu et al., 2017)	LCA	1 kg of digested sewage sludge with 95% water content	Gaziantep, Turkey	Ecoinvent	-
12	(Buonocore et al., 2018)	LCA	1000 m^3 of wastewater	Italy	Ecoinvent 2.2	-

No.	Reviewed work	Evaluation method	Functional unit	Study area	LCIA databases	Model applied
13	(Cao and Pawłowski, 2013)	LCA	500 m^3 liquid raw sewage sludge	-	Ecoinvert	-
14	(Tarpani and Azapagic, 2018)	LCC	1000 kg of thickened sludge on a dry basis	The UK	-	-
15	(Y. Li et al., 2013)	LCA	105 m^3 of wastewater per day	Kunshan, China	Collected from the RRPT	SimaPro 7.0
16	(Corbella et al., 2017)	LCA	1 m^3 of wastewater	-	Collected from references	SimaPro 8.0
17	(Foley et al., 2010)	LCA	a wastewater flow rate of 2200 m3 d^{-1} at a strength of 4000 mg COD L^{-1}	-	Ecoinvent	SimaPro 7.1.8
18	(Mills et al., 2014)	LCA, LCC	1 ton dry mass of sludge	The UK	-	GaBi
19	(Lundin et al., 2004)	LCA, LCC	1 metric tonne of sludge in dry mass	Sweden	-	-
20	(Hospido et al., 2010)	LCA	10 L of a mixture of sludge	Spain	References	-
21	(Li et al., 2017)	LCA	1 t TS	China	References	OpenLCA
22	(Garfí et al., 2017)	LCA	1 m^3 of water	Catalonia (Spain)	Ecoinvent 3.1	SimaPro

Note:

WWTP: wastewater treatment plant. TS: total solids. DS: dry solids/sludge.

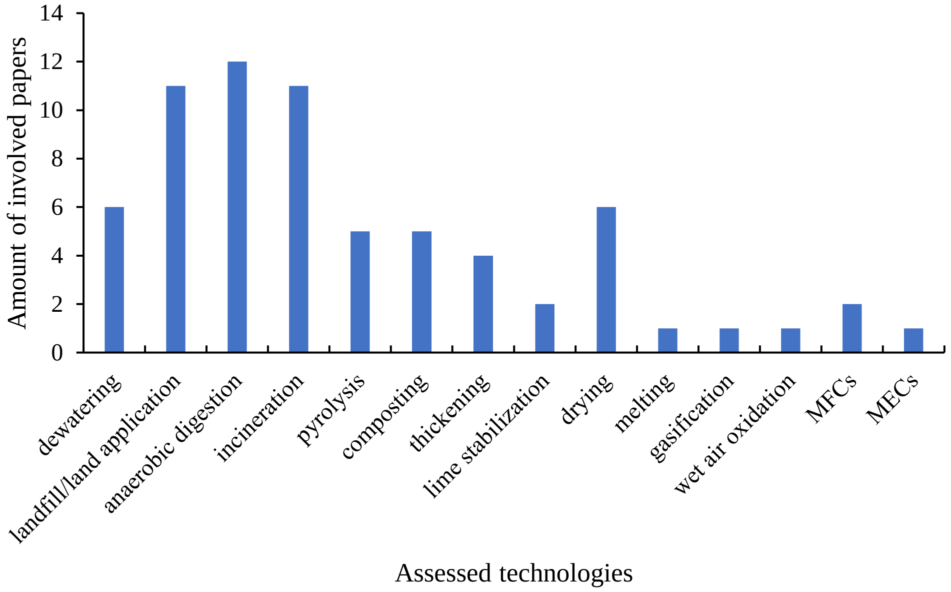


Figure 2.16 Rough statistics of the assessed sludge management technologies in the selected LCA studies

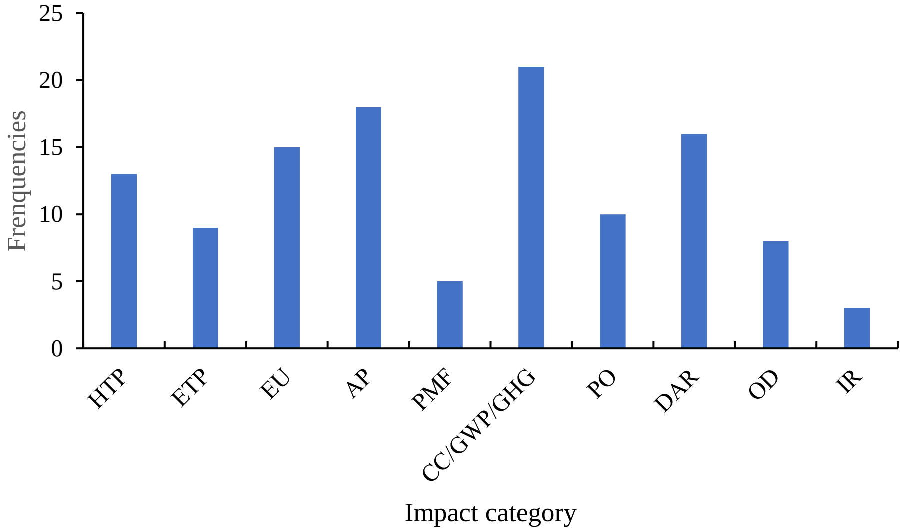


Figure 2.17 Rough statistics of impacts categories included in reviewed LCA studies (HTP: human toxicity potential; ETP: ecological toxicity potential; EU: eutrophication; AP: acidification potential; PMF: particulate matter formation; CC/GWP/GHG: climate change/ global warming potential/ greenhouse gases; PO: photochemical oxidation; DAR: depletion of abiotic resources; OD: ozone depletion; IR: ionizing radiation.)

Life cycle inventory analysis

Life cycle inventory data provides the information of the consumptions and emissions of investigated system for maintaining the normal operation which lead to the influence on the environment, economy and society (Ciroth et al., 2011). The primary inputs (such as energy, resources, and materials) and outputs (such as energy regeneration, gas, ash and metals emissions, digestate) are the parameters frequently used to describe the operation situation of the studied scenario or system. Some research may omit the impact of pathogen and heavy metals based on the specific research goal and assumptions. The related information on environmental and economic data can be collected from enterprises, publications (papers, report, and statistics) and databases (e.g., GaBi and Simapro, see the Table 2.10), while there is limited data on social life cycle assessment. Few studies involving with the technical conditions and social impacts only presented the linguistic descriptions which were collected through surveys or questionnaires (Ciroth et al., 2011; Samolada and Zabaniotou, 2014; Su et al., 2009). More general databases are still expected to be developed.

Impact assessment

According to the objectives of different studies, the researchers may choose different the life cycle impact assessment (LCIA) method to illustrate the characteristics of the investigated systems. CML and IMPACT are commonly used methods for the reviewed LCA papers based on the literature review. Yoshida et al. (Yoshida et al., 2013) identified that the guideline of the Intergovernmental Panel for Climate Change (IPCC) was a popular method among sludge management field as well. For the environmental assessment, the categories of indicators are classified into midpoint categories and damage categories. There are few investigations discussing the endpoints, i.e., damage categories. Most of the environmental LCA studies selected several concerned impact categories to state the environmental influences of the investigated scenarios. Some frequently applied midpoints include climate change (global warming potential), resources depletion, land use, water use, human toxic effects, ozone depletion, photochemical ozone creation, ecotoxic effects, eutrophication acidification, and biodiversity. The environmental impacts categories included in LCA research for sewage sludge treatment are summarized in Figure 2.17. According to Figure 2.17, global warming potential is the most frequently selected impact for environmental assessment due to the increasing concern on climate change and the global warming trend. Acidification potential, depletion of resources and eutrophication potential are also common categories for investigation because of the close connection with production and life.

For the impact analysis for LCC, the major considered indicators are investments and operation costs (Uggetti et al., 2011). Net present value (NPV) and payback period (PB) can also be used to described the economic impacts (Xiao et al., 2018). NPV was applied to decide the total profitability. PE referred to the expected time period after the initial cash was invested into a project could be recovered from the cash flows generated by the investment, which can work as a measure for inherent risk in a project (Xiao et al., 2018). Generally, the research for sole LCC analysis would be more in detail and the considered indicators would be more comprehensive while the studies with both environmental LCA and LCC would consider simpler and more general indicators.

Considering the social LCA assessment system from categories, workers/employees, local community, society, consumers, value chain actors are five suggested stakeholder categories. Corresponding impact categories include human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussion (Ciroth et al., 2011). Although there are limited investigations on social LCA for sewage sludge management, some previous studies provided some indices associated with social impacts which may be useful for future assessment on SLCA. Ren et al. (2017b) used governmental support to address the performance of social-political aspect, which was described by a five-scale evaluation. Samolada and Zabanitou (2014) considered the extent of solution to the sludge management problem, technology maturity and legislation to assess the performance of incineration, gasification and pyrolysis. A report provided the attributes of different technical routes for sludge treatment, such as volume reduction, operating and maintenance capacity and the situation of pathogen free (Asian Development Bank, 2012). According to the guideline of SLCA, there are various social indicators from different perspectives (Padilla et al., 2013). The examples are summarized in Table 2.11. All the information can provide reference for future SLCA work on selecting indicators.

Table 2.11 Social indicators of several common aspects (Padilla et al., 2013)

Aspect	Indicators
Workers/employees	- Freedom of association and collective
	- Expertise
	- Operative risks
	- Training
	- Social benefit
	- Health and safety
	- Equal opportunities
	- Forced labor
	- Working hours
	- Fair salary
	- Child labor
Local community	- Public commitments to sustainability issues
	- Public participation
	- Social acceptance
	- Sustainable behavior
	- Technology development
	- Contribution to economic development

Society	-	Safe & healthy and secure living conditions
	-	Public participation
	-	Social acceptance
	-	Sustainable behavior
	-	Local employment
	-	Community engagement
Consumers/clients	-	Health and safety
	-	Demand satisfaction
	-	Social acceptance
	-	Sustainable behavior
	-	Feedback mechanism

Assessment results and interpretation

Due to the differences in the selection of assessed indicators and the assumptions for the investigated systems, the assessment results may be different even when the same technical route is evaluated by different papers. Although the evaluation results of the technical routes vary from region to region, they still can reflect the overall characteristics of the routes. Hence, it is necessary to investigate the assessment results of different LCA studies to learn about the features of different techniques.

Yoshida et al. (2013) provided the summarization of global warming potential in different studies. From the perspective of technology, incineration of dewatered anaerobically-digested sludge followed by landfilling of ash was demonstrated to have impressive performances compared to the scenarios with land application of the sludge (Yoshida et al., 2018). However, some studies also indicated the shortcomings of incineration technology. Although sewage sludge co-incineration presents higher economic benefits, it leads to greater environmental burden than that of coal-based energy production technology, indicating that sludge co-incineration may not be a preferred choice for sustainable management of sludge (Hong et al., 2013). On the other hand, co-incineration had the best energy balance, but without recovery of phosphorus and owns the highest cost (Lundin et al., 2004).

Some other technologies are also recognized by researchers in different context. Anaerobic digestion (AD) could be the first choice when designing a sewage sludge disposal system and AD integrated with pyrolysis was regarded as an option suitable for high organic content sludge because of its high conversion rate of sludge to energy (Li and Feng, 2018). Hydrothermal-pyrolysis technology (HPT) was discussed and performed as the most favorable scenario for sludge disposal overall, and the optimal disposal proportion was for landfill was also indicated (Xiao et al., 2018). If the driver of sludge treatment includes P recovery, previous work suggested a novel technology proposed by Lederer and Rechberger (2010) combined both advantages of the established practices as well as low emissions, but it required for additional energy. With respect to LCC for resource recovery from sludge, anaerobic digestion, pyrolysis and wet air oxidation can be operated with negative overall life cycle costs if all the recovered products are fully used. Composting is the next preferred option with a total life cycle costs of £35/1000 kg dry matter. Incineration takes the last place with the cost of nearly £54/1000 kg dry matter (Tarpani and Azapagic, 2018).

According to the literature review of the assessment results and interpretation, incineration, AD and the technique routes with both technologies occur frequently. It indicates some obvious advantages of these techniques in different situation. More detailed information about the performances of different technologies in various literature can be found in the LCA review (Corominas et al., 2013; Yoshida et al., 2013).

2.2.8 Summary

The related concept of sustainability and sustainable development were reviewed in this section as well as the application of LCA on sludge sustainable management. Six kinds of sustainability assessment approaches were qualitative analyzed. Three perspectives and nine criteria were considered to construct the criteria system for methods evaluation, covering scientific soundness, feasibility, and utility. Previous studies and analysis reveal that LCSA and MCDM are relatively reliable tools for sustainability evaluation and the combination of both works better which can provide a complete sustainability evaluation (Campos-Guzmán et al., 2019). Composite indicators and energy and material flow analysis are also acceptable evaluation methods. The performance of other three method categories were not so satisfactory which means that they show some disadvantages on the considered criteria at different degree. Based on the literature review and evaluation results, three limitations and suggestions were proposed accordingly to guide the future development of related research on sustainability evaluation methods and sustainability assessment practice. These three points include comprehensiveness, involvement of stakeholders and the long-term investigation for the investigated systems of the sustainability assessment methods. Future research may consider these three directions to improve current sustainability evaluation methods. Although there are powerful tools for sustainability evaluation, some challenges still exist in the practice, like the unfeasibility of exact data on social and technical aspects, which can be a major barrier for conducting sustainability evaluation considering all the sustainability pillars. More efforts are still expected to complete the framework of sustainability evaluation methods and related database.

According to the above literature review, some limitations can also be found out which can guide the working direction for the future. The details are presented as follows.

Limitations

Above literature review proves the wide application of LCSA in sewage sludge management field. However, there also exist some deficiencies and limitations about current research based on above analysis. Three of the limitations are listed and discussed as follows:

Firstly, the evaluation work majorly focused on environmental LCA, less on LCC, and rarely on social LCA. One reason for this phenomenon is lack of related data on social aspect as it has been mentioned in Section 2.2.2. Meanwhile, the application of linguistic terms, interval numbers or fuzzy numbers to address the social performances on the specific indicator also increases the difficulty for direct social assessment on sludge management system.

Secondly, the selection of indicators during assessment is usually limited and has a focus, which leads to the evaluation with emphasis. For example, if a study explores a technical route with higher energy recovery, it may pay less attention on other insignificant environmental impacts. It is a double-edged sword, because it can make the evaluation with more directivity and pertinence as well as overlooking its impacts in other non-focus aspects.

A significant limitation of LCA studies is the large variation of assessment results. There are plenty of factors which can influence the evaluation results. The assessment results show high dependency on the assumptions and management system, including the selection of technical route, the assumptions of treated sewage sludge, the parameters of treatment technologies, the distance of transport, the considered life stages, the involved inventory data, and the choice of impact categories. Almost every step can bring different extent of influence to the evaluation results. As a result, there is no uniform reference standard for evaluation even for the same technology. Although there exists the international standard for the basic steps of LCA research, the assessment results could vary with regions, the development state-of-art of the assessed technologies, and the objectives of evaluation.

Challenges and future work

In response to the shortcomings and limitations mentioned above, the challenges of future work focus on the following aspects:

Firstly, it is suggested to strengthen the project and research cooperation with enterprises and collect data extensively. It is necessary and essential to establish reliable database with available data of not only environmental and economic impacts, but also social impacts. This can be a solid foundation for the establishment of a comprehensive evaluation system. Besides, some other indicators, such as energy efficiency, water consumptions, and P recovery, can also be taken into the considerations for sustainability assessment, which can help to reflect the feature of specific technical route from other perspective. Risk evaluation is also an important aspect to be considered since some influence cannot reflect immediate but can be accumulated and bring heavy pressure to the environment and the human society, such as the accumulation of heavy metals and pathogens to the croplands from sludge agricultural application.

For the second point, it is recommended to conduct targeted evaluation under the premise of having a comprehensive understanding of the performance of each indicator. It could be achieved by gradually improving the assessment for a specific technology under the same sludge management system. This is more conducive to understanding the features of the specific technical route as fully as possible and providing opinions and suggestions for decision-making without bias.

For the third limitation, large discrepancies were found resulting from the differences of basic assumptions and inventory data. Hence, in order to know about the sustainability performance of a specific system under assigned conditions, a targeted LCA research should be conducted to analyze impacts of the environmental, economic, and social aspects. In addition, the related databases should be improved to include more life cycle assessment data around the worldwide, not limited to some specific regions. This will no doubt to contribute to the sustainable development in sewage sludge management field throughout the worldwide.

2.3 Sustainability assessment and decision-making analysis based on process simulation for sludge-to-energy technologies

Besides the traditional treatment and disposal approaches, there are also many emerging technologies which are newly developed and found to be potential for both energy recovery and sludge treatment, such as pyrolysis, gasification (Syed-Hassan et al., 2017), and supercritical water gasification (Amrullah and Matsumura, 2018).

However, these novel technologies are still in the development stages without large-scale of application, leading to the lack of related data of such kinds of technologies. Nevertheless, the performances of these technologies even in the experimental stages are still commendable, especially in the environmental and the energy recovery aspects. Therefore, it is necessary to investigate the potential and possibility of these emerging technologies for commercial application to see the competitiveness of them compared with the traditional ones. There are a few studies conducting experiments for the new technologies. For example, Acelas et al. (2014) designed an experiment to investigate the feasibility of energy recovery together with phosphorus recovery through SCWG of dewatered sludge. Zhu et al. (2015) studied the combined process of gasification and incineration for the dried sewage sludge for syngas production. Although experimental data can provide the basis to understand the features and characteristics, some other tools are still needed for the rough estimations of the technology performances of these technologies on different aspects. Process simulation can help to estimate the performances of investigated technologies in large scale under the assumed conditions. It allows the researchers to analyze the potential and possible impacts for further application, which can provide important reference information for the related decision-makers. currently, some researchers have carried out simulation analysis and studies on parts of technologies. For instance, Bora et al. (2020) conducted techno-economic analysis for the prominent thermochemical technologies to explore the feasibility for poultry litter treatment with energy recovery by simulation. A kinetic reaction model of the pyrolysis technology for biomass treatment was presented by Peter et al. (2017) in

Aspen Plus, which is a software for process simulation. Similarly, the couped pyrolysis and combustion process for oil sludge treatment (Gong et al., 2019) were simulated by Aspen Plus. Tech-economic analysis and performance evaluation were combined together by using process simulation and life cycle assessment (Medina-Martos et al., 2020). However, these studies did not conduct further evaluate the performance data for decision-making process and analyze the different technologies to make comparison. Hence, the research on process simulation combined with sustainability assessment and decision analysis of the emerging technologies for sludge treatment with energy recovery can be improved.

2.4 Decision-making analysis for sludge-to-energy technologies

2.4.1 Preliminary knowledge about multi-criteria decision analysis

Environmental, economic, social, and technical criteria are frequently discussed in the decision-making process for energy systems, which usually represent the interests of different groups of stakeholders. It would be difficult to optimize and ranking the energy options independently and discretely with the considerations of various indicators. Therefore, decision-making analysis plays an essential role for more sustainable energy system design through considering various criteria and objectives (Kumar et al., 2017). Multi-criteria decision-making methods were proposed and developed as a branch of operational research to solve the problems of figuring out the optimal alternative in complex scenarios including various indices, conflicting goals and criteria (Kumar et al., 2017). The common stages of MCDM for sustainable energy usually consist of criteria selection, criteria weighting, evaluation and final aggregation (Wang et al., 2009). The major MCDM process is illustrated in Figure 2.18 (Wang et al., 2009).

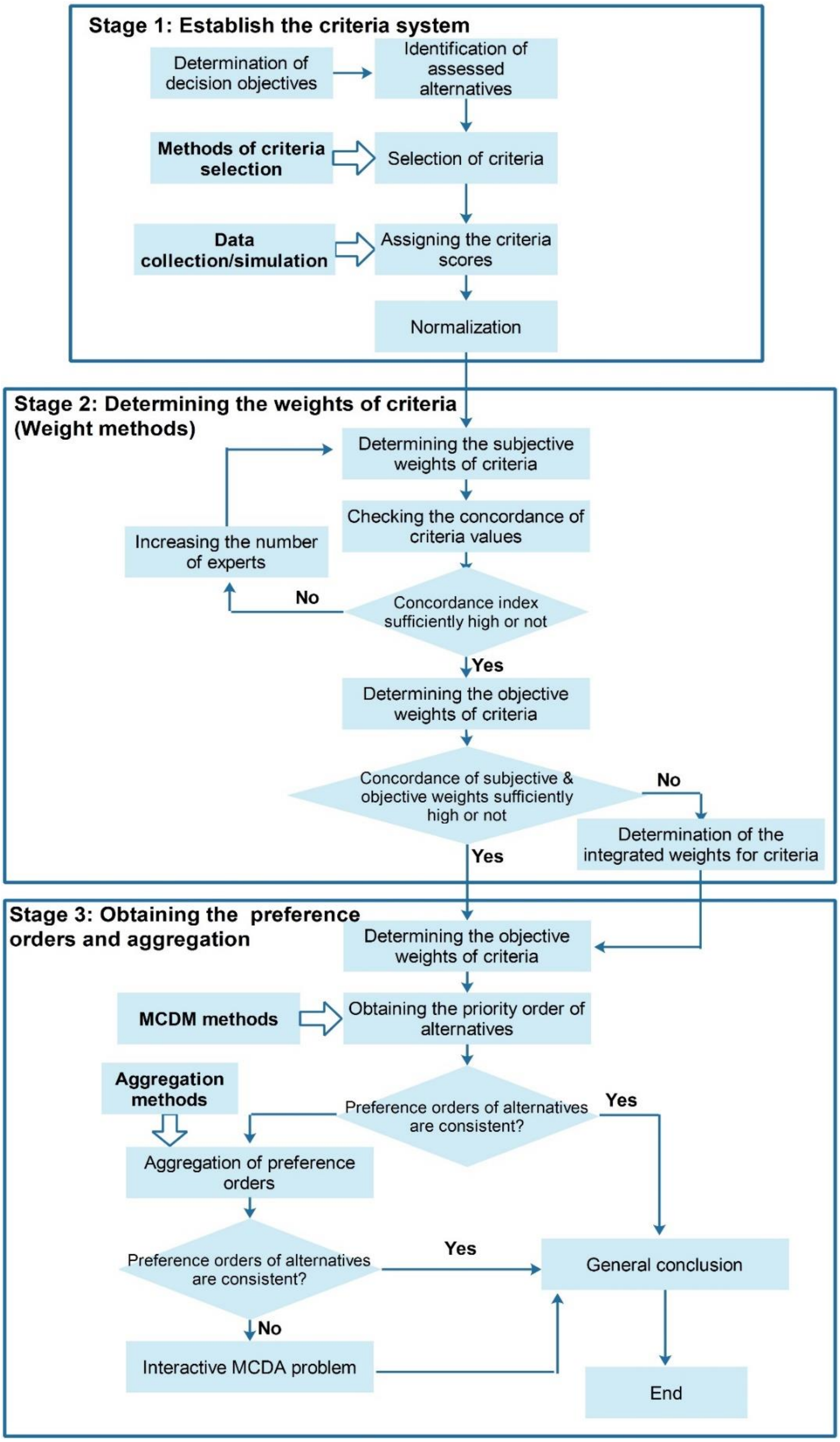


Figure 2.18 The basic steps for MCDA process for sustainable energy decision-making (Kumar et al., 2017)

LCA results can provide the decision analysis reference. Therefore, the criteria of LCA can also be selected as the indicators for the decision analysis system. Some typical criteria applied in evaluation for energy supply systems have been presented by Wang et al. (2009). More detailed description and discussion for the different criteria selected in the evaluation for energy systems can be referred to the reviews of Kumar et al. (2017) and Wang et al.(2009). Currently, there is no uniform and exact standard for criteria system establishment and selection. Nevertheless, the most important objective of criteria system is to reflect and measure the sustainability of the investigated energy systems. Hence, the development of selection of criteria system should consider the reliability, appropriateness, practicality and limitations for the measurement of the related parameters (Wang et al., 2009). Five principles should be obeyed when selecting the “major” criteria during the decision-making process for energy supply systems: (i) system principle; (ii) consistency principle; (iii) independency principle; (iv) measurability principle; and (v) comparability principle (Wang et al., 2009). These principles can provide the guidelines for stakeholders to choose the suitable criteria when building the criteria system, but some “minor” indicators are still possible chosen. Therefore, some objective and rational methods are proposed to help select the “major” criteria and form a rational assessment criteria system. These methods include Delphi method, least mean square (LMS) method, minmax deviation method, and correlation coefficient method. Detailed introduction of these methods can be found in the review of Wang et al. (2009) and related references. One basic principle of the selection methods is to reduce the correlation between criteria and choose the independent indicators. Besides the methods mentioned above, more approaches are developed and extended for more diverse and complicated energy systems, e.g., grey relation method, AHP method, clustering method, principal component analysis and rough set method. Among these approaches, grey relation method and AHP can also be used as MCDA methods to obtain the ranking of investigated alternatives, which are briefly introduced in the following sections (Wang et al., 2009).

Weight is a value assigned to a criterion which indicates the importance compared with other criteria. According to the literature review, there are various methods to decide weights. Some of them can also be applied as criteria selection method and ranking method, such as LMS method and AHP method. A brief summarization of the calculation steps of several classic weighting methods, like AHP and TOPSIS methods, can be found in the review of Wang et al. (2009). Best-worst method (BWM) was developed as a pair-wise comparison approach with simpler calculation steps and more reliable consistency ratios (Rezaei, 2015).

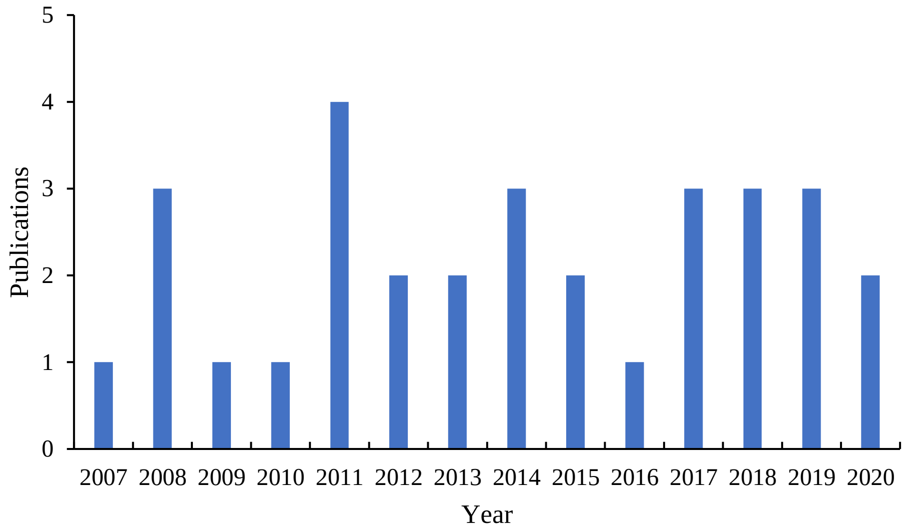
There are three categories in MCDA methods, including elementary methods, methods in unique synthesizing criteria, and outranking methods (Wang et al., 2009). The methods belonging to each category, the features of each category and corresponding calculation steps of several common MCDA methods can be found in research (Wang et al., 2009) and the references provided in it. Some MCDA methods are also worked as weighting methods, such as AHP and SMART. It should be noted that PROMETHEE method and ORESTRE method, which belong to outranking category, have the application potential in solving decision-making problems with hybrid information (Luo et al., 2020). There also exist some other MCDM methods which are different with the classic approaches. The traditional methods are usually applied when the information is exactly expressed by crisp numbers. However, vagueness and uncertainty are widespread in the practice which can be generated from the objective opinions and linguistic descriptions. The imprecision contained leads it difficult to use this kind of information for decision-making directly. Therefore, fuzzy theory was introduced to MCDM field to help with the situation with uncertainty. Currently, many MCDM methods have been developed and applied in the fuzzy environment, such as fuzzy AHP method, fuzzy best-worst method (Guo and Zhao, 2017), fuzzy TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) and fuzzy DEMATEL (Decision-making Trial and Evaluation Laboratory) method (Mardani et al., 2015a; Renganath and Suresh, 2017). Intuitionistic fuzzy (IF) MCDM approaches was also developed during recent years which have been utilized in supplier selection problem (Büyüközkan and Göçer, 2017) and knowledge management system selection (Li et al., 2014). Abdullah provided a brief review of fuzzy MCDM methods and their application according to category (Abdullah, 2013). Mardani et al. summarized the fuzzy MCDM techniques and applications in various fields over the two decades from 1994 to 2014 (Mardani et al., 2015a). More detailed introduction regarding the application of fuzzy theory in MCDM can be can in these two reviews and references.

After the determination of ranking order by MCDM methods, the best alternative usually can be obtained. However, it is necessary to verify the creditability of decision-making because of the possible difference lying in the ranking results generated from the application of a few MCDM methods. This leads to the question “which method is the most suitable one to solve the specific problem?”. Aiming at solving this question, the results obtained from different MCDM methods are suggested to be aggregated and then the best strategy can be selected among all options. Nevertheless, the consideration of aggregation methods is limited in energy decision-making, while they were applied in social and economic systems. Basically, there are two kinds of aggregation methods, i.e., voting methods (including Borda and Copeland methods), and mathematical aggregation methods (including soft and hard aggregation approaches). More related information about aggregation methods can be found in the review of Wang et al. (2009).

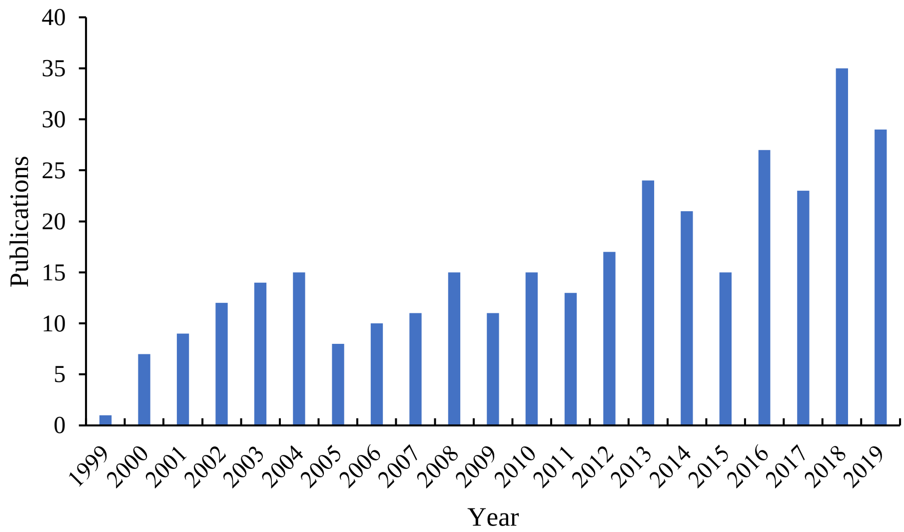
MCDM methods have wide application in diverse disciplines due to the advantages on dealing with multiple attributes and various considerations of aspects, including supplier selection problem (Büyüközkan and Göçer, 2017), service quality assessment (Mardani et al., 2015b), and renewable energy systems (Suganthi et al., 2015). To determine the solar plants sites and technologies, a wide variety MCDM methods were investigated to obtain the influencing factors in the decision-making process for solar plants (Ghasempour et al., 2019). With the consideration of current severe situation of fossil energy and environmental issues, proper and sustainable energy policy should be determined taking account of various criteria and aspects. Large number of research have examined the energy problems by utilizing MCDM methods which was reviewed by Kaya et al. (2018). All the existing literatures reveal that MCDM methods have widely recognized application value in different field, especially in promoting the sustainable development of energy systems management. As a branch of waste management and renewable energy production, MCDM methods also play an important role in the selection of sludge management technologies.

2.4.2 Methodology

According to the searching results from Scopus ("Scopus: Scopus Preview," 2020), there are 31 related articles from 2007 to 2020 if "sludge" and "multi-criteria decision-making" are selected to be the searching keywords. The number of relevant papers published each year was in fluctuations, but it was relatively stable. If the keyword "multiple criteria" is not added as a constraint, there are totally 332 articles during the recent two decades in the field of "sludge" and "decision-making". The total amount of papers tagged with these two keywords presented an increasing trend overall. Hence, it is clear that the decision-making problem of sludge management is gradually recognized and may become a research force in the recent future. However, the MCDM methods applying on sludge management systems are still insufficient which means that the improvements for decision-making problems of sludge management are still expected in the future. Six pieces of MCDM work for sewage sludge management are selected and reviewed in the next subsection according to the basic steps of conducting MCDM techniques.



(a)



(b)

Figure 2.19 The number of publications changing by year: (a) the number of publications related to "sludge" and "MCDM" (2007-2020); (b) the number of publications related to "sludge" and "decision-making" ("Scopus: Scopus Preview," 2020).

2.4.3 Application of MCDM in sludge management field

Evaluated alternatives

In the first stage, the stakeholders should identify the assessed alternatives. In the reviewed literatures, Ren et al. (2017b) assessed three sludge-to-electricity techniques, including incineration, anaerobic digestion (AD) for biogas to power by gas engine, and AD for biogas to power by fuel cell. Landfilling, composting, and drying incineration for urban sewage sludge were evaluated and ranked in the sustainability assessment work (Ren et al., 2017a). Three technologies, i.e. compositing, incineration, and resource utilization, were analyzed in the assessment work of An at al. (2018). Four wastewater treatment alternatives denoted by activated sludge, aerated lagoon, sequential batch reactor, and constructed wetlands, were investigated in the research of Dursun (2018). Three options of the liquidation for sewage sludge were studied: A) agricultural usage of dried sludge; B) incineration of dried sludge in the waste incineration plant; C) incineration of dried sludge in the thermal power station (Upka et al., 2005). Hence, according to the literature review, incineration was a common technology which was the most frequently investigated approach in the reviewed MCDM work. However, the considerations for other sludge management technologies are still insufficient which means that a lot of work are expected to be done in the future to improve this field.

The application of MCDM on sludge management is not limited on the sludge process and final disposal. It can also help with the selection of pre-treatment conditions. Two pre-treatment conditions for hydrothermal treatment of sewage sludge were investigated by Khalil et al. (2005) and the details can be found in the corresponding study.

Establishment of criteria system

Economic, environmental, technical, and social aspects are the major perspectives considered in criteria system. They can help to effectively address the sustainability performances of the sludge management alternatives. Four aspects (economic, environmental, technological, social-political) and thirteen indicators were analyzed to identify the critical barriers which hinder the sustainable development of sludge-to-energy industry by grey DEMATEL method (Ren et al., 2017b). Six criteria were considered to form the evaluation system, including capital cost and running cost (economic aspect), occupied land and environmental risk (environmental aspect), social acceptability, and generalizability as the performance of technological aspect (Ren et al., 2017a). Ten indicators were selected to assess the sustainability performances of the investigated alternatives, such as capital cost and running cost, occupied land, environmental risk, social acceptability, operability, site selection, applicability and management level requirement (An et al., 2018). Eight criteria were identified to form the criteria system including cost, global warming, etc. (Dursun, 2018). The investigation of verifying the efficiency of the pretreatment considered operation conditions and experimental data, including temperature, time, oxidant, total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), total solids (TS) and volatile solids (VS) (Khalil et al., 2005). From the analysis above, although the amount of considered indicators can be different, there are still some common criteria which may be the observation points of stakeholders and decision-makers. These criteria include investment cost (capital cost), running cost (operation and maintenance cost), and environmental risk, where the environmental risk can be reflected by some other sub-indicators, such as whether pathogens free and the emissions of heavy metals to soil.

Involved MCDM methods

Usually, a MCDM work involved with several methods to complete the entire prioritization process in different stages. These methods can be traditional approaches and fuzzy methods. They can also be some novels methods which were newly developed to solve the MCDM problems in more complex situation. In the reviewed work, linguistic grey relation analysis was developed to deal with the situation with linguistic description (5-scale) provided by decision-makers. It first transformed the linguistic terms into grey numbers and then continued the calculation step by step (Ren et al., 2017b). The case study also aggregated different opinions of experts by averaging. BWM was applied to determine the weights of each criterion and the relative performances of the alternatives with the respect to the soft criteria. The sum weighted method, diagraph model, and TOPSIS were used to obtain the ranking order of the assessed technologies (Ren et al., 2017a). 2-tuple fuzzy representation model, linguistic hierarchies, DEMATEL and TOPSIS were combined to handle the decision analysis problem in wastewater management. Fuzzy DEMATEL was employed to determine the weights of each criterion with the consideration of inner dependencies. Then the fuzzy TOPSIS was used to prioritize the alternatives (Dursun, 2018).

AHP, BWM and their derivation methods (i.e., combined with fuzzy sets) were frequently used in weighting process and ranking stage. This is credited by their features of easy to understand and simple to operation. In the reviewed studies, grey relation analysis and fuzzy theory were employed to deal with the linguistic terms. Fuzzy DEMATEL can help to process with the situation where the inner dependency of criteria was considered. All the innovative MCDM methods may provide some new thoughts for the solving the realistic decision-making methods.

Final ranking results

The ranking results varied with the selected MCDM methods and considered assessed criteria. They can also be influenced by the local conditions of technologies, the specific regulations and the preferences of stakeholders. Hence, it is natural to see the differences lying in different MCDM work for sludge management technologies, even when the assessed technologies are the same. According to the literature review, sludge digestion for biogas to electricity by gas engine, was the most preferred alternative, followed by sludge digestion for biogas to produce electricity by fuel cell. The sludge incineration was in the last place due to the unfavored performance overall (Ren et al., 2017b). While another research indicated that the final ranking by descending order was landfilling, drying incineration and composting (Ren et al., 2017a), which means that landfilling had obvious advantages over the other options. However, the analysis results in another study showed that resource utilization was the most preferred one, followed by compositing and incineration (An et al., 2018). By conducting a specific case study, the authors found that the most suitable WWT alternative was aerate lagoon, followed by activated sludge. Sequential batch reactor performed the worst due to the unsatisfied performances on the cost, global warming effect and sustainability (Dursun, 2018). The ranking results of the same case study were compared in research (Upka et al., 2005), which showed that the ranking of AHP, fuzzy AHP and fuzzy SR method, alternative B (incineration of dried sludge in the waste incineration plant) was the best choice, then alternative A (agricultural usage of dried sludge) and C (incineration of dried sludge in the thermal power station), while the ranking results of PO (point evaluation) and WE (weight method) revealed the ranking order was A>B>C. The results were also a proof of the diversity of ranking order by different MCDM methods. Aggregation methods can help to solve this problem, but there was limited discussion on aggregation method in the reviewed MCDM work.

2.4.4 Decision-making analysis for sludge-to-energy technologies under multi-data conditions

In the actual decision-making process, it is common to see multiple types of data and information mixed due to the unavailable of parts of data, or the uncertainty of the accessible information. Different types of data occurring in decision-making process majorly include crisp numbers, interval numbers, linguistic terms, and missing information. In the general case, the information of objective conditions is reflected by crisp numbers which are obtained objectively and accurately through actual measurement, calculation, simulation, or other reliable and scientific approaches. Meanwhile, some information may vary with conditions, and the data within a range, or an interval are all acceptable. Linguistic descriptions are frequently used for the opinion's expression and subjective judgements. Partial data missing easily leads to the result of incomplete information in the decision-making process. Hence, it is necessary to use effective model to handle decision-making problem with hybrid information. Some MCDA methods have been applied and extended to process different types of data. VIKOR method and TOPSIS method were both extended to address the decision-making problem with interval numbers to express the preferences of decision-makers (Sayadi et al., 2009; Yue, 2011). Decision-making problems with both quantitative and qualitative indicators were investigated by an improved MCDA method by converting the interval numbers and fuzzy numbers into precise numbers (Liang et al., 2006). Traditional grey relational analysis (GRA) was modified to deal with the multiple attribute decision-making problems with interval-valued intuitionistic fuzzy formation (Wei and Lan, 2008). In addition, MCDA methods can also be combined with other theories to flexibility handle the decision-analysis problems with missing information. Dempster-Shafer (DS) theory was introduced and combined with analytic hierarchy process (DS-AHP) and data envelopment analysis (DEA) to solve the decision-making problem with incomplete information (Beynon, 2002; Hua et al., 2008; Zhang and Wang, 2018, 2019). Probability theory can also be helpful for the data generation in decision analysis problem with incomplete information (Park et al., 2015). Although many methods were proposed and developed to deal with the decision-making problems with uncertain information, few of them discussed the situation where different types of data exist simultaneously (Li et al., 2018; Lin et al., 2021). Tang et al. (2021) proposed a novel mathematical model for the sustainability prioritization of sludge-to-energy technologies by using fuzzy triangular fuzzy numbers to address the different types of data, including the crisp numbers, interval values and subjective descriptions. However, the missing information situation was excluded in the discussion, which means that the development of a MCDA method to solve the decision-making problem with crisp numbers, interval values, linguistic terms and incomplete information is still necessary, especially for the sludge management field due to the lack of data for many emerging technologies.

2.4.5 Discussion

According to the above literature review, current MCDM work for sludge management technologies have explored many problems. However, there are still some limitations lying in the present studies and challenges that the future work needs to face with. The detailed limitations and challenges are described as follows.

Limitations and challenges

Since the sustainability performances can usually described by LCSA framework, the limitations of current research on LCSA and MCDM for sludge management technologies are similar. First, the criteria selection may not be so comprehensive to address the sustainability performances as thorough as possible. As it has been mentioned in the Section 2.4.1, there are some basic principles to guide the criteria selection. However, considering as many indicators as possible while following the principles is conducive to providing a more comprehensive understanding for decision-makers, especially when the decision-makers are lack of professional background knowledge. Secondly, the assessed alternatives are limited to several common and traditional technologies, such as landfill, incineration, and composting. There are few discussions on the emerging technologies for sludge treatment, like pyrolysis and gasification, biological fermentation, SCWG and MFCs to produce electricity from sewage sludge. These new technologies could be potential and promising in the future for better sustainable management of sludge. Hence, it is still vital to discuss the sustainable performances of these new technologies in the MCDM framework. Some present studies have considered the inner dependency between each criterion and discussed how to process the uncertainty resulting from linguistic descriptions from the impression and preference of stakeholders. Nevertheless, the discussion on the influence between different group of decision-makers for sludge management is quite limit. The fuzzy circumstance considered in present work focused on the uncertainty singly resulted from the linguistic terms. In the practice, the vagueness can be generated from interval numbers, linguistic descriptions, and even incomplete information. There are few studies to consider the solutions towards these situations, which means that this can be a work direction in the future.

Suggestions and improvement for future work

Based on the limitations proposed above, several suggestions are correspondingly provided to guide the future research on MCDM for sludge management. Firstly, build up a reliable database on the sustainability performances on different criteria, covering the information on environment, economic, society and technology. The availability of the related data on LCSA can help to promote the decision-making process. Hence, if the database for LCSA is available, it can reduce the pressure of collecting relevant data on environmental, economic, and social aspects. It can also provide more choices for the criteria selection without the limitation of lack of related data. Secondly, consider more emerging technologies during the decision-making process. Some technologies may be newly developed in experimental stage or initial commercial phase. Then it is necessary to know whether it can be selected in application (in full-scale or in small scale) and corresponding propose some advice based on the evaluation results to promote the development of the specific technology. In addition, previous studies did not explore the situation with multi-data conditions and fail to discuss the circumstance of incomplete information. It is important to consider these kinds of situations since they are possible to occur in the practical decision-making process. Forming a method framework to deal with these problems can be a new work direction in the future. Meanwhile, the influencing between stakeholders is also rarely discussed in the sludge management field. Game theory combined with the MCDM approaches can help with this problem. Soltani et al. (2016) built up a game theory approach for group decision-making aiming at choosing sustainable waste-to-energy techniques, which may provide a research thought for the related application in sewage sludge treatment.

2.5 Decision-making analysis for sludge-to-energy technologies with multiple stakeholders

Decision-making problems usually involve with the interests of different groups of people, not just one party. Competitors, investors, and beneficiaries need to be considered simultaneously in the practice. In this section, the literature review was conducted by using the database in Google Scholar and Scopus to search for the papers with the keywords related to “sewage sludge”, “stakeholder(s)”, and “multiple stakeholders”. Some related studies were also collected by using the keywords “waste-to-energy” and “energy management”. According to the search results, few studies directly summarized and reviewed the involved stakeholders in sludge management system currently. Scientific experts, representative from the authority (government), representative from non-governmental organizations (NGOs), and managers from wastewater treatment plants were considered in the research conducted by Laura et al. (2020). Similarly, three groups of stakeholders were involved in the MCDM research for sustainable development of sewage sludge, including experts with professional background in environmental engineering, experienced environmental engineers, and representatives in the government (Ren et al., 2017b). In this discussion for waste-to-energy technologies, which is topic similar to that of sludge-to-energy, also considered the interests of municipality (government) and the industry (waste treatment facility) (Aplak and Sogut, 2013; Soltani et al., 2016). Therefore, the stakeholders involved with the decision-making problems for sludge management usually include experts with professional knowledge on the technologies, representatives from the government, and representatives from the industry. Sometimes the interests of the groups which can be influenced by the decision, like residents (representatives from NGOs) should also be considered and discussed.

It is necessary to discuss the decision-making problems with multiple stakeholders to help them reach a consensus. Hence, how to incorporate the preference of different groups of decision-makers together and get an agreement on the final decision that reflects the opinions from all the involved parties is a challenge for decision-makers. Group decision-making tools are then developed to deal with this type of decision-making problems.

There are two major categories of methods to process the group decision-making problems. The first category is MCDA-based method which usually integrate the references of different groups of stakeholders into one value, like taking an average (Chang et al., 2013). The other category is introducing other theories to the MCDA methods and combining them together. Game theory is a frequently applied approach to solve the decision-making problems with the consideration of conflicting interests of different stakeholders (Kaushal and Nema, 2013a, 2013b; Siksnelyte et al., 2018). Besides game theory, alternative queuing method and fuzzy Delphi approach can also be helpful for solving group decision-making problems (Anisseh et al., 2009; Tao et al., 2021). This section focuses more on the application of game theory combined with MCDA for group decision-making problems.

Game theory is a powerful tool which is widely used in economics. It can model the interactions and incentive structure between individuals and consider the predicted and actual behaviors of individuals in the struggle or competition and help to obtain the optimized strategy. Due to the advantages and ability of analyzing the mechanisms of the interactions and influences between stakeholders, game theory is also widely applied in other fields, such as biology, international relations, and computer science. Zhao et al. (2012) utilized game theory with life cycle thinking to analyze the environmental risk and carbon emissions in the strategy selection for a green supply chain. Noncooperation and cooperation of the government, manufacturer, recyclers, and consumers were analyzed for electronic waste management by game theory (Kaushal and Nema, 2013a). Fuzzy TOPSIS and game theory were combined together to find the optimal strategies of energy management considering the preferences of the industry and environment (Aplak and Sogut, 2013). Sustainable strategies for waste-to-energy management were studied by applying game theory and fuzzy AHP to analyze the game between municipality and the cement industry (Soltani et al., 2016).

Although there are many studies using game theory together with MCDA approaches to conduct decision analysis, limited of the proposed methods were applied for sustainability selection and prioritization. Discussion on sludge management in detail is rare. Most related discussion and application is on waste management and energy management fields (Aplak and Sogut, 2013; Soltani et al., 2016). Meanwhile, the analysis focused more about two-player game without the consideration of social and technical influences, which are also important aspects in sustainability assessment. In sludge management problem, it is also necessary to consider the attitude of residents since they are affected by the sludge management technologies selection as consumers, especially the users who live near the sludge treatment facilities. It is beneficial to the investigation of decision-making for sludge management whether the interests of residents are taken into account as social influence or the residents are individually taken into the game as a group of stakeholders. However, such kind of discussion is still limited which means that more efforts are expected to improve related research on group decision-making for sludge management.

2.6 Urban sludge-to-energy supply chain design and optimization

According to the pre-query information for the literature review, there is no specific research article on supply chain design and optimization for sludge management. Therefore, the literature review on supply chain design was conducted based on the search results from Scopus and Google Scholar by using the keywords “supply chain design/optimization”, “biomass”, and “waste”. Related records were majorly limited within the recent two decades.

2.6.1 Brief introduction on supply chain

Supply chain refers to a systematic process from supplying a product or service to a consumer. It usually involves with diverse organizations, groups of people, activities, information, and resources. The transformation of natural resources, raw materials and components into a completed product and delivery to the end consumer are considered for supply chain design. With the consideration of sustainable development, used products (waste and residues) may re-enter the supply chain at any point in a complex supply chain system if the residual value is recyclable (Kozlenkova et al., 2015). With the increasingly serve situation of the resources and environment, it is becoming more important to coordinate the relationship between various aspects in the design and management of supply chain. Meeting the requirements of environment and society along all stages of the supply chain can help to ensure that (at least) minimum sustainable performance is reached (Seuring, 2013). Therefore, it is necessary to discuss supply chain design and management for a better sustainable development.

There are various methods and mathematical models which can be applied for supply chain design and management. Multi-objective optimization model and mixed integer linear programming (MILP) approach were frequently used in solving supply chain design and management problem. Aiming at promoting the process of finding out better solutions for designing sustainable supply chain toward bioenergy generation from forestry biomass, a MILP model was developed and applied, which could not only obtain the optimal selection of biomass amounts and sources, but also the transportation modes selection, and necessary transportation routes (Paulo et al., 2015). A general MILP modelling framework for multi-period and multi-echelon ethanol supply chains was performed with the consideration of uncertain conditions and risk mitigation preferences of decision-makers (Giarola et al., 2013). A multi-objective MILP model together with Pareto curves was applied to illustrate the optimization results of the sustainable supply chain design for municipal solid waste, which maximize the economic profits while accounting the technical and environmental indicators (Santibañez-Aguilar et al., 2013). The MILP method was also selected to explore the biomass pyrolysis for biofuel production supply chain facility location, facility capacity at strategic levels and biofuel production decisions at operational levels (Zhang and Hu, 2013). Besides MILP model, mixed integer nonlinear programming (MINLP) optimization approach can also be employed in the supply chain design. Corsano et al. (2011) built up a MINLP model for the design of sugar/ethanol supply chain considering the evaluation of environmental influence.

Some researchers may also construct novel approaches toward specific case of supply chain analysis based on other mathematical models and assessment tools. A mathematical model which can deal with time-staged, multi-commodity, production/distribution system, prescribing facility locations and capacities, technologies and material flows was formulated for the optimization problem of the design for a lignocellulosic biofuel supply chain (An et al., 2011). A novel optimization framework based on biomass element life cycle analysis (BELCA) was developed to solve the planning problem of biomass supply chain (Lim and Lam, 2016). Mota et al. (2015) constructed a multi-objective programming model to design the supply chain with the consideration of three dimensions of sustainability, that is environment, economy and society.

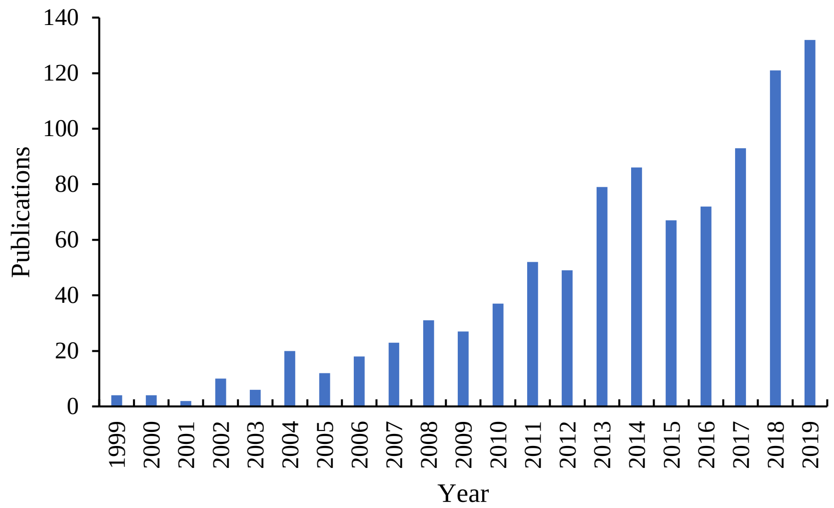
According to the above literature review, MILP and multi-objective programming model are the two common tools to help with the design of different types of supply chains. There also exist some other methods applied in this field, such as MINLP and some novel approaches based on other kinds of assessment methods (MCDM methods, especially AHP approach and life cycle analysis). However, the investigations regarding the application of other approaches are relatively limited. Among the reviewed papers, some considered the uncertainty and risk mitigation preference of the decision-makers, while most of the studies focused on the general simple case. Hence, there is still plenty of room for the improvement of sustainable supply chain design and management for different kinds of products. For more systemic reviews of the methods employed in supply chain design, some overviews can provide more related references and comprehensive information. De Meyer et al. (2014) provided an overview of the optimization methods and models on the decision-making for design and management of the biomass-for-bioenergy supply chain. Seuring (2013) presented a review for the modelling methods applied in supply chain management and pointed out that LCA-based approaches dominated, and the research considered social aspect were limited. Chithambaranathan et al. (2015) formed an integrated grey MCDM approach based on ELECTRE and VIKOR to assess the environmental performances of a service supply chain.

Supply chain can also be regarded as a powerful tool with wide application which can be associated with various disciplines. It can usually provide a more holistic view of the larger picture for the researchers toward the investigated supply chain of a specific product or service. It has been widely applied in various industries and business, like different kinds of traditional energy and resources supply management and waste-to-energy management. Industrial engineering, systems engineering, operations management, logistics, procurement, information technology and marketing all provide valuable experience for strive for an integrated approach for supply chain management (Kozlenkova et al., 2015). Present research in supply chain design management focused on the topics relevant to sustainability and risk management (Lam, 2018). Proper supply chain design for the contribution of better development circular economy is also one of the topics of current supply chain management research. Several different waste-to-energy technologies were assessed and employed to form different types of WTE supply chains aiming at achieving circular economy system (Pan et al., 2015). The state-of-art of the waste biomass-to-energy supply chains (WBSCs) design and management was reviewed by presenting the generic system components and the unique characteristics of WBSCs that differentiate them from traditional supply chains (Iakovou et al., 2010). A risk management approach based on the MILP modelling framework for the economic and environmental strategic design of ethanol supply chains was proposed and developed (Giarola et al., 2013). An environmental performance evaluation for service supply chain was conducted for a better management and development of service supply chain (Chithambaranathan et al., 2015). Some researchers explored the role of sustainable supply chain management as a catalyst of generating valuable inter-organizational resources and the possible sustained inter-firm competitive advantage by collaboration on environmental and social aspects (Gold et al., 2010). Eskandarpour et al. (2015) provided an optimization-oriented review for the sustainable supply chain network design. Sustainable wine supply chain has also been studied as a branch of waste management with the consideration of the influence in new business, economic, social and physical environment (Malindretos et al., 2016). Mota et al. (2015) employed a generic multi-objective mathematical programming model to design and manage the supply chains with the integration of three sustainability pillars. All these literatures indicate the essential role played by supply chain management in sustainable development in the current context. Based on the discussion for the research on supply chain design, waste-to-energy and biomass for bioenergy production have gradually caused wide attention during recent years. These investigations can be regarded as the basis of sludge-to-energy supply chain design and management, which are reviewed in detailed in the next subsection.

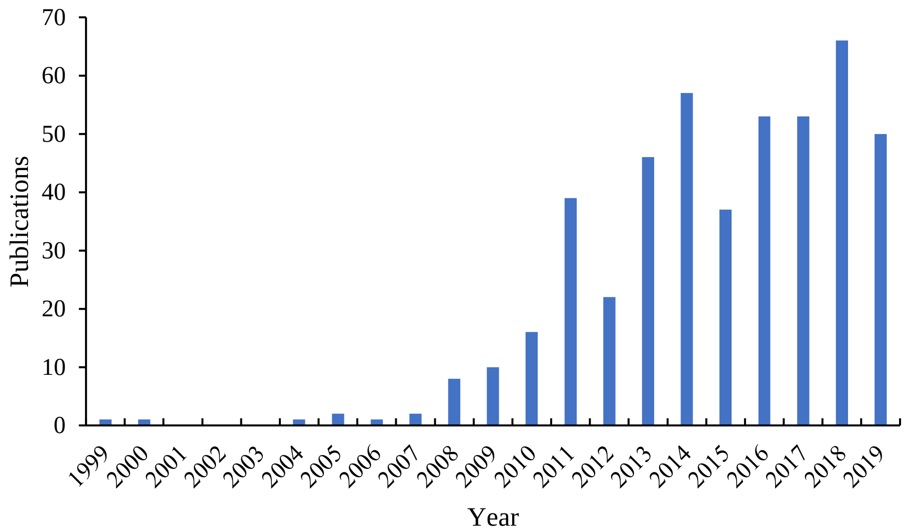
2.6.2 Supply chain design for sludge valorization technologies

To the best of our knowledge, currently there is no study conducted on the sludge-to-energy supply chain design. However, the supply chain design of sludge, which is regarded as a kind of biomass and waste generated from wastewater treatment plants with wide range of sources, can refer to waste-to-energy and biomass supply chain management. Therefore, the literature review of this subsection focuses on the studies on waste-to-energy and different kinds of biomass supply chain optimization to provide a basic outline of the corresponding problem in sludge management field.

According to the database provided in Scopus, there are over 66,000 pieces of work regarding the keywords “supply chain design”, “supply chain optimization” or “supply chain management” from 1999 to 2019. It is obvious that the concern on supply chain management in different disciplines gradually increase (“Scopus: Scopus Preview,” 2020). If the keywords were changed into “sustainable supply chain design”, about 2400 related papers were presented in the searching results during the recent two decades. There are less than one thousand investigations on waste supply chain and half a thousand of studies on biomass supply chain design (see Figure 2.20). Hence, although the total proportion of waste and biomass supply chain design is quite small among all the relevant research on supply chain design, the concerns on sustainable waste-to-energy management still rise and may become a hotspot in the future research. The summary of waste/biomass supply chain also has guiding significance to the study of the sludge-to-energy supply chain management, which makes the review for biomass supply chain management necessary as the basis for the future research of sludge supply chain design.



(a)



(b)

Figure 2.20 The number of publications on (a) waste supply chain design, and (b) biomass supply chain design (“Scopus: Scopus Preview,” 2020)

Previous studies have explored the sustainable biomass or waste supply chain design by diverse approaches. A multi-objective optimization approach was built up to optimize such a biomass supply chain (BSC) accounting for the simultaneous maximization of the net present value and environmental performance (Murillo-Alvarado et al., 2015). Paulo et al. (2015) utilized a mixed integer linear programming

(MILP) model to design a residual forestry biomass supply chain for bioelectricity production. Paolucci et al. (2016) constructed a two-tier approach aiming to optimize a biomass supply chain for pyrolysis processes with the considerations of both economic and environmental aspects. Life cycle analysis was also combined with the biomass supply chain design to address the environmental impacts, which can provide a better understanding of the features of the investigated biomass for higher level applications (Lim and Lam, 2016). A mixed-linear programming method with robust optimization was employed to develop a global reverse supply chain (GRSC) of solid waste (e-waste management) (Xu et al., 2017). A multi-stage mixed integer linear program integrating spatial and temporal dimensions was developed to minimize the total cost of the biofuels supply chain from biomass waste as well as satisfying demand, resource and technology constraints (Huang et al., 2010). A multi-objective mixed-integer linear programming model for the optimal planning of the supply chain of municipal solid waste (MSW) management system was established to maximize the economic benefit while accounting for technical and environmental issues (Santibañez-Aguilar et al., 2013). Fiorese et al. (2013) proposed a method to evaluate the energy balance and environmental and economic feasibility of a biomass-based energy supply system, considering the biomass production, harvesting and transportation as well as capital investment and operating costs. A mixed integer linear programming model was presented to the design and optimization of a general biofuel supply chain as well as investigate the biofuel supply chain facility location, facility capacity at strategic levels, and biofuel production decisions at operational levels (Zhang and Hu, 2013).

There are also some literature reviews on waste/biomass-to-energy supply chain design which can contributes to a more comprehensive and multifaceted understanding of waste/biomass supply chain design. According to the literature review provided by Pan et al. (2015), bio-heating, incineration, and co-digestion were the common technologies applied in constructing waste-to-energy (WTE) supply chain design, because of the generation of various types of bio-fuels which own wide application in energy supplying. Bioethanol supply model, mathematical programming models and MCDM framework have been utilized to optimize the WTE supply chain. Pan et al. (2015) reviewed the frequently employed processes including combustion, gasification, and anaerobic digestion. The involved feedstocks including four major types of waste according to their classifications. The authors pointed out that implementing the WTE supply chains to promote the development of circular economy system usually needs to consider eight key tasks: command and control (CC), economic instruments (EI), information platform (IP), technical assistance (TA), research and development (R&D), public-private partnership (PPP), international collaboration (IC) and environmental education (EE). These taskforces can be roughly divided into four dimensions, i.e., social aspect, economic aspect, environmental aspect, and technical aspect, which are usually influenced and correlated with each other. Meanwhile, they also provided four typical successful examples of WTE supply chains, whose major information have been summarized as follows.

Table 2.12 Summarization of the four major types of WTE supply chain and typical application cases (Pan et al., 2015)

Feedstocks	Target energy	Typical cases
Green fuel pellet (recycled wood waste)	Heating supply	1. Avedøre power station in Denmark, with the ability of burning "wood

		pellets" of up to 70% co-combustion and total plant efficiency of 51% (Hedrick, 2013). 2. Yong-An Industrial Park in Taiwan, with the application of CHP technologies in the integrated energy supply system, successfully reducing the waste and CO_2 emissions.
Paper and pulping industry wastes	Utilized in CHP plant	1. Hua-Lien County (Taiwan), applying biomass like straw residues, driftwood, domestic wastes and waste clam for the biorefinery technology. 2. Employing waste black liquor from pulping process for the generation of dimethyl ether (DME) through Chemrec black liquor gasifier (BLG) (Flink et al., 2007).
Animal residues	Biogas production	1. "Centralized" biogas plant in Denmark (Raven and Gregersen, 2007)s. 2. "On-farm" anaerobic digestion plants in Germany (Wilkinson, 2011). 3. Co-digestion of agriculture wastes, food industries, slaughterhouse waste and animal manure for the biogas production in Linkoping biogas plant (Nordberg, 2013).
MSW/WWPT	Functioned as a district energy supply center	1. Ho-Li Incineration and Cheng-Loong Crop for heat recovery and supply. 2. The Back River WWPT in the Baltimore city utilizes biosolids to produce biogas (Wilkinson, 2011),

These cases had important implications for the practices in other countries. Besides the review of Pan et al. (2015), Sharma et al. (2013) analyzed the development of biomass supply chain design and found out the barriers and challenges for the future work. They have summarized the basic technical routes for the biomass-to-energy. Oil crops, sugar and starch, lignocellulosic, and wet biomass can be converted into biodiesel, ethanol, hydrocarbon or bio-oil, producer gas, pellets, and biogas through different technologies, such as transesterification, hydrolysis-fermentation, pyrolysis-hydrogenation, gasification, and anaerobic fermentation. The generated products or energy can be applied as biofuels for transport, electricity generation and heating supply. They also provided discussion on decision level, supply chain structure, modeling methods and quantitative performance measures in depth. More detailed information and summarization of the employed feedstocks and end-products and be directly found in the research (Sharma et al., 2013).

Ravindran and Jaiswal (2016) explored the research development in respect to the valorization of food industry waste into valuable products, such as biofuels, enzymes and organic acids. In the synthesis analysis of Iakovou et al. (2010), the cost and complexity of the logistics operations in the waste biomass-to-energy supply chain design and management were regarded as the two major barriers that hindered the wide application and promotion of biomass for energy production. According to their review, most studies focused on the thermochemical processes and anaerobic digestion for biogas generation while fewer investigations involved the aerobic technologies and physicochemical approaches. They identified the hierarchy of the decision-making problem, which was shown in Figure 2.21. Detailed discussion can be referred to the review article (Iakovou et al., 2010). It should be noted that the authors argued that the existing research concerned more on the collection of biomass and the energy production, which were the first and the last links in the supply chains, and less efforts were spent on the sustainable supply chain network design systemically. On the other hand, only handful papers discussed the profitability and environmental loads in balance, while the majority still put the economic benefits in a higher priority. All these state-of-art indicated the research gaps of current biomass supply design.

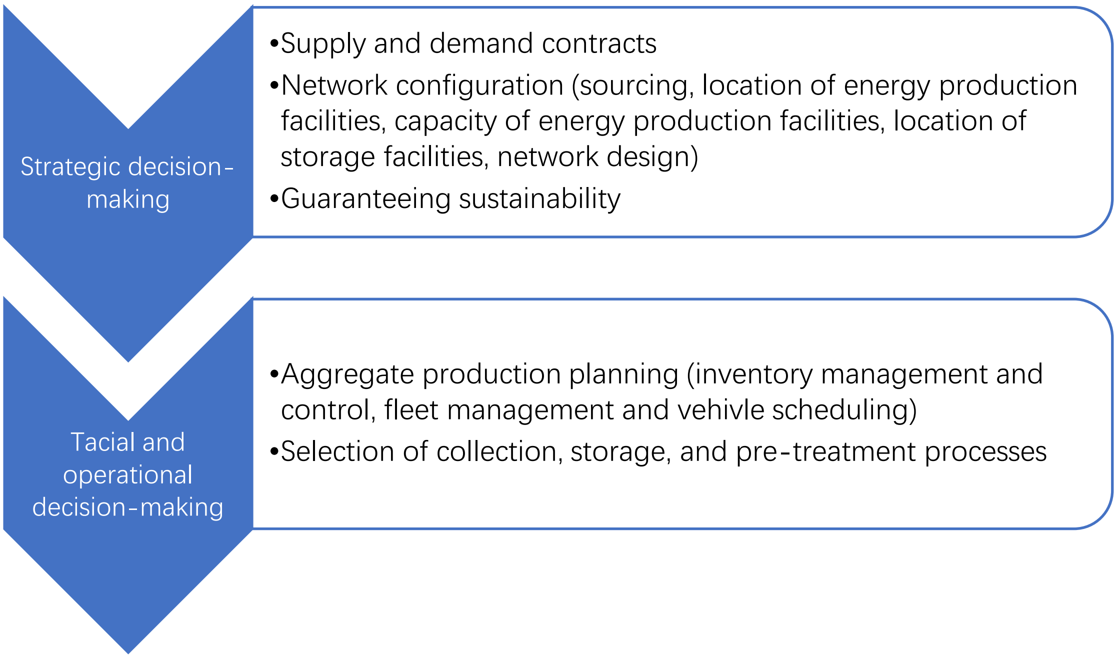


Figure 2.21 The hierarchy of the decision-making process for biomass supply chain design (Iakovou et al., 2010)

De Meyer et al. (2014) summarized and classified the frequently applied optimization models and approaches in the biomass-to-bioenergy supply chains design and management. Similar with the discussion of Sharma et al. (2013), De Meyer at al. (2014) also pointed out that mathematical programming models were commonly employed in the supply chain design and optimization. Besides, the application of heuristics and multi-criteria decision analysis (MCDA) were also discussed and their analysis results showed that most of the reviewed publications applied MCDA on the strategic decision level. More detailed information can be found in the review of De Meyer et al. (2014). Seuring (2013) presented a review for the quantitative methods, which emphasized the application of LCA, equilibrium models, MCDM, and AHP. The author also pointed out that in the three dimensions of sustainability, social aspect was the one that addressed the least compared with economic and environmental dimensions (Seuring, 2013). Hong et al. (2016) reviewed the sustainable biomass supply chain and discussed the related concepts and models in depth. The authors provided the taxonomy, the logistic and common models applied for sustainable supply chain design, including mathematical programming (linear programming and mixed integer linear programming), heuristic approach, hybrid model and IT-driven model (Hong et al., 2016).

Some researchers also have discussed the state-of-art of biomass supply chain management in specific country. Ghosh (2016) reviewed the biomass and bio-waste supply chains for bio-energy and biofuels production in the context of India. The analysis results showed the major challenges that need to be overcome for future better development of biomass supply chain management, such as feedstock supply, efficiency, export of output energy and the government policy, which may provide important reference for the other developing countries to manage related field (Ghosh, 2016). Although there is limited research on waste or biomass supply chain management for the context of China, some studies have investigated the sustainable supply chain design in other fields which may provide reference for the related waste supply chain management. (Zeng et al., 2017; Zhu et al., 2007).

According to the above literature review, there are many types of waste and biomass involved. Some papers analyzed the supply chain which applied a specific biomass as the feedstock, such as the waste from tequila industry (Murillo-Alvarado et al., 2015), wine (Malindretos et al., 2016), forestry waste (Paulo et al., 2015), and MSW (Santibañez-Aguilar et al., 2013). Some articles directly proposed a framework for the general biomass supply chain which may process different types of waste simultaneously. The common categories of the feedstocks have been classified as Table 2.13 according to the classification standards of Iakovou et al. (2010). Pan et al. (2015) classified the types of feedstocks according to the waste source, i.e., agricultural waste, industrial waste, animal waste and municipal solid waste. Sharma et al. (2013) presented the biomass types among over 30 studies regarding biomass supply chain design and revealed that multiple biomass types occupied around half of the reviewed articles.

Table 2.13 The categories of common biomass/waste in supply chain design (Iakovou et al., 2010)

Categories	Organic substrates
Energy crops	Miscanthus, triticale, etc.
Residues	Straw, forest residual wood, etc.
Byproducts	Manure, industrial residual wood, etc.
Waste	Sewage sludge, slaughterhouse waste, agricultural waste, etc.

The end products involving in biomass supply chains are usually the treatment products, such as biofuels (biogas, bioethanol, and bio-oil), and bioelectricity and the application in heating and cooling system (Sharma et al., 2013), where biofuel was the frequently discussed end-product in the sustainable biomass supply chain system. It is crucial to identify the targeted biomass types and end-products for the construction of the entire supply chain (Sharma et al., 2013). From the perspective of investigated scope, it usually includes the allocation of feedstock sources, transportation, storage, main treatment, and the allocation of markets. The factors and related consideration for the scope can be very complex involving with various aspects, such as locations, mode of transportation, and specific technique routes (Sharma et al., 2013).

In the reviewed research for supply chain design and optimization, the mathematical programming models were most frequently used, especially the mixed integer linear programming model. According to the summarization of Sharma et al. (2013), nearly 20 articles among the total 31 reviewed papers applied mixed integer linear programming or integer linear programming methods. Some authors improved the framework for supply chain optimization based on the traditional mathematical models, like two-tier or two-stage approaches (Lam et al., 2013; Paolucci et al., 2016). The application of the mathematical models indicates the feasibility and availability of the programming methods in this field. As for the considered objectives, economic performance is given priority to make profits from the supply chain optimization. The overall costs, entire profits, net present value, financial income, and transportation costs could be the optimization objectives of the supply chain design (De Meyer et al., 2014). If the sustainable supply chain was discussed, the environmental impacts, like greenhouse gas emissions, would also be accounted to evaluate whether the potential negative influence was acceptable. Social aspect was rarely discussed compared with the economic and environmental dimensions. The creation of jobs and social footprint were investigated by two research papers according to the overview of De Meyer et al. (2014). This fact indicated that the related consideration on social dimension is still insufficient and more efforts are still expected to improve this field.

2.6.3 Suggestions for the research of sludge-to-energy supply chain design and management

Based on the above literature review and discussion for biomass/waste supply chain design, some useful experience which is beneficial to the research of sludge-to-energy supply chain management can be obtained, including the suggested models, investigated aspects and structure of the supply chain.

Firstly, some novel methods newly proposed can be considered to apply in solving the sludge-to-energy supply chain problem. According to the previous research, most of them have been verified that they can effectively process the optimization problem of biomass supply chain design. Therefore, it is possible to use these new methods in sludge supply chain optimization, such as the two-tier or two-stage mixed integer linear programming models (Lam et al., 2013; Paolucci et al., 2016). Mathematical programming models, like linear programming, non-linear programming and multi-objective programming, can be reliable tools since they can work as the basis in handling the optimization problems.

Secondly, more aspects except environmental and economic aspects can be considered to provide a more comprehensive performance assessment of the investigated supply chain, especially social indicators. Currently, environmental and economic dimensions were the major focuses in the related research while social dimension was rarely discussed. However, social aspect is also necessary for sustainability evaluation (Ciroth et al., 2011). Therefore, more social indicators which can address the social impacts of the supply chain should be considered in the modelling, which can refer to Section 2.2 in respect to the social life cycle assessment. It should be noted that although the selection of indicators is based on the needs and objectives of the specific supply chain, some special environmental indicators which are rarely considered in the supply chain design, such as the emissions of dust, NO_x and SO_x, are also worthy to analyze due to the characteristics of feedstock sludge and treatment technologies.

Thirdly, multiple tools can be combined and employed at different stages of the supply chain optimization problem. For example, if the sludge-to-energy supply chain design is sustainability-oriented, then the international standards of life cycle sustainability assessment can be applied to form the indicators system and constraints. Multi-objective decision-making approaches or multi-objective programming can help to establish the objective function. Subsequently, mixed integer linear programming model can be used to solve the problem and obtain the optimal values for the decision variables and objective function.

In addition, uncertainty is also worthy to discuss due to the widespread vagueness and unavoidable subjectivity in sludge-to-energy supply chain design, especially when the emerging technologies are considered. As it has been mentioned before (in the literature review section for sewage sludge-to-energy technologies section), many techniques of sludge-to-energy are emerging and still under research, which means the limited maturity of the technologies. The related data on these technologies usually accompany with wide variations, leading to the uncertainty of the following assessment and management. Hence, the consideration of uncertainty and vagueness is essential and necessary. Fuzzy theory and stochastic theory can be utilized to process the problems with uncertainty (Sharma et al., 2013). To further improve the optimization framework for sludge-to-energy supply chain, the planning of supply chain network should also be tested by the proposed approach to verify the feasibility and ability of processing more complex problem. Future research can consider the above aspects to further promote and improve the studies of sustainable supply chain design for sludge-to-energy.

Chapter 3 Sustainability-oriented evaluation and multi-criteria decision analysis framework

In this chapter, an overall picture for the research methods is presented to illustrate the basic working flows of the studies in this project. A brief introduction of the involved methods applied in each chapter is also included according to the categories. In Session 3.1, the logic relationship between the major studies in each chapter (from Chapter 4 to Chapter 8) and the methodology framework are presented and described. In Session 3.2, the applied methods in different chapters are introduced based on the framework to provide a clear recognition for the methodology applied in this research.

3.1 Methodology framework of sustainability evaluation and decision-making analysis

To solve the research problems and fill the research gaps presented in the Introduction Session, literature review and five major studies were conducted in this project. The relationship between each chapter and research gap is shown in

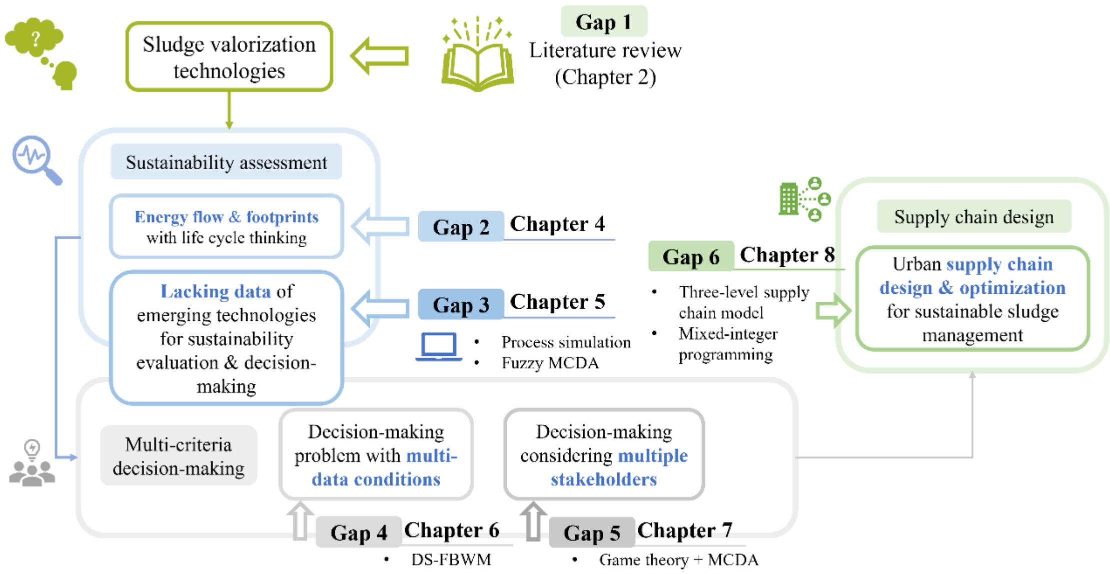


Figure 3.1. According to

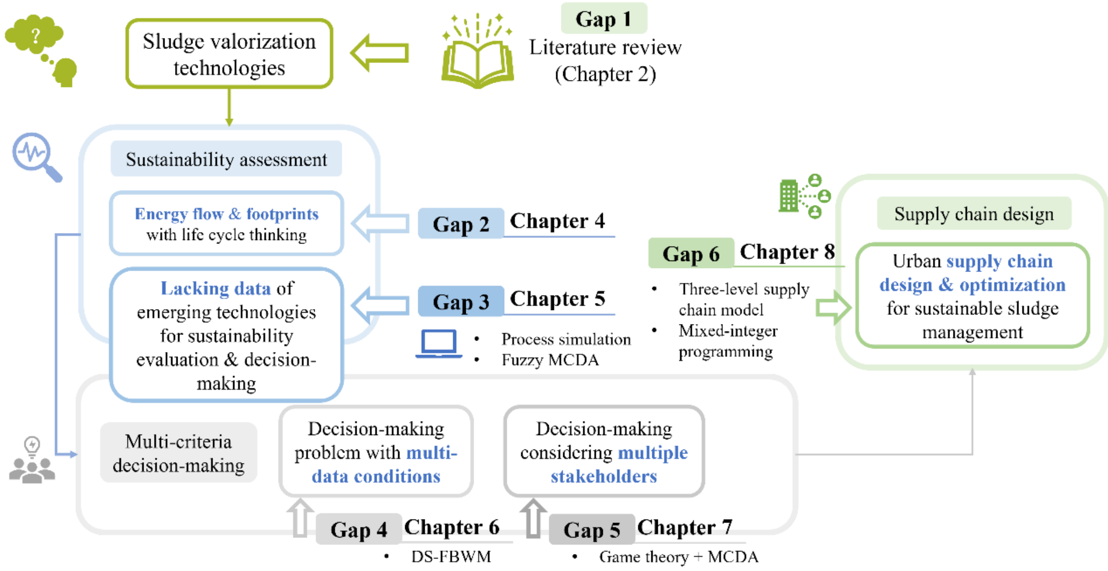


Figure 3.1, there are four major sections involved in this research, including literature review, sustainability assessment, decision-making analysis, and supply chain design for sustainable sludge management. Literature review for the sludge valorization technologies was firstly conducted to understand the basic features of some typical techniques (correspond to research gap 1 in Session 1.2), which has been presented in Chapter 2 (Session 2.1). Sustainability assessment aims to provide comprehensive performance evaluation for the considered alternatives from the perspective of sustainability. Two research gaps are discussed in this stage, including gap 2 and gap 3. These two research gaps are addressed by Chapter 4 and Chapter 5, respectively. For gap 2, a life cycle composite footprint index is constructed to analyze the energy flows and footprints of the concerned elements in sewage sludge in Chapter 4. Data deficiency problem is addressed by using process simulation combined with fuzzy MCDA method in Chapter 5. The study presented in Chapter 5 is not only associated with sustainability evaluation, but also related to decision analysis. With the performance data obtained by

sustainability evaluation, decision-making analysis under different situations can be carried out. Two major types of decision-making problems are discussed in this research, including decision-making problems with multi-data conditions (gap 4 addressed by Chapter 6), and group decision-making problems considering conflicting interests between stakeholders (gap 5 addressed by Chapter 7). Based on all the performance assessment and decision-analysis tools in the former two stages, a supply chain design and optimization model is established to guide the sustainable management of sewage sludge from a macroscopic perspective, which is presented in Chapter 8 (gap 6).

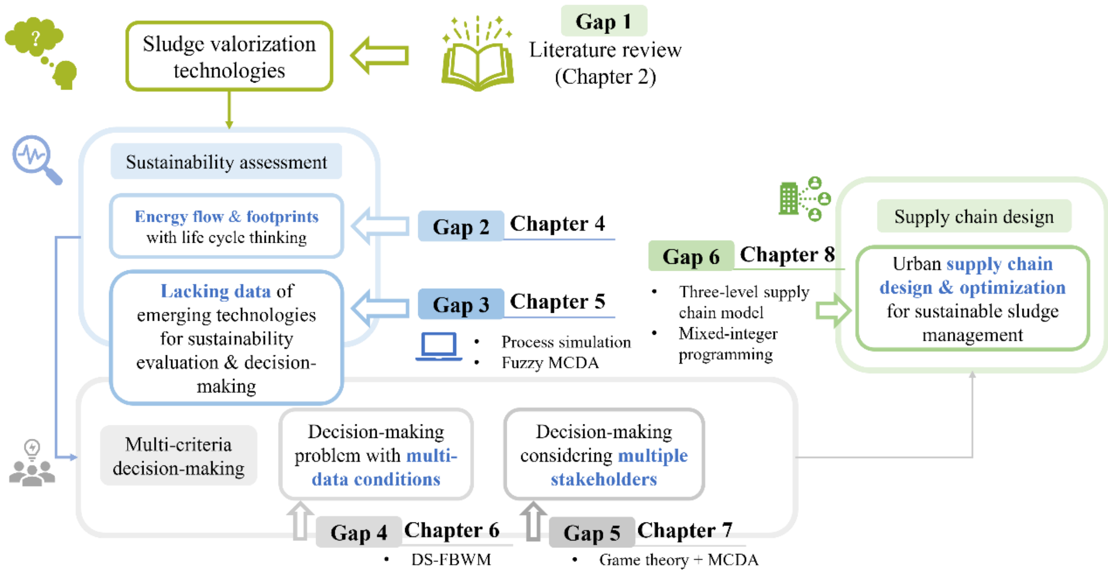


Figure 3.1 Relationship between the major studies in this research

As for the specific working flow for each study, the combination of LCSA and MCDA is the core thought and basis in the main methodology. LCSA is applied for comprehensive sustainability evaluation and MCDA is utilized to conduct decision-making analysis under different conditions. The detailed review on LCSA and MCDA has been presented in Chapter 2. The general framework adopted by in this research is shown by Figure 3.2. The major studies presented in this project basically follow the thinking. After identifying the research question, a clear and specific literature review and relevant data collection are conducted for the specific question. Based on the literature review results and data collection, assessed alternative should be determined and criteria system should also be established to illustrate the performance evaluation and decision-making process. Then, performance evaluation is carried out according to the collected data and principles of LCSA. According to the literature review in Chapter 2, there are three frequently considered aspects in sustainability assessment, i.e., environmental LCA, LCC, and SLCA. Technical perspective can also be selected as the fourth aspect for sustainability performance investigation. These assessment methods are all conducted complying with the instructions of international standards, including ISO14040, ISO14044, ISO14047-14049, ISO14072 for LCA, and ISO15663 for LCC to provide standardized results with respect to their impacts. More specific setting for the indicators is introduced in the corresponding chapter.

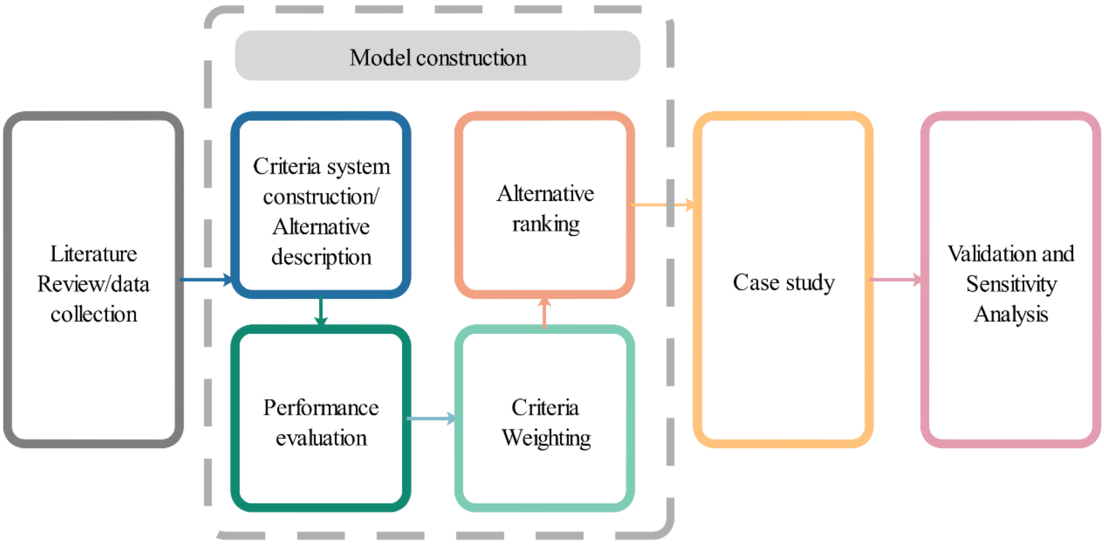


Figure 3.2 The general methodology framework of LCSA combined with MCDA in this research

Criteria weighting is a necessary step to evaluate the importance of selected indicators according to the preference of decision-makers. There are different kinds of weighting approaches which have been reviewed in detail in Session 2.4. Since decision-making under uncertainty (including the vague information provided by decision-makers from linguistic terms) is one of the focuses in this research, MCDA methods combined with fuzzy theory are selected in this research to determine the weights.

Due to the general existing bias and inherent merits and drawbacks of different alternatives, the results of LCSA cannot be directly used to determine the alternative ranking. Data process is necessary for the subsequent performance analysis. MCDA methods are frequently applied and combined with LCSA since they can consider the performance on multiple criteria and prioritize the alternative based on different perspectives. The combination of LCSA and MCDA can compensate the shortcomings of these two method categories. LCSA can provide comprehensive performance evaluation results of different technologies on various aspects and indicators, which can be regarded as scientific and reliable data basis for the subsequent decision-making. MCDA methods can combine the subjective preference with the objective performance data and generate an overall ranking based on the performance information. More detailed introduction and literature review can be found in Chapter 2 and corresponding study in the following sessions.

The combination of LCSA and MCDA is the major part for the model construction. Subsequently, a case study is introduced to verify the feasibility and reliability of the proposed model for solving the specific research problem. Sensitivity analysis and validation analysis are also carried out to explore the stability and robustness of the proposed model by assuming different conditions and scenarios. Specially, Chapter 8 presents a study on supply chain design and optimization, of which the methodology framework is a little bit different from the framework provided by Figure 3.2 since the content of Chapter 8 focuses more on supply chain design, rather than just deciding the best technology. But the major thought is still similar. Detailed description of the methodology framework of Chapter 8 can be referred to the corresponding chapter.

3.2 Specific methods involved in the methodology framework

In this subsection, specific methods applied in this project are briefly introduced according to the procedures of methodology framework. More detailed description on the methods in different studies can be found in the corresponding chapter.

3.2.1 Data collection

Data is the basis for sustainability evaluation and multi-criteria decision analysis. The accuracy and reliability of prioritization is influenced by the reliability of the data. Therefore, data collection for the assessed technologies plays an important role during the entire evaluation and decision-making process. In this project, data collection is majorly conducted by the following three approaches, i.e., collecting from literature review, estimating based on LCSA framework, and process simulation. Different approaches can be combined to obtain reliable data for the further analysis.

3.2.1.1 Data from literature

Literature review is a very common way for data collection. Many research papers, statistics reports, surveys, and patents can provide important reference information for performance evaluation. Tarpani et al. (2018) conducted LCC analysis for wastewater and sludge treatment systems based on the data from literature and some suitable assumptions. Some studies also compared and summarized the LCA results for sewage sludge management (Yoshida et al., 2013). Rillo et al. (2017) analyzed life cycle impact assessment of biogas-fed solid oxide fuel cell system under different scenarios. The data from literature no matter the primary data or the LCSA results can be adopted as the data source for sustainability evaluation and decision-making analysis, if they comply with the following principles for reducing errors.

1. The collected data should be in the same or similar period. For example, the data of two studies are collected from 2009 to 2014.
2. The data collected should be within the same research scope, which means that the investigated life cycle stages should be consistent.
3. The data should be processed and converted based on the same functional unit for clear and scientific comparison. For example, the inventory data of two alternatives are both analyzed by using the generation of 1 kWh of net electricity.
4. The inventory method should be the same. For instance, the LCA data for the assessed scenarios are obtained by applying the ReCiPe 2016 Midpoint (I) method.

3.2.1.2 Data from life cycle sustainability assessment

Researchers may also use LCSA to generate the necessary data based on literature review, field research, experiments, and process simulation for inventory data collection.

Compared with direct data collection solely from literature review, this approach can be more pertinence. It can also effectively help to deal with the situation when the data from literature are not available or eligible. The basic working flow for conducting LCSA in this research is shown by Figure 3.3. An effective LCSA tool called SimaPro is applied. Simulation and literature review are combined to deal with the problem of information insufficiency.

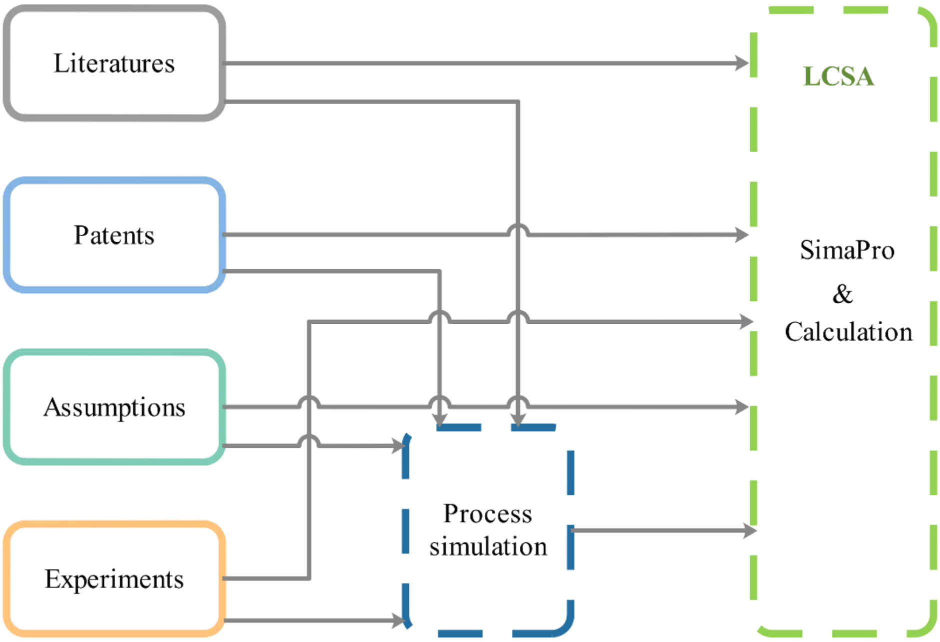


Figure 3.3 Basic flowchart for LCSA in this research

3.2.1.3 Data from process simulation

As it has been presented in Figure 3.3, process simulation results can also be applied to obtain the necessary data for performance evaluation. The detailed literature review on process simulation has been provided in Session 2.3 in Chapter 2. Simulation software can be a powerful tool to analyze and understand the principles of the investigated technologies. Chapter 5 and corresponding appendix (Appendix Part III) introduce the application of process simulation for data collection in details.

3.2.2 Criteria weighting methods

Criteria weights determination is an essential step to analyze the priority of the assessed alternatives. In the process of decision-making, three aspects are frequently considered to decide the relative importance of criterion, including the independency of criteria, the variance of criteria, and the preferences and needs of the stakeholders/decision-makers. Equal-weight method is a common and simple method for weighting which requires the least knowledge for the related process. However, it is also criticized due to the ignoration of the influence and relative importance between de various indicators. Therefore, rank-order weighting methods are developed which means that not all the weights are identical. The rank-order weighting methods can be classified into three categories consisting of subjective weighting methods, objective weighting methods, and the combination of the former two categories (Wang et al., 2009). The major merits and shortcomings of the subjective and objective weighting methods have been discussed in the previous studies (Pöyhönen and Hämäläinen, 2001; Wang et al., 2009). In this project, the weights of criteria are majorly determined based on the opinions and needs of decision-makers, which means that subjective weighting methods are mainly selected. With the propose and development of typical subjective weighting method, i.e., AHP method, has gradually combined with different theories and different variants are generated which can handle different complex situations in decision-making processes. Best-worst method (BWM), which is also a pairwise comparison method for criteria weighting, is frequently used to decide weights since it can provide more reliable consistency ratio within relatively simple calculation steps.

More detailed literature review can be found in Chapter 2 and corresponding studies. The weighting methods applied in this research include fuzzy BWM (Chapter 4, Chapter 6) (Guo and Zhao, 2017), fuzzy AHP (Chapter 4) (Hsieh et al., 2004; Sun, 2010), revised fuzzy BWM (Chapter 5) (Dong et al., 2021), and an individual and group fuzzy BWM (Chapter 7) (Hafezalkotob and Hafezalkotob, 2017). Specific introduction and description on the calculation steps for these methods can be referred to the corresponding studies and chapters.

3.2.3 Alternatives ranking methods

Since detailed literature review on MCDA methods has been conducted in Chapter 2 as Session 2.4, similar content will not be repeated here. Some more systematic and detailed introduction can be found in the previous reviews (Kumar et al., 2017; Wang et al., 2009). The MCDA methods applied in this research cover weighted sum method (Chapter 4), and extended fuzzy PROMETHEE II approach (Chapter 5). Dempster–Shafer theory was combined with fuzzy BWM to deal with the decision-making problems under multi-data conditions (Chapter 6). In addition, game theory is also utilized to solve group decision-making problems and provide decision-making reference (Chapter 7). In the supply chain design and optimization problem, mix-integer programming model is constructed (Chapter 8). Although the analysis approach is different from the traditional and common MCDA method, the results of mix-integer programming model can also provide useful reference to ranking the alternatives and help to figure out a suitable choice.

3.3 Summary

In this chapter, a methodology framework is presented for the sustainability-oriented decision-making analysis to illustrate the core thoughts and working flow of the specific studies. The internal logical relationship between each chapter is also illustrated. The basic logic follows literature review, sustainability evaluation, decision-making analysis and supply chain design and optimization. There are four major steps in the specific working flow in each study, including literature review and data collection, mode construction, case study, and validation and sensitivity analysis. Considering the differences of the investigated problems, the detailed establishment of the model may be different with each other, but it still contains the following basic steps, i.e., criteria system construction and alternative description, performance evaluation, and decision-making analysis. Adjustment can be flexibly conducted based on the specific research problems and conditions.

Chapter 4 Life Cycle Energy-Carbon-Water Nexus Analysis of Sludge-to-Electricity Technologies

In this chapter, a composite sustainability index based on life cycle assessment is developed to evaluate the performance of sludge treatment technologies. Electricity is a common and widely used energy form in the life of the public. Therefore, sludge-to-energy technologies with considerable electricity recovery were studied in detailed in this chapter. In Session 4.1, the problem is described and the corresponding research gaps are figured out. Then the proposed method is constructed in Session 4.2. Performance evaluation of six sludge-to-electricity technologies is investigated as the case study in Session 4.3. Results analysis and discussion are carried out in Session 4.4. The major contributions and limitations are concluded in Session 4.5.

4.1 Problem description

The potential of energy and resources recovery from sewage sludge has gradually recognized by more and more researchers (Fytili and Zabaniotou, 2008). It is important to investigate the energy recovery efficiency because it is one of the major concerns of the feasibility and potential of sludge-to-energy technologies. High organic matters content in sludge can result in high emissions of carbon dioxide during sludge treatment process. Meanwhile, high moisture content leads to the necessity of water recycling from sludge treatment process, otherwise a vast amount of water would be wasted. It is also necessary to analyze the behaviors of some elements which may pollute the environment or be recovered, such as nitrogen, sulfur (S) and phosphorus, for better treatment or recovery. Thus, energy and matters flow analysis, especially energy recovery, water consumptions and carbon emissions, are important to consider when studying the performance of various sludge treatment technologies. Nevertheless, different technologies have different advantages and drawbacks due to the various features, which make it difficult to make a suitable choice among the diverse options. Hence, sustainability assessment to evaluate the performances in different aspect is highly necessary. Life cycle assessment (LCA) considering the full life stages of a product or a process is a powerful tool for environmental and economic influence evaluation (ISO 14040, 2006). The application of LCA on sustainability assessment for targeted systems, including sewage sludge management, has been gradually recognized during the past decades (Yoshida et al., 2013). Current assessment work focused more on the environmental and economic performances of several common sludge treatment technologies, majorly including anaerobic digestion, incineration (Hong et al., 2009; Xu et al., 2014), pyrolysis (Kim and Parker, 2008; Li and Feng, 2018), and wet air oxidation (Svanström et al., 2004; Tarpani and Azapagic, 2018). Although there are plenty of evaluation work for sludge treatment technologies, few studies investigated the aspects beyond environment and economy, such as technical maturity, social acceptability, and some important footprints analysis. According to the above discussion, the following research gaps can be revealed:

1. It lacks an evaluation index to address the sustainability performance based on the concerned footprints for sludge management system.
2. Emerging technologies were rarely discussed in the previous research and the focus

was majorly limited in environmental and economic aspects.

To fill the above-mentioned research gaps, this chapter built up a methodology framework to discuss and analyze the sustainability performances from the perspectives of environment and technology for sludge-to-energy technologies by using a composite footprint index with life cycle thinking. The footprints described in this work included energy, water, carbon (C), nitrogen, and sulfur, while the similar core thought can also be promoted to other matters and elements footprints analysis. Fuzzy Best-Worst Method (BWM) and Fuzzy Analytic Hierarchy Process (AHP) method were applied to integrate the considered footprints together and obtain an overall evaluation result for the investigated scenario. The entire framework of this chapter is illustrated in Figure 4.1.

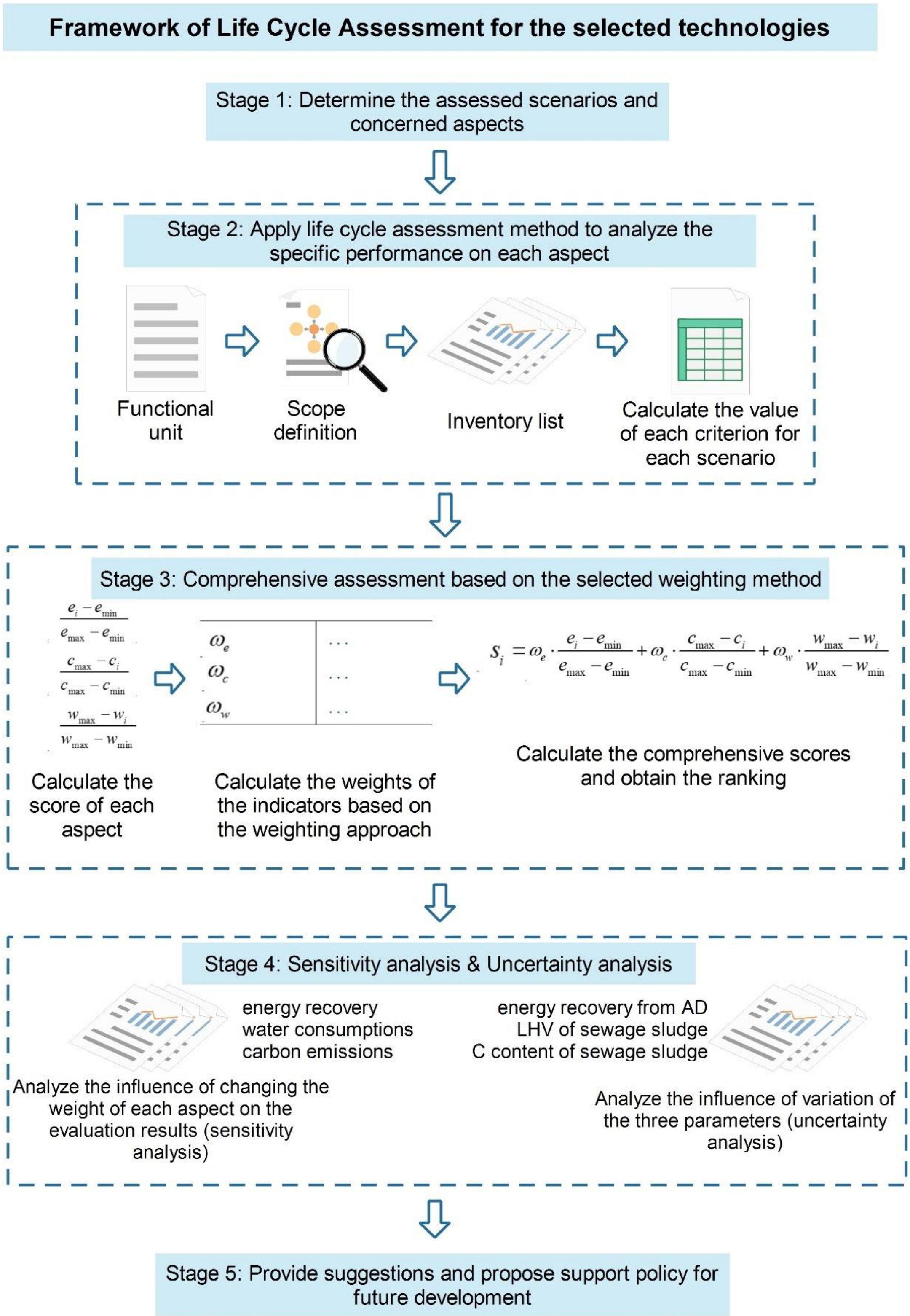


Figure 4.1 The entire methodology framework of life cycle assessment for the selected technologies in this study

4.2 Methodology

In this section, a methodology framework with life cycle thinking was established to investigate the different footprints of sludge management technologies aiming to provide decision-making reference for stakeholders. The footprints of energy, carbon and water were introduced in detailed in Sections 4.2.1.1 – 4.2.1.3 and the similar calculation approach for other types of footprints were presented in Section 4.2.1.4. The investigated footprints were then integrated together to generate an overall assessment score for each scenario by weighting method. The weighting methods applied in this work were fuzzy BWM and fuzzy AHP, which were introduced in Section 4.2.2. The integration method for life cycle composite footprint index was included in Section 4.2.3.

4.2.1 Methods for footprint family

There are different methods for estimating different types of footprints in an investigated system, such as LCA-based approaches and simple spread sheet-based models. CML 2000 and Eco-Indicator 99 assessment tool are frequently used in LCA-based models (Singh et al., 2016). Emission factors and the corresponding embodied factor of the examined energy or element can also be applied to calculate the emissions in each stage accordingly (Moussavi Nadoushani and Akbarnezhad, 2015; Zhuang et al., 2020). In this study, emission factors and data collected from literature review were employed to estimate the energy and materials flows in different alternatives.

4.2.1.1 Energy footprint

Energy consumption was calculated based on the energy and materials input within the entire process provided from the life cycle inventory list and the corresponding lower heating values or energy equivalent of the materials, which are shown in Eq.(4.1).

$$E = \sum_{i=1}^{n} \sum_{j=1}^{k_i} m_j^{k_i} \cdot e^j \tag{4.1}$$

where i refers to the i th process in the entire technology route; n represents the total amount of processes in the technical route; j is the j th material in the i th process and there are k_i types of input materials in the i th process. Hence, $m_j^{k_i}$ means the amount of j th material in the i th process. e^j is the energy equivalent or lower heating value (LHV) of the j th input material. E refers to the total amount of input energy in the investigated technical route.

4.2.1.2 Carbon footprint

Carbon emissions usually includes direct carbon emissions and indirect carbon emissions. Direct carbon emissions refer to the emissions from full combustion of different materials, including dried sewage sludge, natural gas, and coal. Indirect carbon emissions majorly refer to the emissions during the generation process of input energy, i.e., the process of coal-combustion for electricity production, acquisition of natural gas, and coal mining (Man et al., 2018; Man et al., 2019). The calculation for carbon emissions was based on the energy consumptions and corresponding life cycle CO_2 eq emissions from literature review, which is described by Eq. (4.2).

$$C = \sum_{i=1}^{n} \sum_{j=1}^{k_i} E_j^{k_i} \cdot c^j \tag{4.2}$$

where C refers to carbon emissions in the analyzed scenario; $E_j^{k_i}$ is the equivalent energy consumptions during the process i from the j th input material; c^j is the carbon emissions (kg CO_2 eq) for the j th material per gigajoule. Indirect carbon emissions can be calculated in the same way. In this work, the conversion rate of coal combustion to steam for incineration is considered. Hence, the values obtained from Eq. (4.2) need to be divided by the efficiency 90% as the final results for the part of heat supply in incineration.

4.2.1.3 Water footprint

Similar to carbon emissions, water consumptions also cover direct water consumptions and indirect water consumptions. The generation of direct water consumptions and indirect water consumptions can similarly refer to the source of direct and indirect carbon emissions. Direct water consumptions are the water originally contained in the materials or generated from the materials during the treatment process, like combustion. The water consumptions during the generation of input energy contribute to the indirect water consumptions. The water consumptions can be calculated by the life cycle water consumptions from literature review, as shown in Eq. (4.3).

$$W = \sum_{i=1}^{n} \sum_{j=1}^{k_i} E_j^{k_i} \cdot w^j \tag{4.3}$$

where W represents water consumptions in the analyzed scenario; w^j refers to the water consumptions (kg) from the process of j th material per gigajoule. Indirect water consumptions can be obtained by the same equation. Similar to the calculation of carbon emissions, the values obtained from Eq. (4.3) should be divided by the conversion efficiency. In this research, it is assumed that the water can be completely recycled during the process of machine thickening and dewatering.

4.2.1.4 *Other footprints*

Considering the complex compositions of sewage sludge, there are still many types of components or material flows which are worthy to investigate, such as the heavy metals (Cr, Pb, Hg, Zn, etc.), N- and S- contained chemical matters (Hong et al., 2009; Liu et al., 2019). N- and S- contained components can be converted into poisonous and harmful gases, like N_2O, NO_x, and SO_x (Hong et al., 2009). Heavy metals can be discharged into the air as the dust is produced from incineration process or into the soil along with the final landfilling, which can put negative impact to the environment. Therefore, it is necessary to discuss these types of footprints to provide a clearer recognition of the material flows in different processes. In this section, the analysis for the footprints of N and S is briefly introduced to provide a basic thought for the related calculation. The analysis for heavy metals and other elements may also use the similar methods and refer to the ecological risks analysis for sewage sludge agricultural application to cropland (Seleiman et al., 2020).

To analyze the footprints of N and S, it is essential to know about the corresponding content in each kind of material, such as sewage sludge and the input fuels for energy supply. Indirect N and S input should also be noticed since the input electricity may be generated accompanied with considerable amount of N and S contained gases. The related data can be obtained through detection and records in the literature review. Considering the waste combustion is a complex physical and chemical process, it can be assumed that the N- and S- containing chemicals have been sufficiently reacted during the combustion to simplify the analysis. Once the N and S input from different raw materials and energy in each process are clearly analyzed, the footprints of N and S can be correspondingly calculated by the similar approach with carbon and water, as shown in Eq. (4.4) and Eq. (4.5).

$$\bar{N} = \sum_{i=1}^{n}\sum_{j=1}^{k_i} E_j^{k_i} \cdot \bar{n}^j \tag{4.4}$$

$$S = \sum_{i=1}^{n}\sum_{j=1}^{k_i} E_j^{k_i} \cdot s^j \tag{4.5}$$

where $\bar{N}$ and S represent the amount of nitrogen and sulfur contained matters in the examined scenario, respectively; $\bar{n}^j$ and s^j refer to the amount of generation of nitrogen and sulfur contained chemical matters from the process of the j th material per gigajoule.

4.2.2 Weighting method

Considering the vagueness resulted from the uncertainty in data and linguistic description from the stakeholders, it may be difficult to obtain the exact weight of each aspect directly from the preferences of decision-makers. Therefore, fuzzy theory was introduced to address this problem. As it has been reviewed in Chapter 2, fuzzy theory is a common way to deal with the uncertainty in decision-making problems. The concept of fuzzy set provides a convenient point to construct a framework to analyze the fuzzy and uncertain information with wide applicability (Zimmermann, 2010). More detailed advantages of fuzzy set theory can also be found in the reference. Although fuzzy theory is convenient in solving decision-making problems with uncertain information, it cannot be solely applied to address the problem with missing information. Since this chapter focuses more on the uncertain preference rather than missing information, fuzzy weighting methods were selected in this context and the methodology framework for the decision-making problems with missing information is described in Chapter 6. In the chapter, two weighting methods, fuzzy BWM and fuzzy AHP, were selected and applied to decide the weight of each index. These two methods were selected since they are commonly used pairwise comparison approaches and easy understanding. Best-worst method was chosen because it can significantly reduce the times of comparison and has a better performance on consistency ratio compared with traditional AHP method (Rezaei, 2015). Fuzzy BWM possesses the advantages of BWM and the ability of processing vagueness. AHP method was employed since it is a classical pairwise comparison method for weighting and decision-making. The operation is simple and easy to understand even for the decision-makers without related professional knowledge. Fuzzy theory combined with AHP method also allows it to process the vague information generated from the subjective recognition of the stakeholders. Fuzzy BWM and fuzzy AHP are still similar from the perspective of the core thought because both are pair-wise comparison method and combined with fuzzy set theory. The major differences lie in specific processing steps and comparison times. Fuzzy BWM only needs to compare the importance of the best criterion over the other criteria and the importance of the other criteria over the worst criterion, while fuzzy AHP method requires to compare the importance between any pair of the criteria in the same level. Section 4.2.2.1 and 4.2.2.2 provide a brief introduction of the calculation principles of fuzzy BWM and fuzzy AHP applied in this work.

4.2.2.1 Fuzzy BWM

The calculation principles of fuzzy BWM in this work complied with the method provided in the study of Guo and Zhao (2017). The general calculation steps of fuzzy BWM to determine the fuzzy weights were shown in Figure 4.2 (Guo and Zhao, 2017).

4.2.2.2 Fuzzy AHP

Fuzzy AHP applied in this chapter complied with the method provided in the previous studies (Hsieh et al., 2004; Sun, 2010). The general calculation steps of fuzzy AHP to determine the fuzzy weights were shown in Figure 4.3 (Hsieh et al., 2004; Sun, 2010).

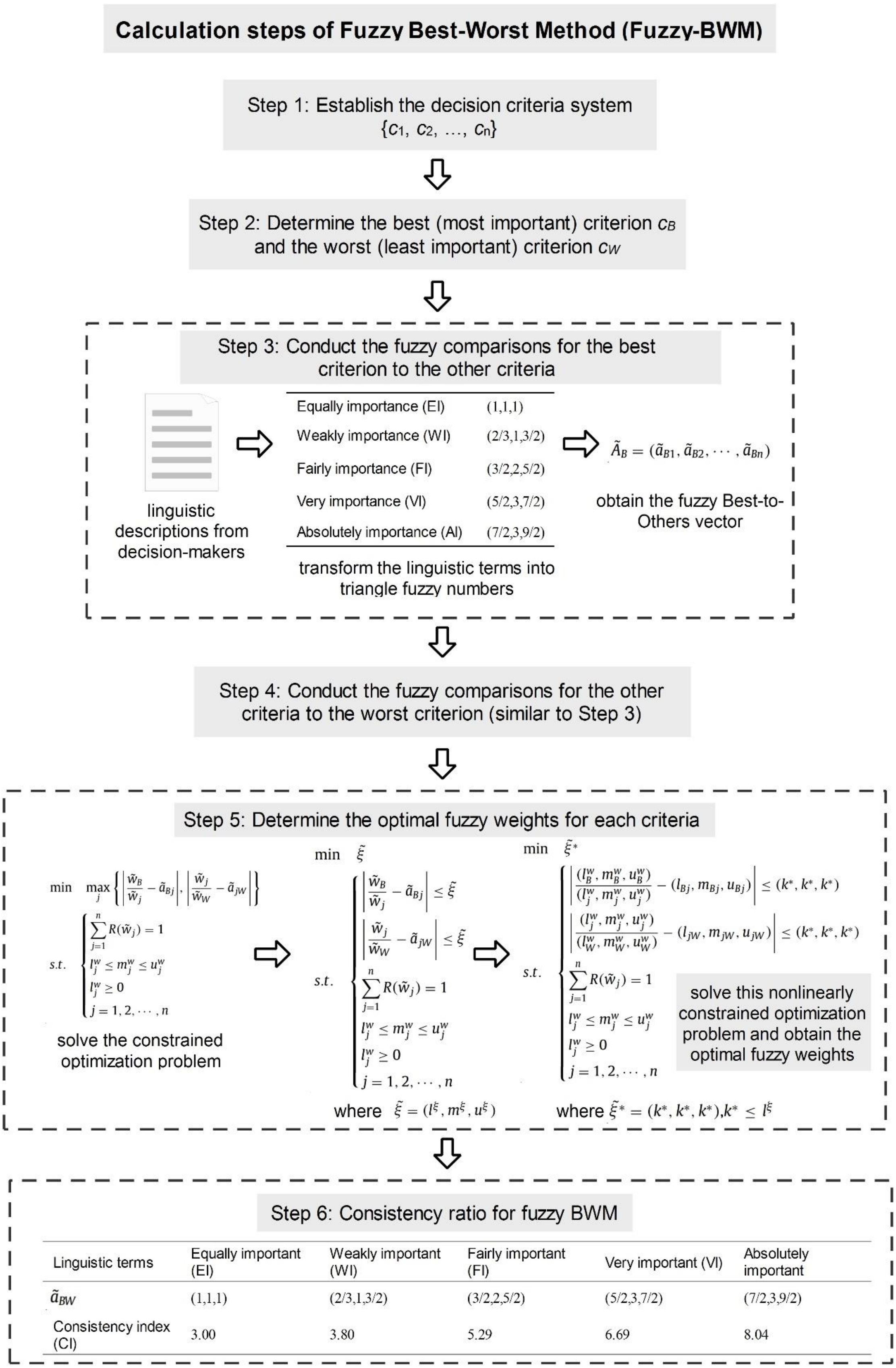


Figure 4.2 The calculation steps for fuzzy BWM (modified from Guo and Zhao (2017))

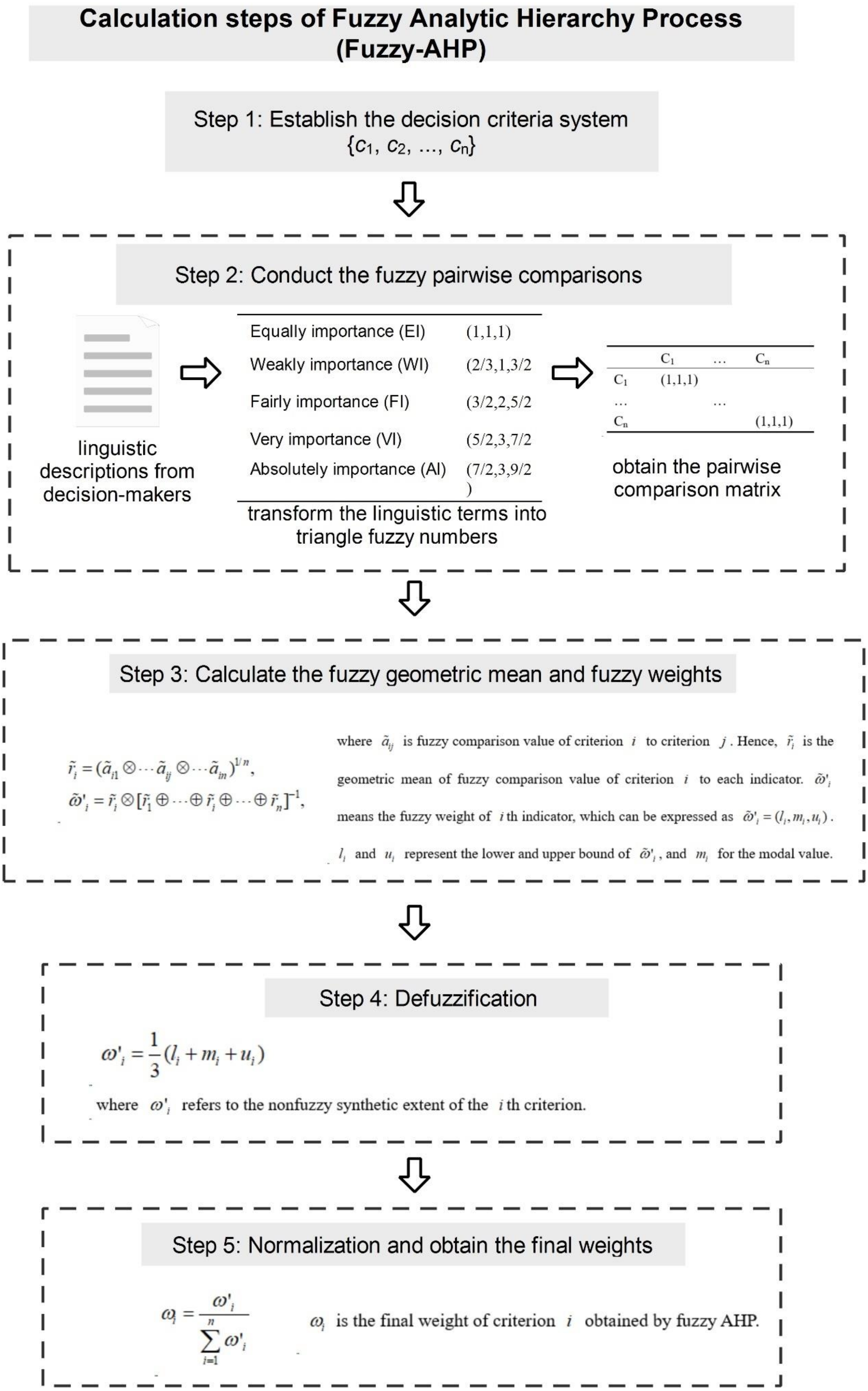


Figure 4.3 The calculation steps for fuzzy AHP (modified from Hsieh at al. (2004) and Sun (2010))

4.2.3 Life cycle composite footprint index

Based on the analysis of different types of footprints and the corresponding weights, a composite footprint index can be generated. A normalization step is first conducted to process the calculated results. The different types of footprints can be regarded as assessed criteria, which can be classified into beneficial criteria and cost criteria. Beneficial criterion means that higher value of the criterion is preferred, like energy recovery. On the contrary, cost criterion refers to the indicator that lower value is preferred. In this context, cost criteria include carbon emissions, water consumptions, and the emissions of oxynitride and oxysulfide. The score on beneficial criterion and cost criterion can be calculated by Eq. (4.6) and Eq. (4.7), respectively.

$$s_{benefit}^{i} = \omega_{benefit} \cdot \frac{b_i - b_{\min}}{b_{\max} - b_{\min}} \tag{4.6}$$

$$s_{c'}^{i} = \omega_{c'} \cdot \frac{c'_{\max} - c'_i}{c'_{\max} - c'_{\min}} \tag{4.7}$$

where $s_{benefit}^{i}$ refers to the score of the i th assessed alternative on the beneficial criterion, that is energy recovery in this work. $s_{c'}^{i}$ means the score of the i th assessed alternative on the cost criterion, which can be carbon emissions, water consumptions, oxynitride emissions and oxysulfide emissions. Accordingly, $\omega_{benefit}$ and $\omega_{c'}$ represent the weight of beneficial criterion and cost indicator, respectively. Weights assignment can be adjusted according to the preference of stakeholders and practical situation. $b_{\max}$ and $b_{\min}$ mean the maximum and minimum value of the beneficial criterion. b_i is the performance value of the i th alternative on the beneficial criterion. Similarly, $c'_{\max}$ and $c'_{\min}$ refer to the extremum in the cost criterion, while c'_i is the performance value of the i th scenario on the corresponding cost indicator. Then, the score of composite footprint index for alternative i can be expressed as Eq. (4.8).

$$s_i = \sum s^i_{benefit} + \sum s^i_{c'} \tag{4.8}$$

where s_i is the overall score of i th alternative.

4.3 Case study: Life Cycle Composite Energy-Carbon-Water Index of Six Sludge-to-Energy Alternatives

Life cycle composite energy-carbon-water index was applied to analyze and evaluate the performances of six sewage sludge treatment scenarios aiming to guide the future development of research and management on sludge treatment. The process of each selected techniques is shown in Figure 4.4. In the basic scenario (T), there are three treatment steps including thickening, anaerobic digestion, and dewatering. A composting step is added after the dewatering as the Scenario TC. Drying the dewatered sludge is the last step of Scenario TD. Scenario TI is the Scenario T with incineration as the final stage. Melting is added after the incineration as the Scenario TIM. Scenario T added by a single melting process is marked as Scenario TM. These six alternatives are selected because the following reasons: i) sludge treated by Scenario T will be directly disposed after dewatering, which can be regarded as control alternative. It is also common that subsequent operations like sanitary landfills are directly conducted after dewatering in some regions. ii) Composting is a general way to produce fertilizer from the biomass and obtain some economic benefits. However, agricultural usage of the fertilizer generated from sewage sludge is still worth discussion due to the complex compositions in sludge, which may cause soil pollution. iii) Scenario TD, TI, TIM and TM are all the technique routes based on thermochemical treatment. Drying is usually applied to further reduced the moisture of sludge to meet the requirements for the post treatment. Incineration is a widely applied approach for thorough sludge treatment, but it usually requires considerable energy supply with large amount of carbon emissions. Melting is another potential way for sludge treatment with energy recovery. Scenario TI, TIM and TM are used to compared with each other to analyze the features of each technology. All in all, these scenarios show typical characteristics on either energy aspect or environmental aspect. Therefore, it is necessary to further investigate the performance of these alternatives for better management of sewage sludge.

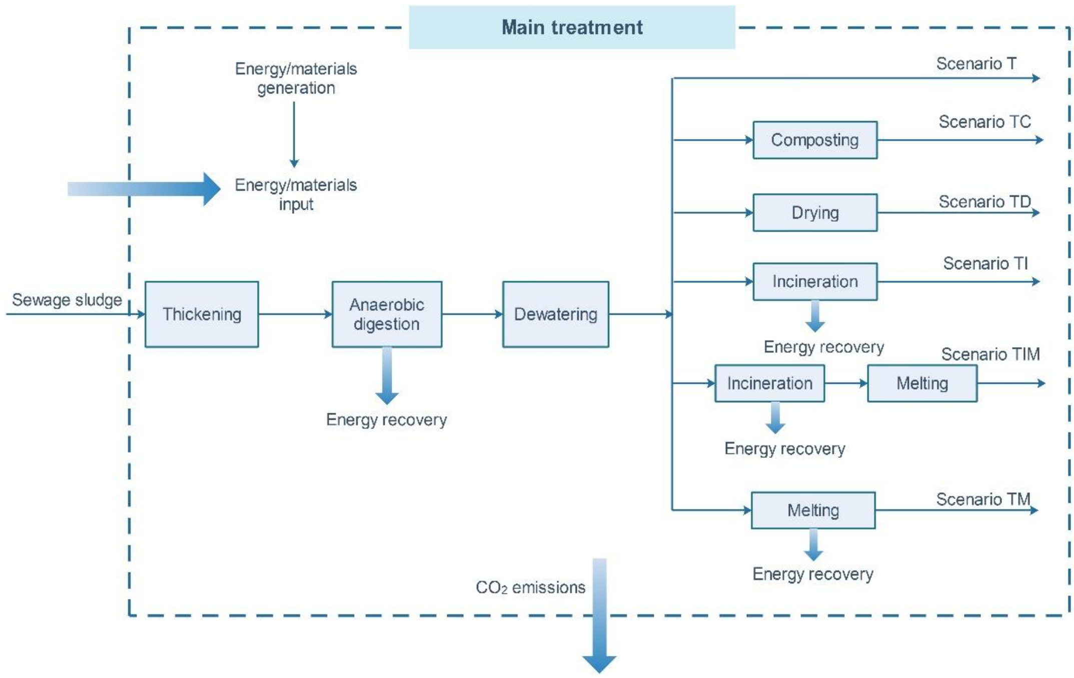


Figure 4.4 System boundary and procedures for each option in this work (adapted from (Hong et al., 2009))

The analysis is conducted for the main-treatment considering the production process of energy and materials input, while the post-treatment, and transportation for post-treatment is excluded, that is a gate-to-gate research. Energy and materials inputs, CO_2

emissions, energy recovery, and the equivalent consumption and flows of water were included in this work. Indirect CO_2 emissions and water consumptions, majorly referring to the emissions and consumptions from electricity and natural gas production, were considered in this study. According to the statistics data (Agency, 2009; BP, 2018), although the ratio of electricity generation from renewable resources has gradually increased, coal is still the dominate material for electricity production in some developing countries, especially in China. Hence, electricity was assumed to be generated from coal combustion (Jaramillo et al., 2007) and steam was regarded as the heating medium in incineration with a high conversion rate of 90% from coal combustion. The major features of different kinds of treated sludge applied in this study were collected in Table A2.1 in Appendices (Hong et al., 2009). Life time of building, electric facility and equipment were supposed to be 30, 15, 7 years, respectively. The functional unit was selected to be the treatment of one ton of dry sludge (DS) of sludge. All the energy and materials input, CO_2 emissions and water consumptions were calculated based on this functional unit. Life cycle inventory list includes all the factors which can be used to analyze the energy, carbon, and water flows, such as different forms of energy input and output, carbon emissions, water consumptions and related coefficients for the indirect consumptions and emissions. Inventory data for the life cycle assessment related to the process were collected based on literature review. Inventory indicators considered in this study consist of all the materials and energy consumed in the sludge treatment process, covering the consumption of electricity, heat, and natural gas. Relevant data were listed in Table A2.2. Detailed results and analysis based on the proposed framework are presented in the following sections.

4.3.1 Energy recovery analysis

Energy consumptions were calculated based on the energy and materials input within the entire process provided in the reference (Hong et al., 2009) and their corresponding lower heating values. Detailed data sources of calculation for energy flows were listed in the Appendix Part II.

Based on the inventory list and collected data, corresponding energy flows for each scenario were calculated, which were shown in Figure 4.5. Major data regarding different forms of energy input, energy recovery and loss were listed in Table 4.1. The energy from sludge takes the overwhelming majority of the total energy input, but the energy recovery from the treatment process is unsatisfactory with the highest amount of electricity generation from Scenario TM of 4941.72 MJ/t-DS. The amount of energy recovered from Scenario TI and Scenario TIM are perfectly equivalent because there is no energy recovery from the melting process after incineration. This also reveals that energy recovery can be mainly conducted through AD, incineration, and fluidized-bed gasification and melting, where the latter two methods contribute the main part of the total quantity of energy recovery. Other treatment methods such as drying and composting mainly aim to reduce the volume of sludge and apply it as a fertilizer, but the benefits from them are insignificant due to the increasing total energy input and less energy recovery.

Table 4.1 Main results of energy flow for each scenario

	T	TC	TD	TI	TIM	TM
Energy input						
Electricity	1699.2	1951.2	2124.00	2796.48	3139.2	3041.64

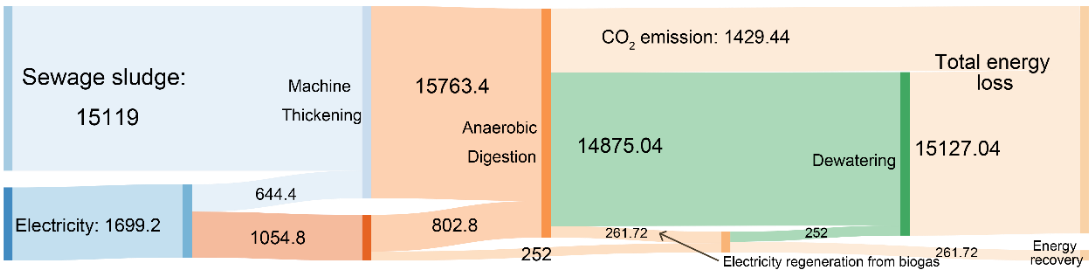
Heat			5760			
Gas consumption				1652.80	1652.80	
Sewage sludge[a]	15119	15119	15119	15119	15119	15119
Total input	16818.20	17070.20	23003.00	19568.28	19911	18160.64
Energy recovery						
Electricity generation	261.72	261.72	261.72	3604.32	3604.32	4941.72
Energy loss						
Energy carried by CO_2	1429.44	1429.44	1429.44	2604.75	2604.75	1429.44
Total energy loss	16556.48	16808.48	22741.28	15963.96	16303.68	13218.92

Unit: MJ/t-DS

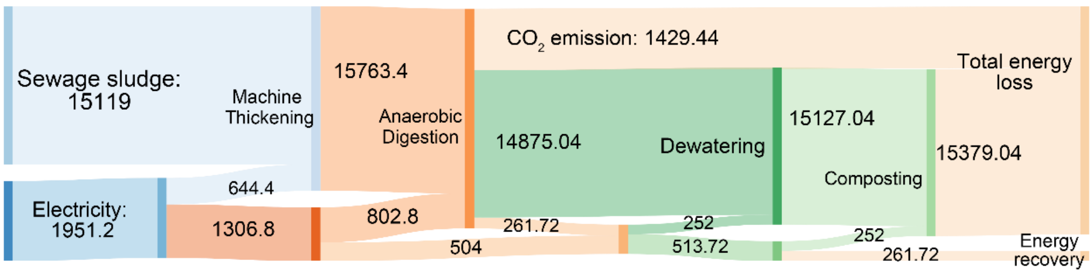
1 kWh=3600 kJ

a: LHV of sewage sludge was estimated as 6500 Btu/lb (Cooper et al., 1999).

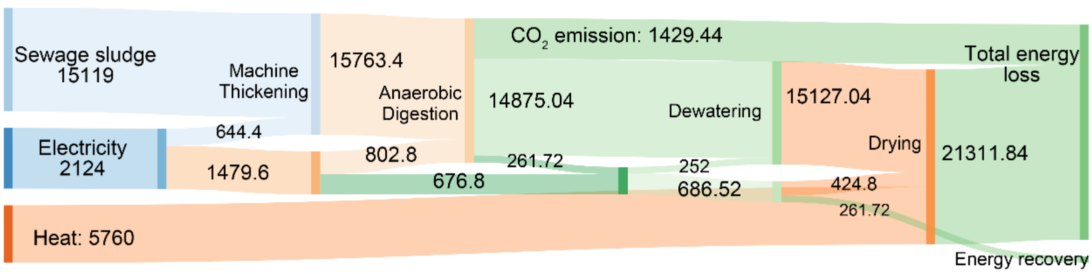
1 Btu/lb=2326 J/kg



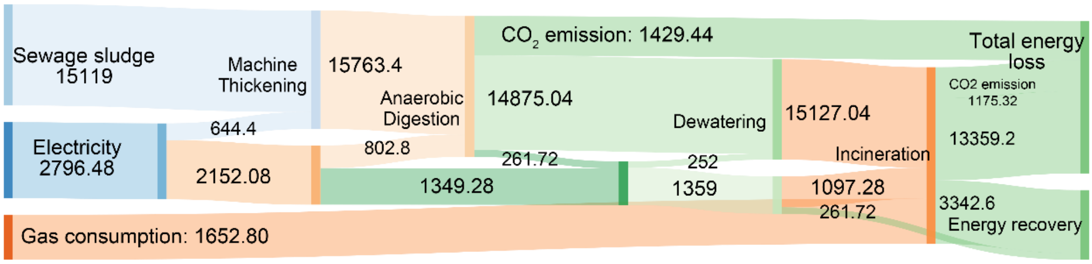
(a) Scenario T



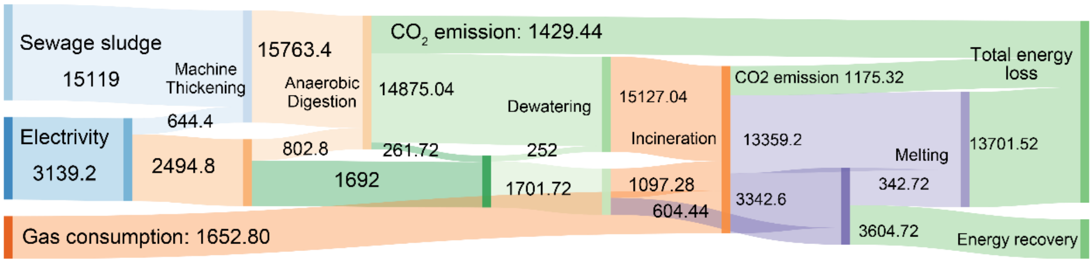
(b) Scenario TC



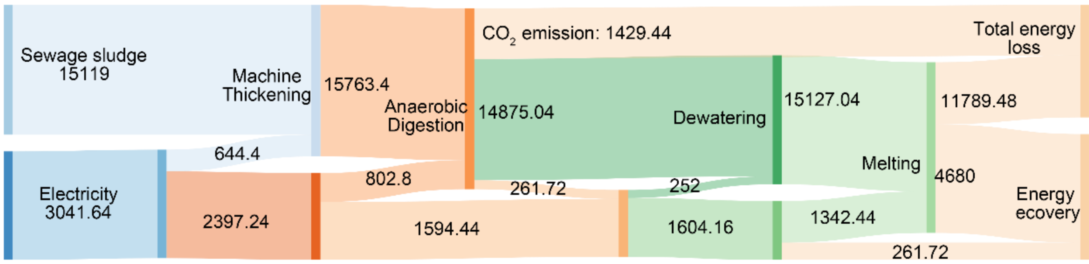
(c) Scenario TD



(d) Scenario TI



(e) Scenario TIM



(f) Scenario TM

Figure 4.5 Energy flows for the six alternatives. Data were presented by MJ per functional unit.

Energy contribution of each process for the investigated alternatives was shown in Table 4.2. Except the energy from sludge, electricity and heat consumption in drying are also considerable with over 25% contribution. Energy consumed in incineration for Scenario TI and TIM share the similar proportion for around 14%. Energy recovery from the former three alternatives is almost negligible (less than 2%) compared with the total energy consumed. Although energy recovery from Scenario T and TIM are the same value, total energy loss in the latter one is a bit higher than that of the former one due to the adding process of melting. Melting process does not increase the energy recovery amount but may improve the extent of sludge treatment. Compared with

Scenario TI and TIM, the total amount of energy recovery from Scenario TM increases with a certain degree, which can cancel the entire energy consumed for over 25%. It indicates the obvious advantages of energy recovery of the gasification and melting technology.

Table 4.2 Contribution ratio of energy inputs from each process

	T (%)	TC (%)	TD (%)	TI (%)	TIM (%)	TM (%)
Energy input						
Machine thickening	3.83	3.77	2.80	3.29	3.24	3.55
AD	4.77	4.70	3.49	4.10	4.03	4.42
Dewatering	1.50	1.48	1.10	1.29	1.27	1.39
Composting		1.48				
Drying			26.89			
Incineration				14.05	13.81	
Melting					1.72	
Gasification and melting						7.39
Sewage sludge	89.90	88.57	66.73	77.26	75.93	83.25
Energy recovery	1.56	1.53	1.14	18.42	18.10	27.21

4.3.2 Carbon emissions analysis

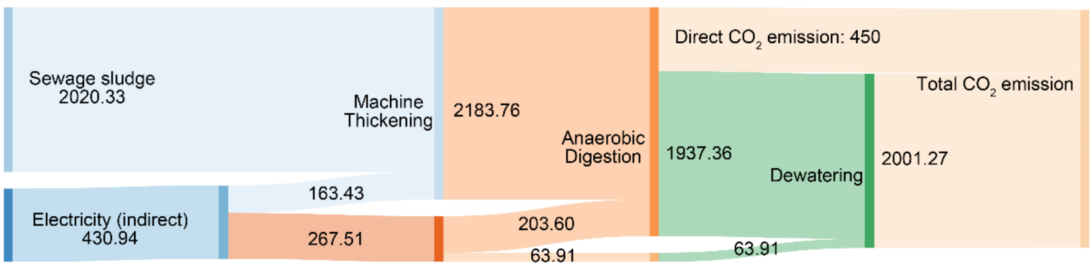
Major data about carbon flows analysis were listed in Table 4.3 and corresponding carbon flows for each scenario are described in Figure 4.6. The highest total amount of carbon emissions belongs to Scenario TD with 3138.53 kg/t-DS, closely followed by TIM and TI, then the Scenario TM. Scenario TM and TIM own the same amount of direct CO_2 emissions because of the shared processes of AD and incineration, but the total input of Scenario TIM is higher than that of TI, which means that the left amount of carbon is discharged in other forms. Scenario T and TC own relatively less amount of CO_2 input, but the entire treatment for sewage sludge is inadequate because not only the valuable matters are not recycled but also the harmful substances are not completely disposed during the process. Although drying may promote the complete treatment of sewage sludge, energy recovery is not included throughout the whole process leading to the lack of commercial competitiveness.

Table 4.3 Data of carbon flows analysis for each alternative

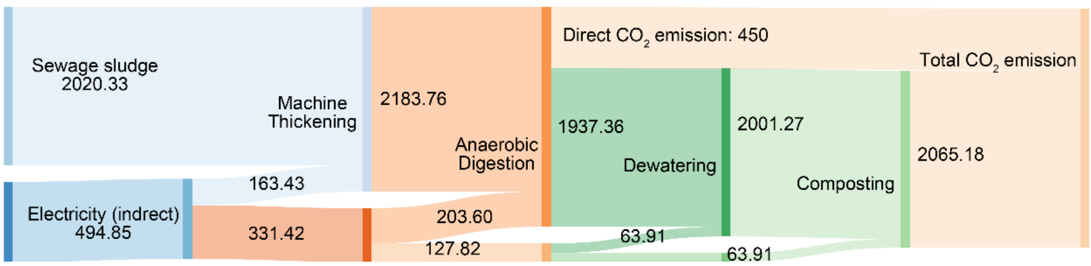
	T	TC	TD	TI	TIM	TM
Carbon input						
Electricity (indirect)	430.94	494.85	538.67	709.22	796.14	771.39
Heat (indirect)			579.52			
Natural gas (indirect/direct)				2.15/150.74	2.15/150.74	
Sewage sludge[a]	2020.33	2020.33	2020.33	2020.33	2020.33	2020.33
Total CO_2 input	2451.27	2515.18	3138.53	2882.44	2969.36	2791.73
Direct CO_2 emission	450	450	450	820	820	450

Unit: kg/t-DS

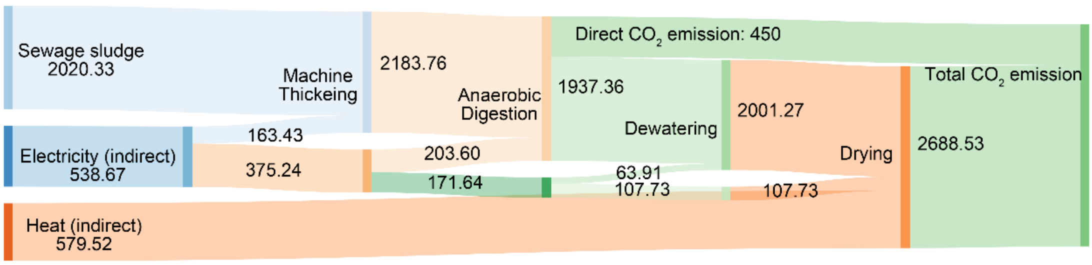
a: The amount of carbon dioxide carried by sewage sludge was estimated according to the C content of 55.1 wt.% (Cooper et al., 1999) based on the assumption of full combustion.



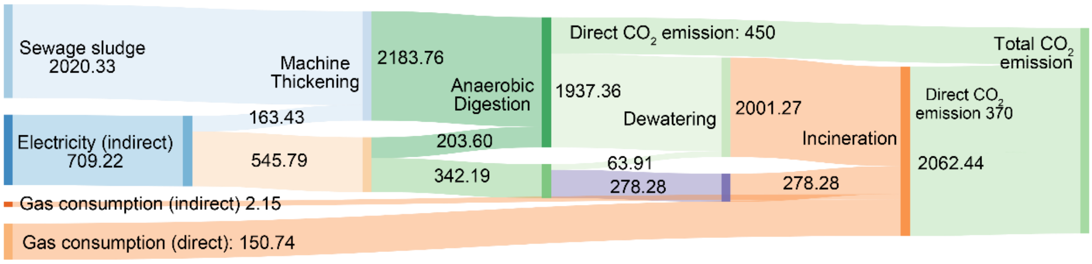
(a) Scenario T



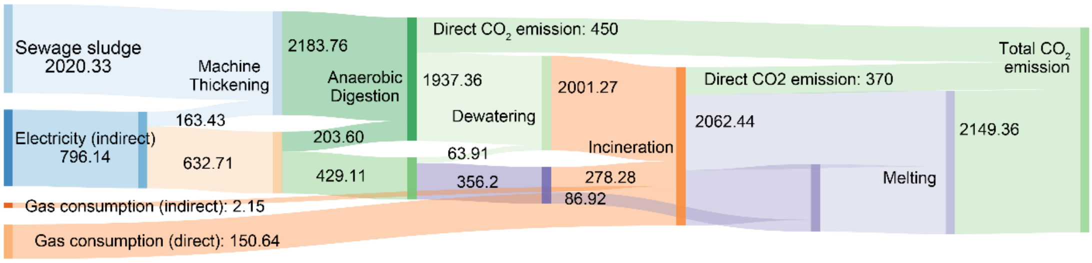
(b) Scenario TC



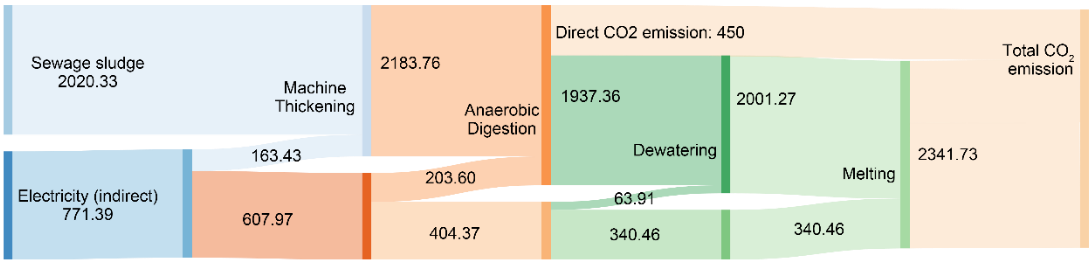
(c) Scenario TD



(d) Scenario TI



(e) Scenario TIM



(f) Scenario TM

Figure 4.6 Carbon flows for the selected alternatives. Data were presented by kg per functional unit.

Contribution of each life stage for CO_2 emissions of the selected options is shown in Table 4.4. Sludge is still the major source of carbon emissions. The carbon input for drying from heating and electricity is also significant which contributes about 20% of the total emission in Scenario TD. Direct CO_2 emissions from Scenario TI and Scenario TIM are obvious, both occupying around 30%. Similar to the situation of energy flows, the carbon emission contribution of Scenario TI and TIM are almost the same, except the part of input electricity for melting. Carbon emissions from both AD and machine thickening are in charge of about 7% for the first two alternatives while the percentages of these two processes are a bit less than 7% for other four options. In addition, the part of gasification and melting contributes over 10% for Scenario TM. Direct carbon emissions majorly come from AD and the incineration of sludge, which take up ranging from about 15% to 30%, where the highest ratios belong to the Scenario TI and TIM. Results also show that the process with energy recovery usually accompanied by a certain amount of carbon input.

Table 4.4 Contribution ratio of carbon inputs from each process

	T (%)	TC (%)	TD (%)	TI (%)	TIM (%)	TM (%)
Carbon input						
Machine thickening	6.67	6.50	5.16	5.62	5.45	5.80
AD	8.31	8.09	7.28	7.93	7.70	8.18
Dewatering	2.61	2.54	2.02	2.20	2.13	2.27
Composting		2.54				
Drying			21.71			
Incineration				14.82	14.39	
Melting					2.90	
Gasification and melting						12.08
Sewage sludge	82.42	80.33	63.82	69.44	67.43	71.68
Direct CO_2 emissions	18.36	17.89	14.22	28.18	27.37	15.96

4.3.3 Water consumption analysis

Major results for water flows analysis of each scenario were collected in Table 4.5 and the corresponding diagrams of water flow for the analyzed options were shown in Figure 4.7. Moisture content in sewage sludge is still the most important source of water input for the entire system. Although the data of total water loss listed in Table 4.5 are not as considerable comparing with the amount of total water input, it is still worthy to discuss due to the daily large amount of sewage sludge treatment and the unsatisfactory water recycled in the practice.

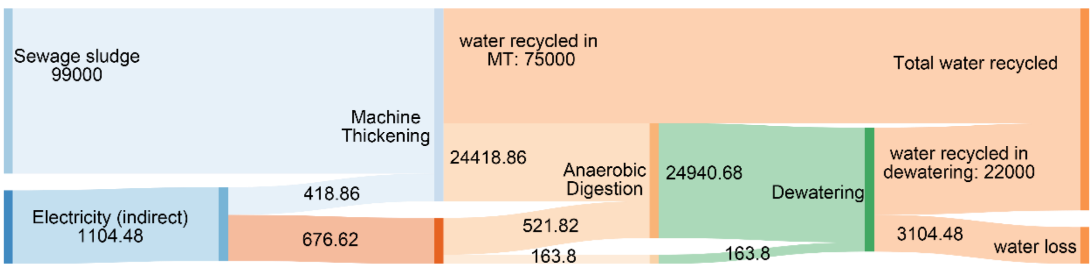
All the alternatives share the same quantity of recycled water because all the treatment process have the common steps for water recycling, that is machine thickening and dewatering. Meanwhile, the water content in injected sludge is also the same for all the options. Hence, the slight differences in total water loss were resulted from the different method applied for sludge treatment and energy recovery. The least water loss belongs to Scenario T with the least number of disposal steps. As the amount of thermochemical treatment steps increases, the total water loss also rises, where the Scenario TIM owns the highest value, closely followed by Scenario TM, then the Scenario TI. Apart from the input from sludge, water indirectly coming from electricity generation is also significant while the part of natural gas is negligible.

Table 4.5 Data of water flows analysis for each alternative

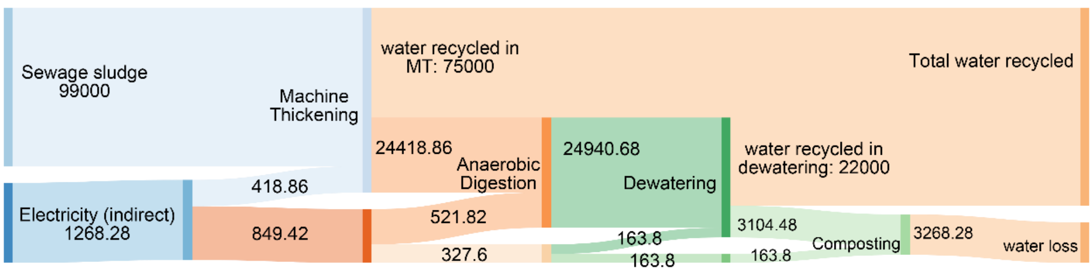
	T	TC	TD	TI	TIM	TM
Water input						
Electricity (indirect)	1104.48	1268.28	1380.60	1817.712	2040.48	1977.07
Heat (indirect)			177.74			
Natural gas (indirect/direct)				14.88/29.67	14.88/29.67	
Sewage sludge (direct)[a]	99000	99000	99000	99000	99000	99000
Total water input	100104.48	100268.28	100558.34	100862.26	101085.03	100977.07
Water recycled from thickening and dewatering	97000	97000	97000	97000	97000	97000
Total water loss	3104.48	3268.28	3558.34	3862.26	4085.03	3977.07

Unit: kg/t-DS

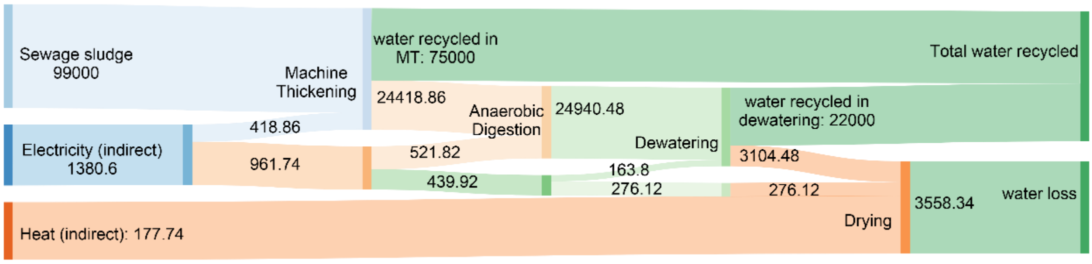
a: Water brought by sewage sludge was calculated by the data in Table A2.1 (in Appendices). Since the water content is 99 wt%, to obtain 1 t of dry solids needs to treat 100 t sewage sludge.



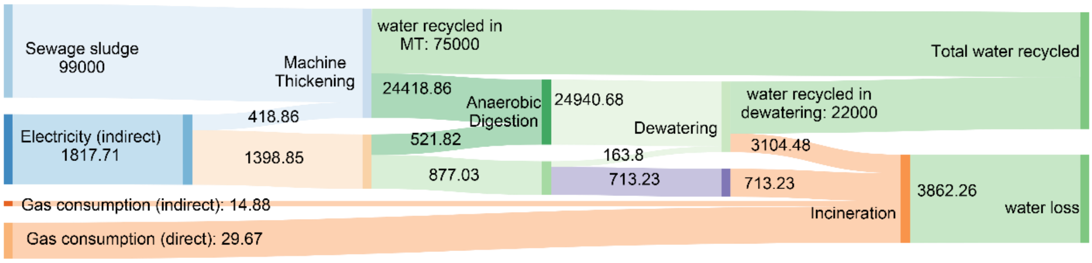
(a) Scenario T



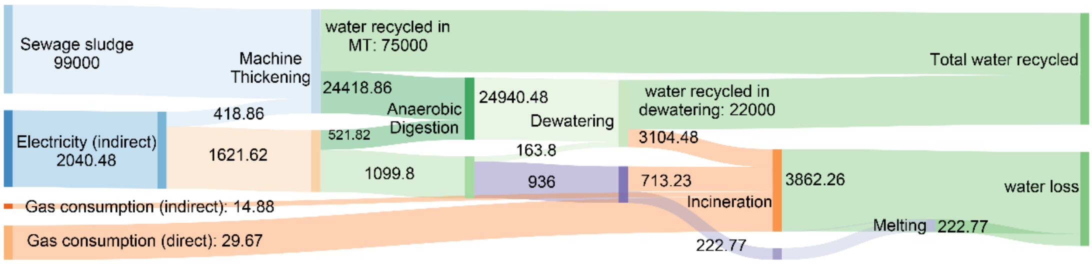
(b) Scenario TC



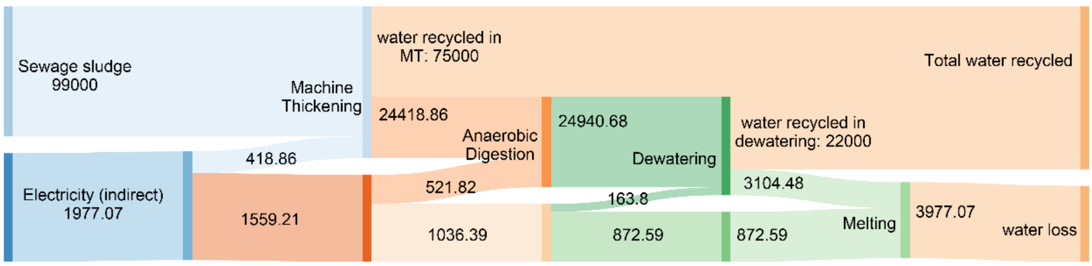
(c) Scenario TD



(d) Scenario TI



(e) Scenario TIM



(f) Scenario TM

Figure 4.7 Water flows for the selected alternatives. Data were presented by kg per functional unit.

Detailed data of the contribution ratio of each process was provided in Table 4.6. For all the alternatives, the sum of water input proportion from the operation processes (excluding the part from sludge) is less than 3%. Meanwhile, the contribution rates from the operation process almost remain the same among all the alternatives. The ratios actually change, but the variations are too tiny relative to the whole system which causes them can be ignored. The percentages of total water loss for each alternative keep the same ranking with that of water loss because of the nearly same amount of total water consumption. The amount of water loss in the Scenario TI, TIM and TM, are similar and much higher than that of Scenario TD considering the quantity. There also exists more water loss in Scenario TD compared with T and TC due to the process of drying.

Table 4.6 Contribution ratio of water inputs from each process

	T (%)	TC (%)	TD (%)	TI (%)	TIM (%)	TM (%)
Water input						
Machine thickening	0.42	0.42	0.42	0.42	0.41	0.41
AD	0.52	0.52	0.52	0.52	0.52	0.52
Dewatering	0.16	0.16	0.16	0.16	0.16	0.16
Composting		0.16				
Drying			0.45			
Incineration				0.75	0.75	
Melting					0.22	
Gasification and melting						0.86
Sewage sludge	98.90	98.74	98.45	98.15	97.94	98.04
Total water loss	3.10	3.26	3.54	3.83	4.04	3.94
Total water recycled	96.90	96.74	96.46	96.17	95.96	96.06

4.3.4 Aggregated energy-carbon-water index for sustainability evaluation

A combined evaluation can be obtained by scoring the option from 1 to 6 and 6 is the optimal case among all the options based on the above analysis, which were shown in Table 4.7.

Table 4.7 Performances on energy recovery, carbon emissions, and water loss and combined ranking of the selected scenarios

	Unit	T	TC	TD	TI	TIM	TM
Energy							
Energy recovery rate	%	1.56	1.53	1.14	18.42	18.10	27.21
Ranking	-	3	2	1	5	4	6
Carbon emissions							
Total carbon emissions	kg-CO_2 eq	2451.27	2515.18	3165.52	2909.44	2996.36	2818.73
Ranking	-	6	5	1	3	2	4
Water consumption							
Water loss rate	%	3.10	3.26	3.54	3.83	4.04	3.94
Ranking	-	6	5	4	3	1	2

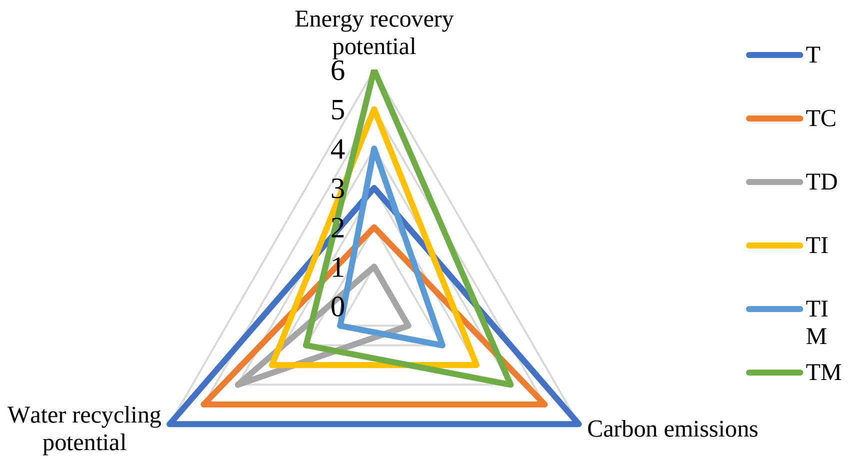


Figure 4.8 Radar map for the performances of the six scenarios on three dimensions

Data in Table 4.7 reflected that the former two scenarios show more advantages on carbon emissions and water consumptions and the latter three options perform well in energy recovery, which can be directly described by a radar map (Figure 4.8). The values in Figure 4.8 correspond to the ranking results in Table 4.7. The features of different technologies are more intuitive in Figure 4.8. Scenario T and TC perform more prominently on the carbon emissions and water consumption aspects, while alternative TI, TIM and TM show more superiority on energy recovery and lack of competitiveness on the other two perspectives. As for Scenario TD, it performs badly especially on the energy recycling and carbon emissions. Figure 4.8 also clearly indicates the future improvement direction for the sludge treatment technologies combined with energy recovery, which was discussed in detail in Section 4.4.

Although Table 4.7 provides a ranking with the initial results, such kind of ranking could introduce bias, for example, the first three scenarios are much lower than the other three but actually they show some advantages in certain aspects. In order to make comparison across different aspects, normalization and weighting for the indicators are conducted. Fuzzy BWM and fuzzy AHP were applied to obtain the overall scores for the performance evaluation of these six alternatives. Table 4.8 collected the normalization results based on the above analysis. It provides more precise information on the merits and shortcomings of each energy recovery technology. According to Eq. (4.6) and Eq. (4.7), the alternative shows more superiority on the specific aspect if the value is closer to 1. Thus, Scenario T has the best performance on carbon emissions and water consumptions, although the energy recovery is poor. Scenario TC has similar performances with Scenario T on the three aspects. Alternative TD performs badly on both energy recovery and carbon emissions. Scenario TI, TIM and TM have remarkable outcomes on energy recovery, but all of them present disadvantage on carbon emissions and water consumptions, especially the Scenario TIM with the worst case on water consumptions.

Table 4.8 The scenarios' performances on the three aspects

	T	TC	TD	TI	TIM	TM
$\frac{e_i - e_{\min}}{e_{\max} - e_{\min}}$	0.0161	0.0150	0	0.6628	0.6506	1
$\frac{c_{\max} - c_i}{c_{\max} - c_{\min}}$	1	0.9105	0	0.3585	0.2368	0.4855
$\frac{w_{\max} - w_i}{w_{\max} - w_{\min}}$	1	0.8330	0.5371	0.2272	0	0.1101

4.3.4.1 Aggregated results by fuzzy BWM

The weights can be determined based on the calculation principles of the provided weighting methods as well as the preferences of decision-makers flexibly. The results presented here are only an example to demonstrate the feasibility of this methodology framework. According to the fuzzy BWM (Guo and Zhao, 2017), the weights of energy recovery, carbon emissions and water consumptions were calculated to assess the combined performances of the six scenarios (Step 1 in Figure 4.2). In this study, energy recovery is the major focus. Therefore, the criterion energy recovery is selected to be the best criterion. Since the total amount of recycled water are the same for the six scenarios, water consumption is chosen to be the worst criterion (Step 2). The fuzzy reference comparison of the best criterion to the other criteria and the other criteria to the worst criterion were listed in Table A2.3 and Table A2.4. Then the corresponding fuzzy best-to-others vector and others-to-worst vector can be expressed as Eq. (4.9) (Step 3) and Eq. (4.10) (Step 4).

$$\tilde{A}_B = [(1,1,1), (3/2,2,5/2), (5/2,3,7/2)] \tag{4.9}$$

$$\tilde{A}_W = [(5/2,3,7/2), (2/3,1,3/2), (1,1,1)]^T \tag{4.10}$$

The nonlinearly constrained optimization problem can be built according to the method (Guo and Zhao, 2017) and above analysis, which was shown by Eq. (4.11).

$$
\min \quad \tilde{\xi}^*
$$

$$
s.t. \quad \begin{cases}
\left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_1^w, m_1^w, u_1^w)} - (l_{11}, m_{11}, u_{11}) \right| \le (k^*, k^*, k^*) \\
\left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_2^w, m_2^w, u_2^w)} - (l_{12}, m_{12}, u_{12}) \right| \le (k^*, k^*, k^*) \\
\left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{13}, m_{13}, u_{13}) \right| \le (k^*, k^*, k^*) \\
\left| \dfrac{(l_1^w, m_1^w, u_1^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{13}, m_{13}, u_{13}) \right| \le (k^*, k^*, k^*) \\
\left| \dfrac{(l_2^w, m_2^w, u_2^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{23}, m_{23}, u_{23}) \right| \le (k^*, k^*, k^*) \\
\left| \dfrac{(l_3^w, m_3^w, u_3^w)}{(l_3^w, m_3^w, u_3^w)} - (l_{33}, m_{33}, u_{33}) \right| \le (k^*, k^*, k^*) \\
\sum_{j=1}^{3} R(\tilde{w}_j) = 1 \\
l_j^w \le m_j^w \le u_j^w, \ j = 1, 2, 3 \\
l_j^w \ge 0, \ j = 1, 2, 3
\end{cases} \tag{4.11}
$$

The optimization problem can be rewritten as Eq. (4.12) by substituting the concrete numbers.

$$\min \quad k^*$$

$$s.t. \quad \begin{cases} l_1 - 1.5u_2 \le ku_2; \, l_1 - 1.5u_2 \ge -ku_2; \\ m_1 - 2m_2 \le km_2; \, m_1 - 2m_2 \ge -km_2; \\ u_1 - 2.5l_2 \le kl_2; \, u_1 - 2.5l_2 \ge -kl_2; \\ l_1 - 2.5u_3 \le ku_3; \, l_1 - 2.5u_3 \ge -ku_3; \\ m_1 - 3m_3 \le km_3; \, m_1 - 3m_3 \ge -km_3; \\ u_1 - 3.5l_3 \le kl_3; \, u_1 - 3.5l_3 \ge -kl_3; \\ l_2 - 1.5u_3 \le ku_3; \, l_2 - 1.5u_3 \ge -ku_3; \\ m_2 - m_3 \le km_3; \, m_1 - m_3 \ge -km_3; \\ u_2 - 0.67l_3 \le kl_3; \, u_2 - 0.67l_3 \ge -kl_3; \\ \frac{1}{6}l_1 + \frac{2}{3}m_1 + \frac{1}{6}u_1 + \frac{1}{6}l_2 + \frac{2}{3}m_2 + \frac{1}{6}u_2 + \frac{1}{6}l_3 + \frac{2}{3}m_3 + \frac{1}{6}u_3 = 1; \\ l_1 \le m_1 \le u_1; \\ l_2 \le m_2 \le u_2; \\ l_3 \le m_3 \le u_3; \\ l_1 \ge 0; \, l_2 \ge 0; \, l_3 \ge 0; \\ k \ge 0 \end{cases} \tag{4.12}$$

The label j (j=1,2,3) represents the criteria energy recovery, carbon emissions, and water consumptions, respectively. The fuzzy weight for each criterion can be obtained by solving the optimization problem (4.12). The solutions were listed in Table 4.9.

Table 4.9 The optimal fuzzy weights for the three criteria

Variable	Value
$\tilde{\xi}$	(0.4168,0.4168,0.4168)
$\tilde{\omega}_e$ a	(0.4420,0.5573,0.6726)
$\tilde{\omega}_c$ b	(0.2306,0.2306,0.2306)
$\tilde{\omega}_w$ c	(0.2122,0.2122,0.2122)

a: fuzzy weights of energy recovery;
b: fuzzy weights of carbon emissions;
c: fuzzy weights of water consumptions.

Then the crisp weight of each aspect can be corresponding calculated which were shown as

$\omega_e = 0.5573, \omega_c = 0.2306, \omega_w = 0.2122.$

The value of objective function k is 0.4168. The consistency index for this situation is 6.64. Hence the consistency ratio is 0.4168/6.64=0.0628, which is close to zero leading to the high reliability of this result. By using the obtained weights, the total scores for each scenario were obtained, which were listed in Table 4.10.

Table 4.10 Combined scores of the six scenarios obtained by fuzzy BWM

Scenario	T	TC	TD	TI	TIM	TM
Combined score	0.4517	0.3950	0.1140	0.5002	0.4171	0.6926

4.3.4.2 Aggregated results by fuzzy AHP

Fuzzy AHP (Hsieh et al., 2004; Sun, 2010) was also applied to calculate the weights of three footprint indices (Step 1 in Figure 4.3). The fuzzy pairwise comparisons between the three criteria were conducted according to the opinions collected from stakeholders, which are shown in Table 4.11 (Step 2). Then, according to the calculation principles in the research of Hsieh et al. (2004) and Sun (2010), the fuzzy value of $\tilde{r}_i$ and $\tilde{\omega}_i$ for each indicator can be obtained as follows:

$$\tilde{r}_1 = (1.5536, 1.8171, 2.0606),$$
$$\tilde{r}_2 = (0.6437, 0.7937, 1),$$
$$\tilde{r}_3 = (0.5754, 0.6934, 0.8434),$$

$$\tilde{\omega}_1 = (0.3979, 0.5499, 0.7432),$$
$$\tilde{\omega}_2 = (0.1649, 0.2402, 0.3607),$$
$$\tilde{\omega}_3 = (0.1474, 0.2098, 0.3042).$$

According to the calculation results above and the defuzzification step, corresponding weight of each index can be computed.

$\omega'_e = 0.5637, \omega'_c = 0.2552, \omega'_w = 0.2205$

By normalization, the final weights for the performance criteria can be calculated, which are shown as follows

$\omega_e = 0.5423, \omega_c = 0.2456, \omega_w = 0.2121.$

Table 4.11 The fuzzy pairwise comparison matrix of the selected criteria

	C1	C2	C3
C1	(1,1,1)	(3/2,2,5/2)	(5/2,3,7/2)
C2	(2/5,1/2,2/3)	(1,1,1)	(2/3,1,3/2)
C3	(2/7,1/3,2/5)	(2/3,1,3/2)	(1,1,1)

By using the obtained weights, the total scores for each scenario were calculated, which were listed in Table 4.12.

Table 4.12 Combined scores of the six scenarios obtained by fuzzy AHP

Scenario	T	TC	TD	TI	TIM	TM
Combined score	0.4664	0.4084	0.1139	0.4957	0.4110	0.6849

4.3.4.3 Aggregated results analysis

According to the aggregated results obtained from fuzzy BWM and fuzzy AHP, both methods indicated the same ranking order of the six scenarios: TM>TI>T>TIM>TC>TD. Scenario TM performs the best which is credited by the large amount of energy generation from gasification and melting process. Scenario TI also has impressive performance with a total score around 0.5. Although Scenario TI and TIM share the same amount of energy recovery, the aggregated performance of Scenario TIM is inferior to that of Scenario TI because of the extra energy consumptions, more carbon emissions and worse water consumptions. On the contrary, Scenario T is not remarkable on the energy recovery, but the advantages on the other two aspects leading to a better score than Scenario TIM. Scenario TD has the lowest score which is resulted from the unsatisfactory performances on all of the aspects, especially the former two. From the analysis above, it is found that scenarios with large amount of energy recovery are usually accompanied by considerable quantity of carbon emissions and water consumptions. These two drawbacks may influence the further promotion of sludge-to-energy technologies if there is no effective measure to ease or solve the problems.

In actual production practice, different weights may be assigned to the three aspects due to the different preference of stakeholders, which can directly influence the decision-making results. Therefore, different groups of weights were set to find out the specific impact on the assessment results.

4.3.5 Sensitivity analysis

Three groups of weights distribution were designed to investigate the changes in assessment results, called Group A, B, and C. Each group has eight weighting assignment alternatives. The detailed values were provided in Table A2.5 – Table A2.7 (in Appendices). For each group of weights assignment, the weight for the specific aspect gradually increases, while the weights for the other two aspects were set to be equal to see the influence of weights changing on the specific aspect.

4.3.5.1 Weight variation analysis for energy recovery

According to the results in Table 4.8 and Eq. (4.8), combined assessment scores for each scenario with the assigned weights distribution in Table A2.5 were obtained and described by Figure 4.9. The scores of Scenario TI, TIM and TM present an increasing trend as the weight of energy recovery rises. On the whole, the performance of Scenario TM is better than TI and TIM because the entire line of TM is above the other two lines.

On the other hand, the grades of Scenario T, TC and TD tend to decrease as the emphasis on energy recovery rises, while the former two have remarkable reduction and the latter one has a slight decline. The score of Scenario T and TM are close to each other. When the weight on energy recovery is larger than 0.4, Scenario TM shows more superiority on the assessment. Alternative TI and TIM also exhibit advantages over Scenario T when the weight of energy recovery is larger than 0.6. Scenario TD is the least preferred one almost all the time because of the bad performance on the three aspects.

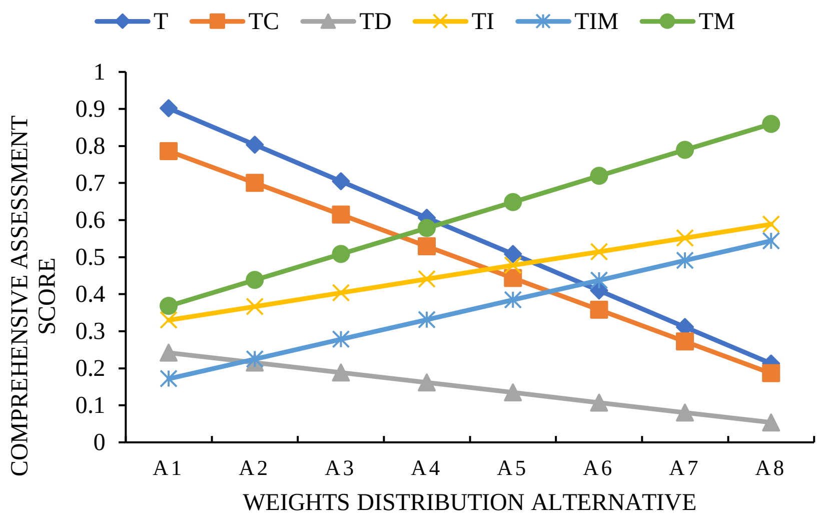


Figure 4.9 Combined scores for the six alternatives with the increasing weights of energy recovery

4.3.5.2 Weight variation analysis for carbon emissions

Combined scores for the six alternatives with the assigned weights distribution in Table A2.6 can be calculated and the results are plotted in Figure 4.10. When the weights of carbon emissions are emphasized, the scores of Scenario T and TC have obvious increase while the grades of the other four options all decrease. Among the cases with declining scores, Scenario TD shows a more obvious downward trend and the scores of the other three alternatives keep relatively flat decline, with the scenario

TM at around 0.5, TI at around 0.4, and TIM at about 0.3. It indicates that the weights on carbon emissions cannot put much influence on the scores of the scenarios with large amount of energy recovery due to their relatively average performances on carbon emissions compared with the other two aspects (see Table 4.8). As for the Scenario T and TC, increasing weights of carbon emissions can make these two scenarios more preferred. When the weight is set to be 0.8, the score of Scenario T is even over 0.9 which occupies the absolute advantage among the six options, closely followed by the Scenario TC with the highest score of about 0.8. Still, Scenario TD is the worst method with the lowest score of 0.05 when the weight of carbon emissions is set to be 0.8.

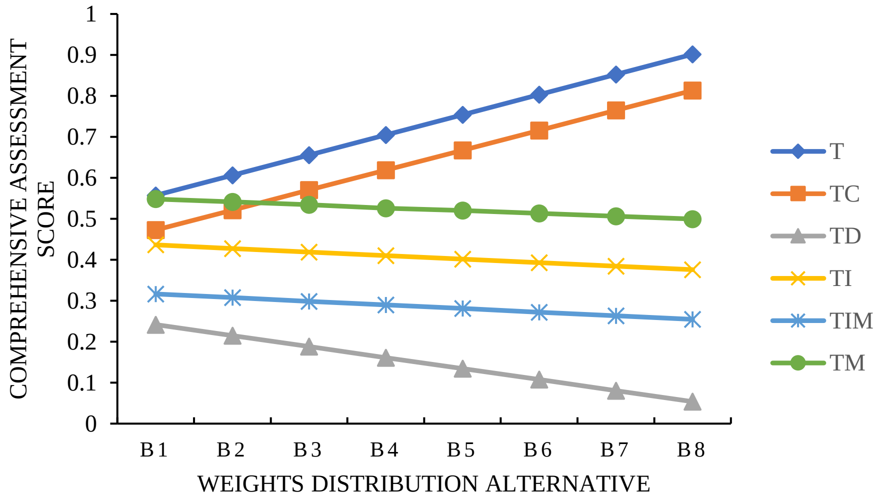


Figure 4.10 Combined scores for the six alternatives with the increasing weights of carbon emissions

4.3.5.3 *Weight variation analysis for water consumptions*

Using the similar calculation method, the assessment results with the assigned weights distribution in Table A2.7 can be obtained and illustrated in Figure 4.11. According to Figure 4.11, the grades of Scenario T, TC and TD tend to increase, especially that of Scenario TD which significantly increases from 0.05 to above 0.4 as the weight of water consumptions rises. On the contrary, dramatical decline happens to the scores of Scenario TM, TI and TIM, where the most significant change occurs in the line of Scenario TM decreasing from about 0.7 to 0.2. When the weight of water consumptions is larger than 0.7, alternative TI would have a better performance than alternative TM. Although Scenario TD performs badly under the weight assignment of Group A and Group B, the performance of Scenario TD is better than that of Scenario TIM when the weight of water consumptions is larger than 0.5 and can further exceeds Scenario TI and TM if the weight is or above 0.7. Considering the results in Table 4.8, the score of Scenario TD on water consumption is the only non-zero value among the three aspects for TD. As for the Scenario T and TC, their advantages are obvious in terms of carbon emissions and water consumptions based on above discussion. Thus, emphasizing the importance of saving water can improve the preference of Scenario T, TC, and TD.

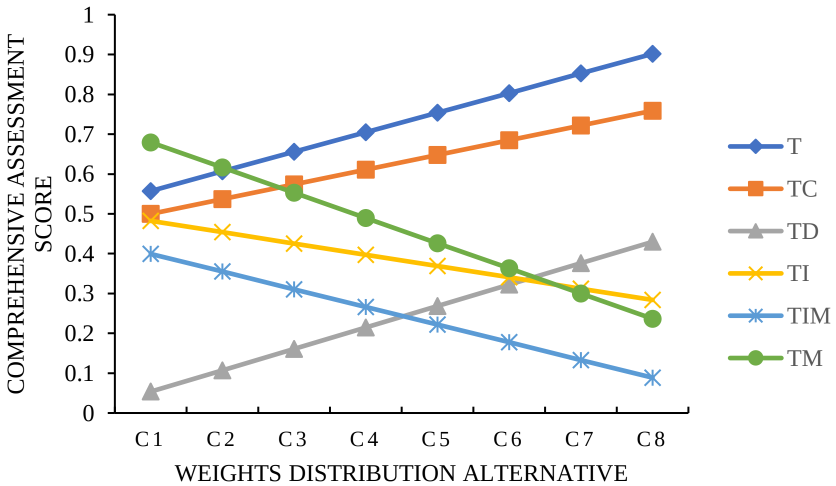


Figure 4.11 Combined scores for the six alternatives with the increasing weights of water consumptions

4.3.6 Uncertainty analysis

Several assumptions were specifically made in the case study to analyze the energy and materials flows, including the energy recovery among from different technologies (mainly refer to anaerobic digestion and incineration or melting in this study), the LHV of sewage sludge, and the carbon content in sewage sludge. These parameters may have significant influence on the evaluation results of the sludge-to-energy alternatives. Therefore, uncertainty analysis was conducted to analyze the influence of the variation of the parameters from the perspective of energy recovery amount in AD, LHV of sewage sludge, and the C content in sewage sludge.

4.3.6.1 Analysis of the variation on the energy regeneration from anaerobic digestion

The energy regeneration amount from AD usually varies with plenty of indicators, such as the investigated regions, the treated sewage sludge, and operating conditions, which leads to a wide variation of energy recovery amount from anaerobic digestion. In the case study, the electricity recovery from AD was only 261.72MJ/t-DS (Hong et al., 2009), while the value in another research was recorded as 2215.37MJ/t-DS (Xu et al., 2014), which indicates the large distinction between the related data in different research. Therefore, the energy recovery amount from AD was set to belong to the interval [196.29, 2159.19] to investigate the influence of the variation of this parameter, where 196.29 is the three quarters of the data applied in original case study (261.72), and 2149.19 is 4.5 times of the same data. Corresponding result was calculated and analyzed every 0.25 increase of the coefficient, that is, the situation when energy recovery amount was 0.75, 1, 1.25, …, .4, 4.25, 4.5 times of the original data, respectively. The energy recovery efficiency of each situation was shown in Table A2.8 in the Appendices.

According to the data in Table A2.8, the energy recovery efficiency of all the scenarios increased with the rise of coefficient, while the influence on the efficiency of difference alternatives were different. The increase of energy recovery efficiency on Scenario T, TC, TD kept consistent with the rise of coefficient. When the coefficient was set to be 0.75 of the initial data, the energy recovery efficiency of T, TC, and TD decreased by one quarter. When the coefficient was set to be 4.5, the energy recovery rate of these three alternatives increased by 3.5 times of the original data. This is because anaerobic digestion is the only process for energy recovery in the three alternatives. Therefore, the variation of energy recovery amount in AD was fully reflected in the final energy recovery efficiency of the three options. On the other hand, energy recovery efficiency of Scenario TI, TIM and TM was insensitive to the variation of energy recovery amount from AD. The changing of energy recovery efficiency on Scenario TI and TIM kept the same, both within the range of [-1.82%, 25.41%] since the energy recovery sources of these two alternatives were the same. The energy recovery rate of Scenario TM was even more insensitive than TI and TIM, whose changing was only within the range of [-1.32%, 18.54%]. This is because the energy recovered from AD was only a small part in the entire treatment process of Scenario TI, TIM and TM, but the improvement on energy recovery amount in AD can still contribute to the total recycling process.

The variation of the score on energy recovery for the six alternatives was also analyzed, which was shown in Table A2.9. According to the analysis results, the changing on energy recovery among from AD put no influence on the final score on energy recovery aspect for Scenario TD and TM, both still in the last and first place, respectively. The scores of Scenario T and TC showed an increase trend with the rise of coefficient, while the scores of TI and TIM presented a slight downward trend. Similar with the variation trends presented by energy recovery efficiency of the alternatives, the changing of coefficient had considerable impact on the final energy recovery scores of Scenario T and TC, which kept the same variation percentage within the range of [-24.18%, 332.39%]. On the contrary, the scores of TI and TIM almost unaffected by the changing of coefficient, especially for Scenario TI, which at most decreased by 0.03%. The score variation range of TIM was a bit wider than that of TI within the interval of [-0.41%, 0.03%].

4.3.6.2 Analysis of the variation on the on the LHV of sewage sludge toward the assessment

The LHV of sewage sludge is influenced by many factors, such as the type, source, and treatment state of sewage sludge. According to the literature review (Fytili and Zabaniotou, 2008; Manara and Zabaniotou, 2012), the LHV of different types of sewage sludge can vary from 12000 MJ/t-DS to 29000 MJ/t-DS. Therefore, the uncertainty analysis for the variation of LHV of sewage sludge was conducted through setting the LHV within the range of [12095.2, 18142.8] (MJ/t-DS), which was 0.8 and 1.2 times of original data as the lower and upper bound, respectively. Corresponding result was calculated and analyzed every 0.05 increase of the coefficient, that is, the situation when energy recovery amount was 0.80, 0.85, 0.9, …, .1.1, 1.15, 1.2 times of the original data, respectively. The energy recovery efficiency of each situation and relevant variation between the initial results were shown in

Table A2.10. According to the analysis results in Table A2.11, the energy efficiencies of all the alternatives decreased as the LHV of sewage sludge increased. The energy recovery efficiency variation of T and TC were similar, both within the range around [-15%, 22%] as the LHV decreased. The changing trends of TI, TIM and TM were similar, which all increased by around 18% when LHV was four fifths and declined by about 13% when LHV was 1.2 times of initial data. The influence of changing LHV of sewage sludge was not as significant as that of changing energy recovery amount from AD on the final energy efficiency for the assessed alternatives. However, all the options were influenced by the LHV variation obviously, the variation of energy recovery efficiency ranging from approximately 10% to 20% in absolute value. The influence on the score of energy recovery under different assumption for LHV of sludge was also investigated and were shown in Table A2.11.

The energy recovery performances of TD and TM always remained in the same ranking as where they were in the case study. Although the energy recovery efficiency showed a decrease trend with the rise of LHV in all the alternatives, the scores of different scenarios presented different variation trends. The energy recovery scores of Scenario T and TC gradually fallen down by about 12% if the LHV of sludge was set to be 1.2 times of initial data. On the contrary, the scores of TI and TIM showed a slight upward trend. This may be resulted from the difference in energy recovery source. Since anaerobic digestion is the only source of energy recovery in Scenario T, TC, and TD, they were significantly influenced by the energy input to the total system and the output from anaerobic digestion. On the other hand, the energy efficiencies of Scenario TI, TIM and TM remain relatively stable under different situation because the energy recovery from thermochemical process (e.g., incineration and melting) contributed a main part in the total process.

4.3.6.3 Analysis of the variation on the carbon content in sewage sludge

Carbon content is also an important property of sewage sludge, which is associated with many factors. In the case study, the carbon content was assumed to be 55.1 wt% (Cooper et al., 1999). While the carbon content was measured within the range of [23.52, 46.48] (wt%) in another report (Phyllis2Database, 2020). In this section, the carbon content in sewage sludge was assumed to be within the range of [20%, 55%] and corresponding result was calculated and analyzed every 2.5 wt% increase of the C content. The total carbon emissions under each situation and the comparison with original results were collected in

Table A2.12.

Based on the data results in

Table A2.12, the total carbon emissions in all the alternatives decreased as the C content in sewage sludge decreases. The difference between investigated point and the initial result in the case study was only associated with the difference between C content. Therefore, the variation in value under the same C content situation of all the alternatives was the same. Scenarios T and TC presented similar variation trends within the range around [-52%, -0.15%] as the C content increased. The later three options showed alike tendency within the variation range about [-44%, -0.13%]. Scenario TD was less influenced by the changing of C content in sewage sludge compared to other alternatives, but still decreased by [-40.66%, -0.12%]. The score of carbon emissions under different C content situation was also analyzed and results revealed that the scores kept consistent with those in case study. This is because the normalization step canceled the influence caused by changing C content. Direct carbon emission rate under each situation was calculated and the corresponding difference with initial result in the case study was also obtained, which were shown in

Table A2.13.

The direction carbon emissions rate performed a significant decline trend as the C content in sewage sludge increased. Since the total amount of direct carbon emissions from the treatment process was assumed to be fixed, the improvement on C content of sewage sludge only contributed to the indirect forms of carbon emissions and the total amount of possible carbon emissions. This situation was particularly evident in the first two alternatives (T, TC) whose direct carbon emission rates could be around double when the C content was 20 wt%. The direct carbon emission rates of TI, TIM and TM could increase by about 75-85% at most. The rate of TD was relatively stable, and the increase was less than 70% when the C content was 20 wt%.

4.4 Discussion

4.4.1 Sensitivity analysis

The features of the six alternatives can be figured out according to the above analysis. Improving the weight of energy recovery efficiency can make the Scenario TI and TIM more preferred, closely followed by Scenario TIM. Variation on carbon emissions' weight has insignificant influence on the assessment results of Scenario TI, TIM and TM, which means that these scenarios show less competitiveness compared with Scenario T and TC when the importance of carbon emissions is emphasized. However, the weight of water consumptions has remarkable impact on the assessment results. Due to the extra input of energy and materials for sludge thermochemical process, water consumptions in the process of TI, TIM and TM are much more than that those of the other alternatives. Hence, these three scenarios present obvious interiority on the aspect of water loss. When stakeholders put emphasis on water consumptions, Scenario T and TC are more suitable for the sludge treatment; when the weight for energy recovery is higher, Scenario TI, TIM and TM are more in line with the decision-makers' expectations.

4.4.2 Uncertainty analysis

Based on the above analysis under different assumptions for energy recovery amount from AD, LHV, and C content in the sludge, more characteristics of the six investigated alternatives can be obtained. The major pointed can be summarized as follows.

Scenarios T, TC, and TD were easily influenced by the variation of the three parameters, especially the former two options. It can be evidently reflected by the results in Section 4.3.6.1 and Section 4.3.6.3. Scenario TD was also sensitive to the changing of energy recovery amount from AD, but it kept relatively stable in the analysis for the other two assumptions. This is because T and TC shared quite similar treatment route and the only difference was the added composting in TC, with relatively low additional energy and materials input. Drying in Scenario TD required plenty of extra energy and materials supply, which was regarded as the major energy consumption step in the technique route. Meanwhile, anaerobic digestion was the only source for energy recovery in the three alternatives, leading to the high sensitivity of T and TC on the energy recovery amount from AD and LHV of sewage sludge.

The variation trends of Scenarios TI, TIM and TM were similar, especially the first two alternatives, due to the alike treatment route and considerable amount of energy recovery from thermochemical process, i.e., incineration and melting. In total, the energy efficiencies and corresponding scores of these three alternatives were less influenced by the changing of energy recovery amount from AD and LHV of sewage sludge compared to the other three options, which is resulted from the considerable amount of energy regeneration from incineration or melting.

4.4.3 Implications

Corresponding suggestions can be put forward based on the features of these scenarios.

On the one hand, further developing current sludge treatment technologies in order to improve the energy recovery efficiency and reduce the investment is recommended. Since extra energy input is necessary and unavoidable for energy recovery process, which means that reducing the carbon emissions and water consumptions may not be feasible, it is essential to optimize the technology itself and make the sludge-to-energy technologies more attractive and competitive. Process design, facility design, and operating conditions improvement may all be the entry points for future optimization research aiming at improving energy recovery rates to balance the corresponding input. In addition, recycling and reusing the free water in sewage sludge is also important to reduce the water loss. On the other hand, it is suggested to detect the specific contents of the treated sludge to know the features before determining the treatment route as well as considering the local development status of different treatment technologies. According to the discussion on sensitivity analysis and uncertainty analysis, some important properties and parameters of treated sludge may have great influence on the treatment effectiveness. Hence, conducting an additional step for detection on the treated sludge in the region is suggested if it is possible. The determination of treatment technologies should also consider the diverse development status of sludge-to-energy technologies and features of different sources of sludge in different regions. The sludge in some regions may be more suitable for anaerobic digestion with a relatively mature technology to realize effective utilization. Some regions may be suitable to conduct incineration for more thorough treatment. It is acknowledged that incineration is the most thorough method for sludge treatment with considerable potential for energy recovery. Improving the energy recovery rates from incineration and anaerobic digestion as well as the energy exchange efficiency for utilization is also one of the directions for future research.

Apart from the efforts of research and industry, the government is also expected to make reasonable charge standards and provide incentive policy and sufficient financial support to guarantee the basic development of relevant research and encourage the industries to conduct sludge treatment with energy and resource recovery as thorough and complete as possible. A previous report recorded current situation on the related policy and measures on sludge manage in different cities in China (Asian Development Bank, 2012).

Therefore, it should be acknowledged that some energy recovery technologies are still not competitive enough compared with some basic treatment, especially when the advanced methods are limited by the technical maturity. Meanwhile, the advantages of applying sludge incineration mainly reflected by the contribution of reducing the environmental burden on some specific indicators, such as human and ecosystem toxicity, acidification and eutrophication, but the unsatisfactory energy recovery, possible air pollution, and external resource depletion may limit the wide application of incineration in developing countries (Lombardi et al., 2017). More efforts are still needed to figure out the potential of recycling energy and resources from digested sludge to decide whether it is necessary to conduct further treatment. This study also indicates that the assessment for sewage sludge treatment methods with energy recovery should be conducted in detail based on the specific conditions of the development of local technologies and legislation.

4.5 Summary

In this chapter, a life cycle composite footprints index was proposed and relevant assessment methodology framework was developed for sludge-to-energy technologies evaluation. Fuzzy BWM and fuzzy AHP were applied to obtain the weights of concerned aspects and overall scores of the composite footprint index. Life cycle composite energy-carbon-water index was applied to assess six scenarios for sewage sludge treatment combined with energy recovery, including dewatering, composting, drying, incineration, incinerated ash melting, gasification and melting. A gate-to-gate analysis was conducted to study the energy, carbon, and water flows for each alternative. Results showed that Scenario TM had a better performance, followed by Scenario TI and T, then the Scenario TIM and TC. Alternative TD took the last place with a total score of 0.1140. To analyze the influence of different weighting assignment on each aspect, sensitivity analysis was conducted which included three groups of weight distribution. Results showed that Scenario TM, TI and TIM were favored by the increasing weight of energy recovery. The weight of carbon emissions had no significant effect on the combined assessment of these three options while the scores of the other scenarios had obvious changes as the weight of carbon emissions rises. The scores of scenarios with large amount of energy exhibit a downward trend due to the undesirable performances on water consumptions. On the contrary, Scenario T, TC and TD all showed an increasing trend when the importance of water consumptions was emphasized. Uncertainty analysis was also carried out to examine the influence of assumptions on energy recovery amount from AD, LHV and C content in sewage sludge.

Results revealed that the variation of the former two parameters have significant influence on Scenario T and TC. Other options were less affected than the first two alternatives, especially Scenario TD. Future research may also consider analyzing the compound effect of different parameter on the evaluation.

The results also pointed out that one of the major barriers of current energy recovery technologies from sewage sludge is the low energy recovery rate, leading to the less advantage in balancing energy and materials input. The focus of future work should be improving the entire performance of sludge treatment technologies, especially the energy production yields. Water recycling during the process of mechanical dewatering is also critical because of the existence of large amount of free water in sewage sludge. Considering the carbon tax, sludge treatment plants may need to add extra disposal for carbon capture, which also contributes to a higher investment for the entire system. Hence, local government should provide suitable financial support as incentives to maintain the operations and promote the development of waste management plants. LCA is a powerful tool to evaluate the performances of selected alternative. Nevertheless, the assessment work should be conducted according to the specific situation of the specific region because the evaluation results are deeply influenced by the assumptions on the features of sewage sludge and technologies.

Chapter 5 Sustainability Assessment and Alternative Selection for Sludge Valorization Technologies Based on Process Simulation and Fuzzy Multi-Criteria Decision Analysis

In Chapter 4, we have constructed a novel composite index to discuss the sustainability performances of sludge-to-energy technologies with life cycle thinking. Sustainability prioritization and alternative selection can be conducted based on the assessment results. However, lacking performance data is a common situation in sustainability assessment and decision-making process, especially for emerging technologies. In this chapter, a sustainability-oriented evaluation and decision-making framework is constructed based on process simulation and fuzzy multi-criteria decision analysis tool to handle such kind of problem. In Session 5.1, the research problem is described and the research gaps are highlighted. The investigated technical routes are introduced in Session 5.2 as well as the established methodology framework. Detailed results and discussion are presented in Session 5.3. Finally, the major contributions and limitations of this work are summarized in Session 5.4.

5.1 Problem description

Many multi-criteria decision-analysis (MCDA) methods have been employed to solve the decision-making problem of waste management. Nevertheless, uncertainty is commonly shown in the actual decision-making process, either from the situation of lack of accurate data or the subjective judgment and preferences from decision-makers. One of the solutions to address the uncertainty from the linguistic terms provided by decision-makers is to use fuzzy MCDA models, which combine fuzzy theory and MCDA methods together. Although these theoretical models can effectively integrate the opinions of the experts, the evaluation and selection of results usually show high dependence on the expertise of the decision-makers. Moreover, experimental analysis and process simulation are often applied to make up for the lack of data by many scholars. Besides solely process simulation, techno-economic analysis and life cycle assessment (LCA) tool were also used for the evaluation of hydrothermal carbonization for sewage sludge based on the process simulation results (Medina-Martos et al., 2020). Similarly, process simulation was applied to conduct techno-economic analysis for the thermochemical conversion of poultry waste as well (Bora et al., 2020). In addition, Ding et al. (2021) in their review about the use of LCA for sewage sludge treatment and disposal-based energy recovery, highlighted thar conversion of sludge into energy is a crucial part of a sustainable sludge management strategy. Previous studies have verified the feasibility of using experimental analysis and process simulation to obtain the data for performance evaluation of the waste management alternatives. However, depending on the data obtained from experiments could be limited by the applicable scale, and current application of process simulation majorly focuses on the basic techno-economic evaluation without final selection recommendation. In order to address the problem of lacking data for the emerging sludge management technologies and provide insightful suggestions under the situations with uncertain preferences, a decision analysis framework is constructed based on process simulation and fuzzy multi-criteria decision analysis method.

5.2 Methodology

The objective of this work is first to compare and analyze the sustainability performances of several potential waste-to-wealth technology routes which are conceptually designed using simulation tools, and then to provide valuable suggestions using the decision-making process for future waste management reference and the development of emerging technologies. The methodology framework of this work majorly includes three parts (i.e., process identification and process simulation, sustainability evaluation, and decision analysis) which are shown in Figure 5.1.

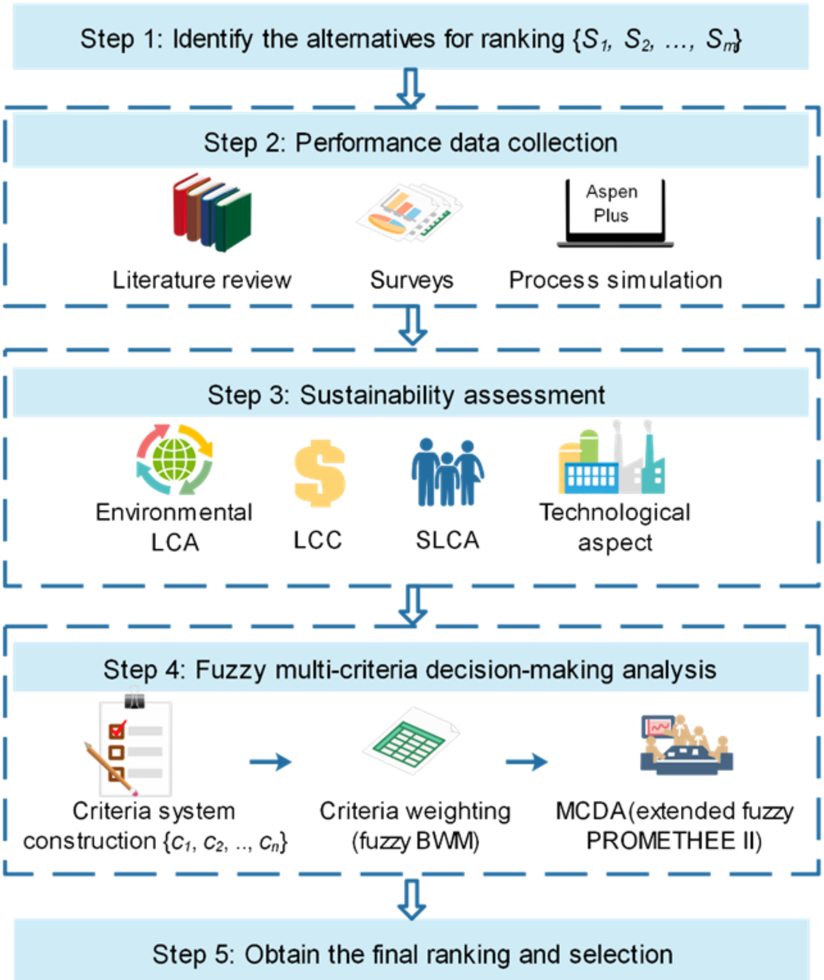


Figure 5.1 Methodology framework of the sustainability prioritization for waste-to-wealth alternatives

In this chapter, sewage sludge, a kind of byproducts from wastewater treatment plant, is selected as an example to verify the proposed decision-making framework for waste-to-wealth management. The evaluated alternatives are identified and introduced in Section 5.2.1 together with the basic assumptions for the process simulation. Based on the performance data of technical alternatives, sustainability assessment can be conducted by using LCSA, which are described in Section 5.2.2. Then the prioritization for the alternatives can be conducted based on the evaluation results and the core approach is shown in Section 5.2.3.

5.2.1 Sludge valorization process and simulation

Four sludge valorization technical routes are considered as the alternatives for evaluation and selection in this study, which can be listed as follows:

i) Scenario 1 (S1): AD-based treatment for steam and power generation.

ii) Scenario 2 (S2): Incineration-based treatment for power generation.

iii) Scenario 3 (S3): Gasification-based treatment for syngas generation.

iv) Scenario 4 (S4): SCWG-based treatment for syn-gases and power generation.

The four technologies are selected as the investigated objects because the following reasons. Firstly, incineration is still the major treatment approach for the municipal solid waste (Ma et al., 2020), which has been widely accepted in many countries. Although incineration has been regarded as a thorough treatment for different kinds of waste, the accompanying environmental burdens cannot be ignored. Therefore, it is necessary to discuss whether the emerging technologies could be potential and attractive to the traditional methods. Secondly, the potential of gasification (Syed-Hassan et al., 2017) and SCWG (Amrullah and Matsumura, 2018) as relatively newly developed methods for sewage sludge treatment with value-added products production has gradually been recognized. Nevertheless, both technologies are still under development stages without large-scale application and the related data is quite limited. It would be helpful to study the potential of commercial application of these two technologies in order to provide suggestions to guide the further improvement. Moreover, anaerobic digestion is a common technology for sewage sludge stabilization with power generation from the produced biogas, which already has well established process and market with practice (Tarpani and Azapagic, 2018). Sludge digestion with power generation is usually credited by the economic benefits (Tarpani and Azapagic, 2018), but it remains to be investigated whether the solely use of anaerobic digestion for sludge treatment without subsequent operations is acceptable from other dimensions of sustainability, especially environment. Based on the above considerations, the four sludge valorization technologies according to the data conditions and assumptions in Hong Kong are studied and simulated by using the proposed model.

As it has been mentioned in the Introduction section, some technologies, especially for the emerging technologies, face with the problem of lacking performance data on a pilot or commercial scale. In this study, process simulation by using process simulation software (Al-Malah, 2016) based on the parts of previous experimental data combined with theoretical model is applied to deal with the data deficiencies. The involved assumptions for the process simulation are listed as follows:

a. The composition of the input sludge has been shown in Table 5.1 (Shao et al., 2009). All the simulation process are conducted with the same compositions of input sludge and total amount.

b. The major treatment of sewage sludge for valorized products generation are considered in the simulation processes. The final use of the products and electricity and disposal of residues are excluded in this research.

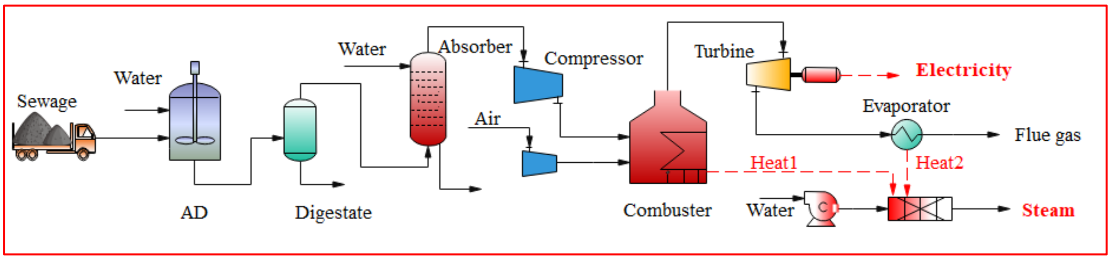
c. According to the literature, the actual daily capacity of the sludge treatment facility (T PARK) was 1058 ton of dewatered sludge per day on average and the maximum of daily treatment capacity is 2000 t (Drainage Services Department, 2017). Therefore, it is assumed that all the processes receive and treat 1058 t sludge/day with the working hour of 24 h/day and 8000 h/year (which means that the facility is assumed to operate 8000/24=333 day/year).

Table 5.1 Mass fraction of sludge composition (Shao et al., 2009)

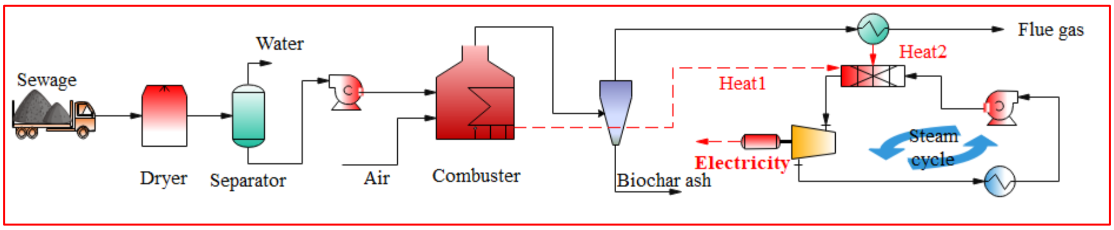
	Proximate analysis[1]				Ultimate analysis				
	MC	AC	VM	FC	C	H	N	S	O
Composition (wt%)	64.1	23.4	75.3	1.3	47.54	7.99	2.02	0.50	18.55

1 MC: Moisture content; AC: Ash content; VM: Volatile matter; FC: Fixed carbon.

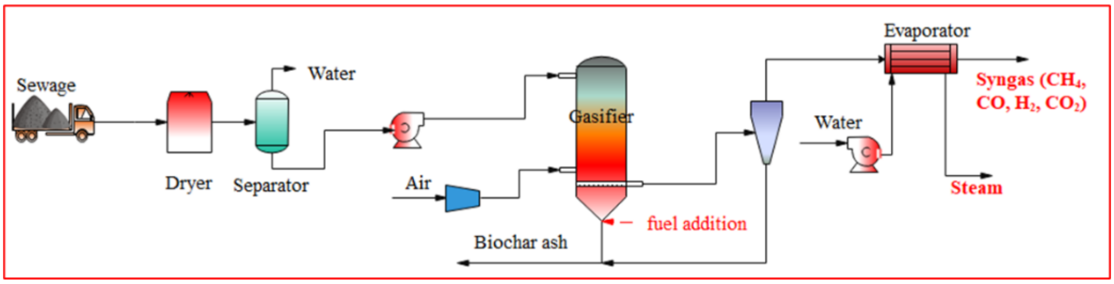
The flowcharts for the four alternatives in process simulation by chemical process simulation software with the collaborations with Chongqing University are shown in Figure 5.2. More detailed descriptions for the process simulation and related reactions are presented in the Appendix Part III. According to the process simulation results, basic data about corresponding technology can be obtained which can be further applied as the life cycle inventory data for the sustainability evaluation and decision-making analysis.



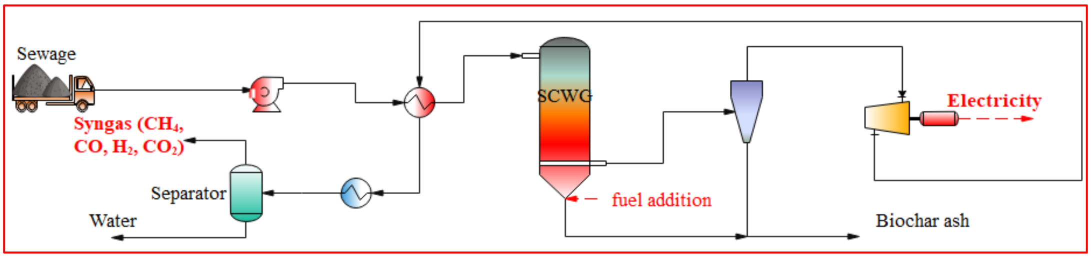
(a) Anaerobic digestion



(b) Incineration with power generation



(c) Gasification



(d) SCWG

Figure 5.2 Process flowcharts for the major treatment technologies in the four alternatives

5.2.2 Sustainability evaluation

LCSA as a powerful tool for addressing the sustainability performances has been widely applied in different fields for sustainability evaluation because of the ability of considering the influences alongside the entire life cycle stages (Liu and Ren, 2021).

Besides three common sustainability pillars, technical performances can be similarly assessed, which have been performed in previous studies (Liu et al., 2020b; Ren et al., 2017b).

Based on the simulation results, sustainability evaluation can be conducted with the application of life cycle assessment tool, an effective tool for the quantification of environmental impacts associated with a process or a technology (Farjana et al., 2019). The functional unit is selected to be one dry ton of sewage sludge. System boundaries of the environmental assessment have been shown in Figure 5.3. The energy and materials input, emissions and energy outputs during the major treatment process, transportation between the sludge treatment facility to the final disposal site as well as the final disposal are considered. The further application and upgrading of the products (e.g., syngas upgraded to pure fuel gas, reformation) are excluded from the scope. SimaPro is applied to evaluate the environmental performances of the four alternatives on the indicators. The economic performances and energy efficiency can be analyzed based on the simulation results by Aspen Plus and previous studies (Hong, Hong, Otaki, & Jolliet, 2009), while the other indicators in social and technical aspects are assessed by decision-makers with linguistic terms in this study, which can be further transformed into fuzzy numbers (Tong et al., 2020) or grey numbers (Ren et al., 2017b) for quantitative analysis. The transformation rules between linguistic descriptions and corresponding triangular fuzzy numbers (TFNs) applied in this study are shown in Table 5.2.

Table 5.2 Transformation rules of linguistic terms and their corresponding TFNS (Tong et al., 2020)

Linguistic terms	Denotations	TFNs
Very Low	VL	(0,0,0.1)
Low	L	(0, 0.1,0.3)
Medium Low	ML	(0.1,0.3,0.5)
Medium	M	(0.3,0.5,0.7)
Medium High	MH	(0.5,0.7,0.9))
High	H	(0.7,0.9,1)
Very High	VH	(0.9,1,1)

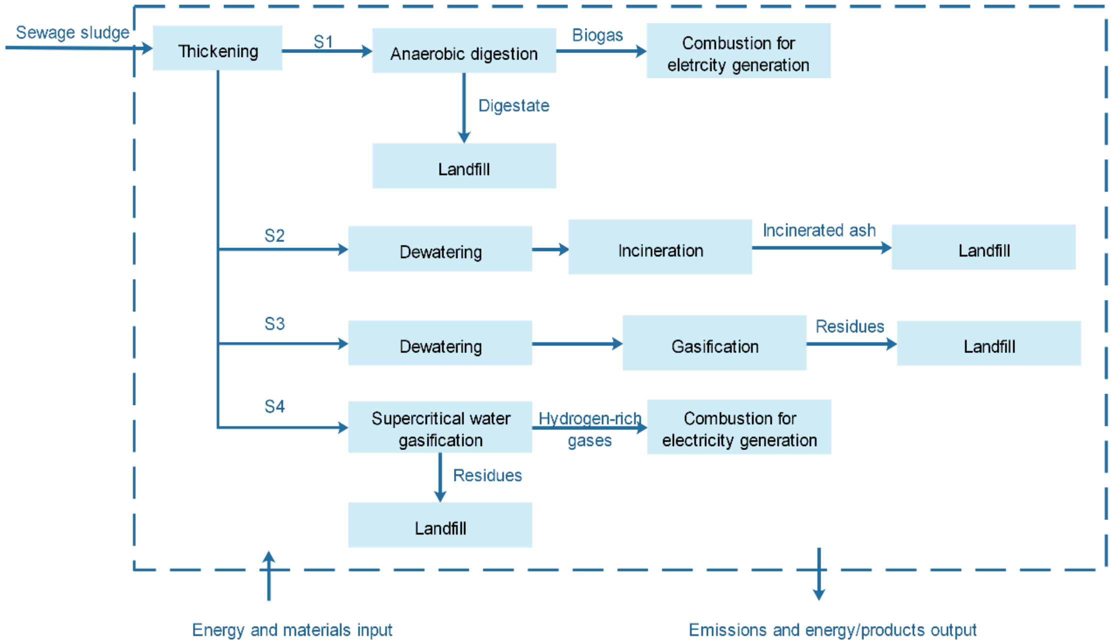


Figure 5.3 System boundaries of the four simulated sludge valorization technologies in process simulation

5.2.3 Fuzzy multi-criteria decision-making

Generally, prioritization ranking of the alternatives are determined by the performance data on the considered criteria and the corresponding weight in multi-criteria decision-making method. In this session, the criteria system is firstly constructed and presented in Session 5.2.3.1. Then the weighting method to calculate the fuzzy weights based on the preferences of stakeholders is introduced in Session 5.2.3.2. Afterwards, the principles for conducting prioritization ranking with fuzzy PROMETHEE (Preference ranking organization method for enrichment evaluation) II approach is described in Session 5.2.3.3.

5.2.3.1 Criteria system

A criteria system is essential for performance evaluation and prioritization of the target systems. In this section, a criteria system consisting of four dimensions, i.e., environmental, economic, technical, and social aspect, is constructed to help with the assessment of waste management technologies. In this study, four impact categories in life cycle inventory assessment (LCIA) are selected as environmental indicators to evaluate the environmental impacts of the investigated processes with life cycle thinking. More detailed descriptions of the indicators in each aspect are presented in Table 5.3. The criteria system shown in Table 5.3 is an example for the framework, which can be flexibly adjusted based on the reality and needs of the stakeholders. Basic rules and suggestions for the criteria selection during decision-making process were discussed in the previous research (Wang et al., 2009).

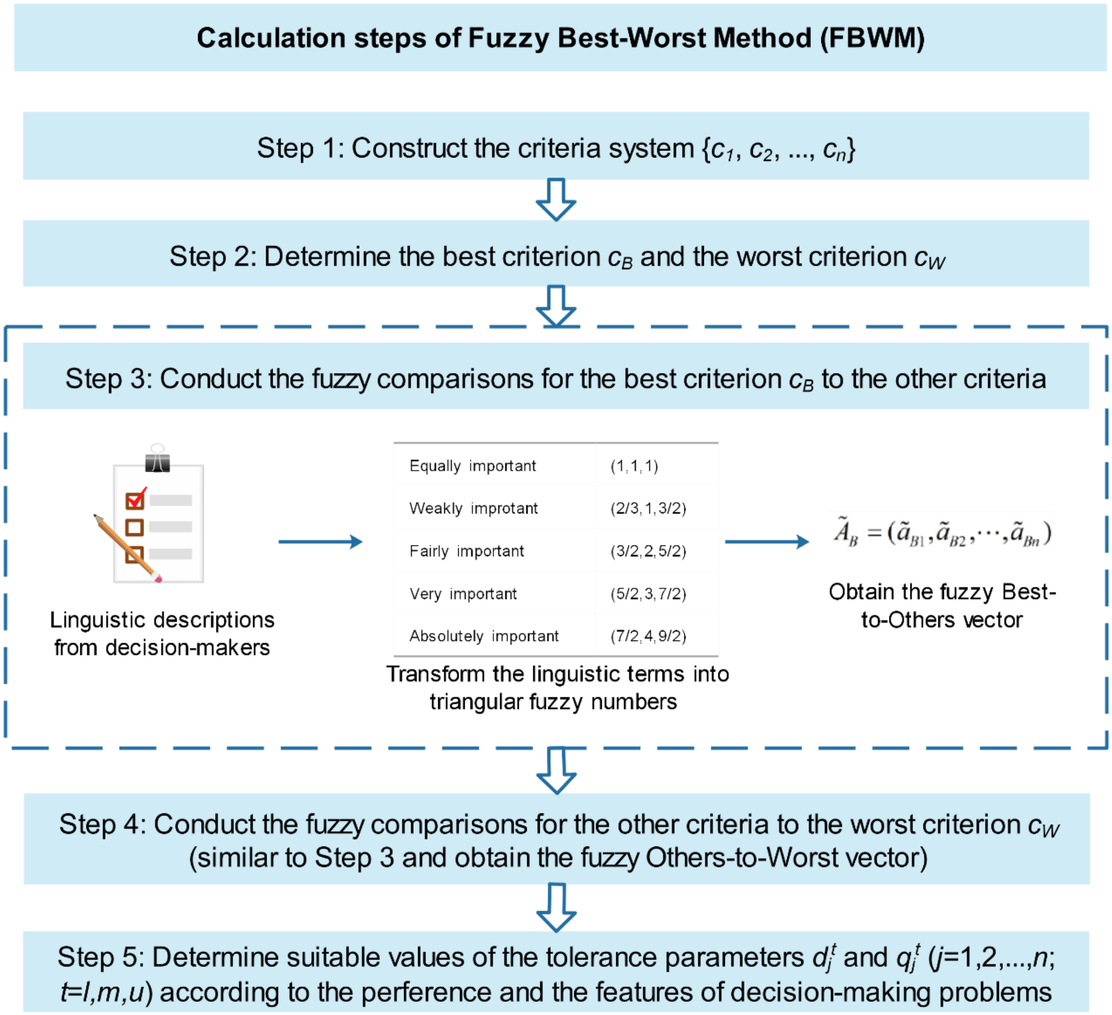
Table 5.3 Criteria system for the sustainability assessment

Aspect	Criteria	Description
Environmental (AS1)	Climate change (C_1)	The impacts caused by greenhouse gases (Clary, 2013; IPCC, 2021)
	Acidification potential (C_2)	The compounds which are precursors to acid rain (Dincer and Abu-Rayash, 2020).
	Human toxicity (C_3)	The impacts of toxic substances on human health (Čuček et al., 2015).
	Eutrophication (C_4)	The potential to cause over-fertilization of water and soil, which can lead to the increased growth of biomass (Čuček et al., 2015).
Economic (AS2)	Total capital costs (C_5)	The capital investment of the technological alternatives, which majorly involves the equipment cost and construction costs.
	Total operating costs (C_6)	The sum of all annual cost including raw material cost, utility cost and operating labor cost etc.
	Production sales (C_7)	The direct profits that come from the selling of products
Technological (AS3)	Energy efficiency (C_8)	The ratio of total amount of energy recovery and total amount of energy consumption (Yang et al., 2020).

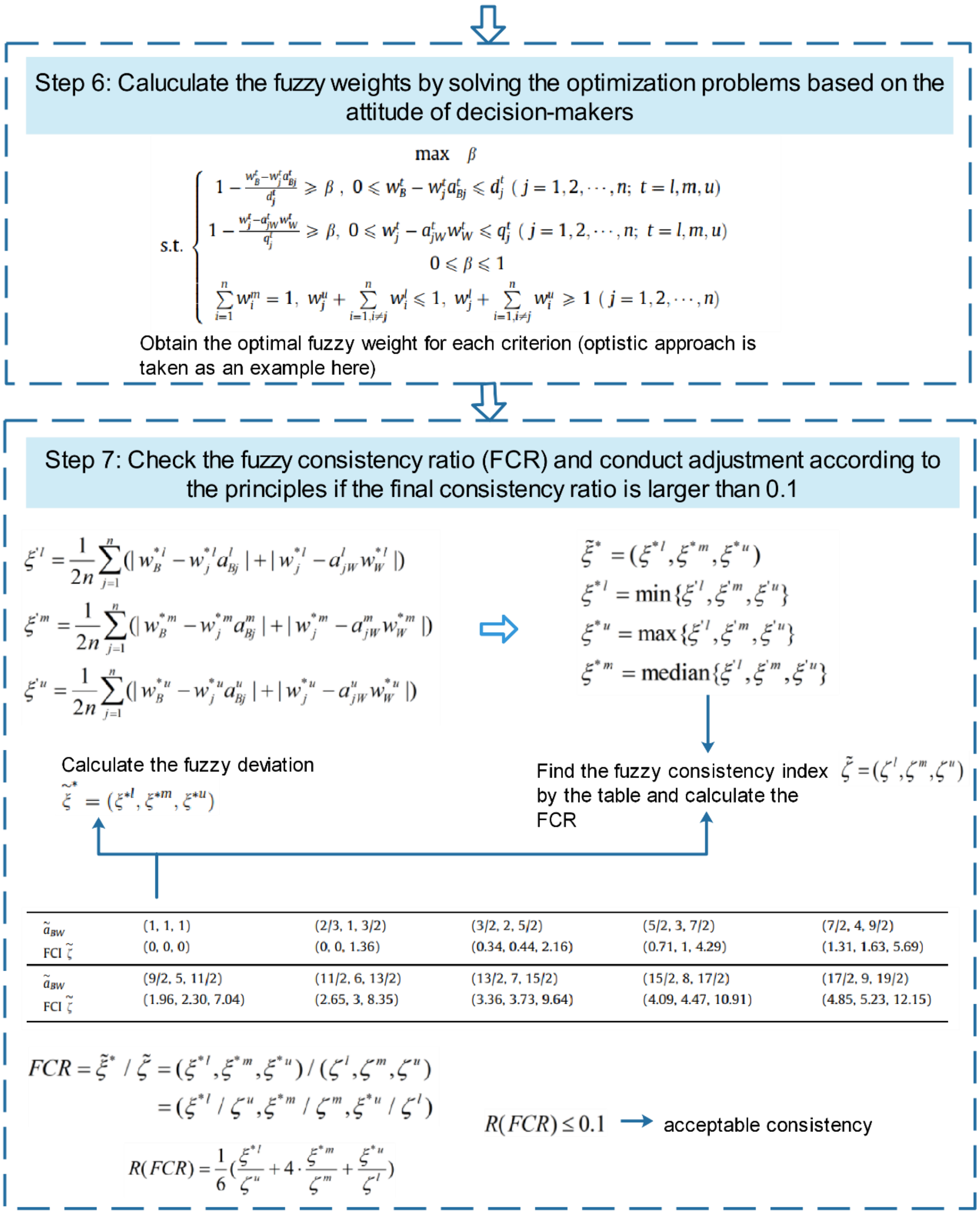
	Technical maturity (C_9)	The maturity and applicable scale of the technology.
	Technology accessibility (C_{10})	The accessibility to the technology from national or foreign companies (Torkayesh et al., 2021).
Social (AS4)	Social acceptance (C_{11})	The degree of public acceptance of the technology.

5.2.3.2 Weighting method

Frequently applied weighting methods for decision-making process include AHP (analytic hierarchy process), SWING, SIMOs and best-worst method (Rezaei, 2015; Wang et al., 2009). Among these methods, best-worst method (BWM) as a kind of pairwise comparison weighting method with less comparison steps and more reliable consistency ratios has been widely applied in many fields and further developed to address more complicated MCDM problem. By introducing fuzzy theory into BWM, it was first extended as fuzzy BWM to deal with the linguistic description of the stakeholders' preferences on the criteria (Guo and Zhao, 2017). A new fuzzy BWM and the concept of fuzzy consistency ratio were proposed by Dong et al. (2021) which can provide more flexible selection on the optimization model for calculating the fuzzy weights according to the attitude of decision-makers. In order to flexibly handle the decision-making problem with uncertain preferences, the fuzzy BWM constructed by Dong et al. (2021) is selected to decide the weight of each criterion. The detailed description for the calculation principles and the specific model for different situation based on the decision-makers' attitude can be found in the study of Dong et al. (2021) and a brief summarization for the major calculations steps are presented in Figure 5.4 .



(a) Step 1-5 for the fuzzy BWM: data collection and process



$\tilde{a}_{BW}$	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(7/2, 4, 9/2)
FCI $\tilde{\zeta}$	(0, 0, 0)	(0, 0, 1.36)	(0.34, 0.44, 2.16)	(0.71, 1, 4.29)	(1.31, 1.63, 5.69)
$\tilde{a}_{BW}$	(9/2, 5, 11/2)	(11/2, 6, 13/2)	(13/2, 7, 15/2)	(15/2, 8, 17/2)	(17/2, 9, 19/2)
FCI $\tilde{\zeta}$	(1.96, 2.30, 7.04)	(2.65, 3, 8.35)	(3.36, 3.73, 9.64)	(4.09, 4.47, 10.91)	(4.85, 5.23, 12.15)

(b) Step 6-7: fuzzy weights calculation and consistency check

Figure 5.4 Major calculation steps of fuzzy best-worst method (modified from (Dong et al., 2021)). The detailed principles for adjusting the fuzzy comparisons are not shown in the figure, which can be found in the corresponding paper.

5.2.3.3 Extended fuzzy PROMETHEE II method

PROMETHEE method is an outranking method for alternatives prioritization which was proposed by Brans (1984) and further improved by Brans and Vincke (Brans and

Vincke, 1985). There are two versions of PROMTHEE methods, that is PROMETHEE I and PROMETHEE II method. The former version allows incomparability (Wang et al., 2009) and provides partial ranking while the latter can generate complete ranking for all the alternatives. Therefore, PROMETHEE II approach is selected to obtain the complete ranking of the investigated technologies. To address the vagueness and uncertain preferences of stakeholders, PROMETHEE II approach is extended to the fuzzy version based on the fuzzy set theory and the method proposed by Tong et al. (2020). With the proposed extended fuzzy PROMOTHEE II method, the investigated alternatives can be effectively evaluated in a relatively simple operation steps, which can contribute a lot to the entire decision-making process, especially for the decision-making problems with more alternatives and criteria. Before the description of the specific steps of the proposed fuzzy PROMOTHEE II method, the definitions of the symbols are introduced, which are shown by Table 5.4.

Table 5.4 Definition of the related parameters in the model

Items	Denotations
Set of technology alternatives	$\{S_1, S_2, \ldots, S_m\}$
Set of decision-makers	$\{D_1, D_2, \ldots, D_l\}$
Criteria set	$\{c_1, c_2, \ldots, c_n\}$
Weights of criteria	$\{w_1, w_2, \ldots, w_n\}$

The detailed steps of extended fuzzy PROMETHEE II methods are described as follows (Tong et al., 2020).

Step 1: Build up the normalized fuzzy performance matrix.

Assumed that the normalized fuzzy performance matrix is denoted by $X = [x_{ij}]_{m\times n}$, $i = 1, 2, ..., m,\ j = 1, 2, ..., n$. If E and F represents the benefit criteria set and the cost criteria set, respectively, then the normalization rules can be expressed by Eqs. (5.1) - (5.4). According to the difference in evaluation scales and the data accessibility for the different indicators, the normalization methods vary with the data forms of the specific criterion and corresponding category. Eq. (5.1) and Eq. (5.2) show the normalization approach for the indicator with crisp numbers, and Eqs. (5.3) and (5.4) are for the indicator described by linguistic terms, which are further transferred into triangular fuzzy numbers,

$$x_{ij} = \frac{a_{ij} - \min_i a_{ij}}{\max_i a_{ij} - \min_i a_{ij}},\ j \in E \tag{5.1}$$

$$x_{ij} = \frac{\max_i a_{ij} - a_{ij}}{\max_i a_{ij} - \min_i a_{ij}},\ j \in F \tag{5.2}$$

where x_{ij} refers to the normalized performance data for the indicator with crisp numbers for evaluation in Eq. (5.1) and Eq. (5.2), addressing the performance of the i th scenario on the j th criterion. a_{ij} is the initial performance data of the i th scenario on the j th criterion.

$$x_{ij} = (a_j^L / a_{ij}^{N+}, a_j^M / a_{ij}^{N+}, a_j^N / a_{ij}^{N+}),\ j \in E,\ a_j^{N+} = \max_i a_{ij}^N \tag{5.3}$$

$$x_{ij} = (a_j^{L-} / a_{ij}^N, a_j^{L-} / a_{ij}^M, a_j^{L-} / a_{ij}^L),\ j \in F,\ a_j^{L-} = \min_i a_{ij}^L \tag{5.4}$$

where $x_{ij} = (r_{ij}, s_{ij}, t_{ij})$ is the given performance data by the experts for the j th criterion of the i th alternative. r_{ij}, s_{ij}, and t_{ij} mean the lower bound, medium bound and upper bound of the performance data, respectively.

Supposing that there are l experts in the decision-making group. It is necessary to integrate the opinions of different experts together. The integration method for the triangular fuzzy number can be determined by Eq. (5.5).

$$a^L = \frac{1}{l}\sum_{k=1}^{l} a_k^L,\ a^M = \frac{1}{l}\sum_{k=1}^{l} a_k^M,\ a^N = \frac{1}{l}\sum_{k=1}^{l} a_k^N \tag{5.5}$$

where (a^L, a^M, a^N) refers to the integrated triangular fuzzy number based on the preferences of l decision-makers.

Step 2: Construct the preference function $P_j(x_{ij}, x_{kj})$ for the j th criterion.

There are six general types of preference functions in PROMETHEE method, which are shown in Table 5.5. Among all types of preference function, Gaussian rule was considered as the most frequently used one according to the previous research (Tong et al., 2020). Hence, the Gaussian rule is selected as the preference function in this study, which can be expressed by Eq. (5.6).

Table 5.5 Six basic preference functions of PROMETHEE approach (Tong et al., 2020)

Preference function	Definition	Preference function	Definition
Usual rule	$P(d)=\begin{cases}1, d>0\\0, d\le 0\end{cases}$	Multiclass rule	$P(d)=\begin{cases}1, d>p\\0.5, q<d\le p\\0, d\le q\end{cases}$
"Half" rule	$P(d)=\begin{cases}1, d>p\\0, d\le p\end{cases}$	Indifference interval linear priority rule	$P(d)=\begin{cases}1, d>p\\\dfrac{d-p}{p-q}, q<d\le p\\0, d\le q\end{cases}$
Linear priority rule	$P(d)=\begin{cases}1, d>p\\\dfrac{d}{p}, d\le p\end{cases}$	Gaussian rule	$P(d)=\begin{cases}1-e^{-\frac{d^2}{2\sigma^2}}, d>0\\0, d\le 0\end{cases}$

$$P_j(x_{ij}, x_{kj}) = 1 - e^{-(d_{j(x_{ij}, x_{kj})})^2/2\sigma^2},\ i \ne k, i,k = 1,2,...,m \tag{5.6}$$

where σ is the threshold value between the indifferent and strict preference areas. $d(x_{ij}, x_{kj})$ refers to the normalized Euclidean distance between the scenario i and scenario k on the j th criterion based on the triangular fuzzy numbers, which is determined by Eq. (5.7). Since the all the performance data have been normalized by Eqs. (5.1) - (5.4), the distance between two alternatives on the j th criterion can be decided by Eq. (5.7), no matter the criterion j is benefit criterion or cost criterion.

$$d_{j(x_{ij},x_{kj})} = \begin{cases} \{[(r_{ij}-r_{kj})^2+(s_{ij}-s_{kj})^2+(t_{ij}-t_{kj})^2]/2\}^{1/2}, \, x_{ij} > x_{kj} \\ 0, \text{else} \end{cases} \tag{5.7}$$

where $i \neq k$, $i,k=1,2,...,m$. In order to process the indicator evaluated by crisp numbers, their data form is also extended into triangular fuzzy number. For instance, if the performance data of i th alternative on criterion j can be described by exact number a_{ij}, then the extended TFN can be expressed as $x_{ij}=(a_{ij},a_{ij},a_{ij})$ to keep the exact information that is known as much as possible.

The calculation for Euclidean distance between two triangular fuzzy numbers involves with the comparison between them. The comparison principles applied in this research complies with the research of Akyar et al. (2012). The detailed comparison principles can be found in the corresponding reference, which are omitted here.

Step 3: Compute the preference index $\pi(x_i,x_k)$ according to the preference function. The preference index reveals the priority of the i th alternative is higher than that of the k th option. Higher value of $\pi(x_i,x_k)$ indicates the stronger preference of the former option. The preference index can be determined by Eq. (5.8).

$$\pi(x_i,x_k)=\sum_{j=1}^{n} w_j \times P_j(x_{ij},x_{kj}) \quad i \neq k, i,k=1,2,...,m \tag{5.8}$$

where w_j ($j=1,2,...,n$) is the weight for each criterion.

Since the weights have been defuzzied in the weighting method, the results obtained by Eq. (5.8) are the form of exact numbers, not TFNs.

Step 4: Determine the leaving flow $\phi^{+}(x_i)$ and the entering flow $\phi^{-}(x_i)$ for each alternative i. The leaving flow $\phi^{+}(x_i)$ and the entering flow $\phi^{-}(x_i)$ indicate the strength and the weakness of the ith alterative compared with others, respectively. the calculation principles for $\phi^{+}(x_i)$ and $\phi^{-}(x_i)$ are shown by Eq. (5.9) and Eq. (5.10).

$$\phi^{+}(x_i) = \sum_{k=1}^{m} \pi(y_i, y_k) \quad i \neq k, i, k = 1, 2, ..., m. \tag{5.9}$$

$$\phi^{-}(x_i) = \sum_{k=1}^{m} \pi(y_k, y_i) \quad i \neq k, i, k = 1, 2, ..., m. \tag{5.10}$$

Step 5: Calculate the net flow $\phi(x_i)$ and obtain the final ranking for all the alternatives. The higher value of $\phi(x_i)$ is preferred because it is regarded to have better performance. The net flow $\phi(x_i)$ can be determined by Eq. (5.11).

$$\phi(x_i) = \phi^{+}(x_i) - \phi^{-}(x_i) \quad i = 1, 2, ..., m. \tag{5.11}$$

Based on the results of $\phi(x_i)$, the prioritization ranking for all the investigated scenarios can be generated.

5.3 Results and discussion

5.3.1 Decision making analysis

Detailed results of the process simulation and corresponding sustainability performance data are presented in Table A3.1 and Table A3.2 in the Appendix Part III. Accordingly, the ranking of the four alternative sludge valorization technologies can be obtained by conducting the proposed methodology framework, which are described as follows.

Step 1: Construct the normalized fuzzy performance matrix based on the simulation results and sustainability assessment data.

According to the data presented in Table A3.1 in the Appendix and the normalization rules in the methodology, the normalized performance matrix can be obtained, as shown in Table 5.6.

Table 5.6 Normalized performance matrix for the four sludge management alternatives

Aspect	Criteria	S1	S2	S3	S4
AS1	C_1	0.0000	0.9499	1.0000	0.9911
	C_2	0.0000	0.9559	0.9857	1.0000
	C_3	0.0000	1.0000	0.8840	0.9361
	C_4	0.0000	0.9771	0.9147	1.0000
AS2	C_5	0.4689	0.5236	1.0000	0.0000
	C_6	0.0000	0.5795	1.0000	0.8534
	C_7	0.6981	0.0000	1.0000	0.3953
AS3	C_8	1.0000	0.0000	0.8437	0.7924
	C_9	(0.5,0.7,0.85)	(0.8,0.85,1)	(0.15,0.3,0.5)	(0.15,0.3,0.5)
	C_{10}	(0.8,0.85,1)	(0.5,0.7,0.85)	(0.5,0.7,0.85)	(0.15,0.3,0.5)
AS4	C_{11}	(0.59,0.82,1.00)	(0.18,0.35,0.59)	(0.18,0.35,0.59)	(0.59,0.82,1.00)

Step 2: Establish the preference function $P_j(x_{ij}, x_{kj})$ over the j th criterion

By using the Eqs. (5.6) - (5.7) and the comparison rules between the triangular fuzzy numbers, the intensity of the preference for the four sludge valorization alternatives over each criterion can be obtained with the threshold $\sigma = 0.5$. The corresponding results are shown in Table 5.7.

Table 5.7 Intensity of preference for the four alternatives on each criterion

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
P(S1,S2)	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.95	0.00	0.13	0.43
P(S1,S3)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.33	0.13	0.43
P(S1,S4)	0.00	0.00	0.00	0.00	0.48	0.00	0.24	0.12	0.33	0.62	0.00
P(S2,S1)	0.93	0.94	0.95	0.94	0.01	0.63	0.00	0.00	0.13	0.00	0.00
P(S2,S3)	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.62	0.00	0.00
P(S2,S4)	0.00	0.00	0.01	0.00	0.56	0.00	0.00	0.00	0.62	0.33	0.00
P(S3,S1)	0.95	0.95	0.90	0.92	0.57	0.95	0.24	0.00	0.00	0.00	0.00
P(S3,S2)	0.01	0.00	0.00	0.00	0.49	0.41	0.95	0.88	0.00	0.00	0.00
P(S3,S4)	0.00	0.00	0.00	0.00	0.95	0.06	0.67	0.01	0.00	0.33	0.00
P(S4,S1)	0.95	0.95	0.93	0.95	0.00	0.89	0.00	0.00	0.00	0.00	0.00
P(S4,S2)	0.01	0.01	0.00	0.00	0.00	0.20	0.37	0.85	0.00	0.00	0.43
P(S4,S3)	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.43

Step 3: Calculate the preference index $\pi(x_i, x_k)$ and the weight of each criterion. Before the preference index $\pi(x_i, x_k)$ can be calculated, the fuzzy weights of the criteria should be firstly determined by using the fuzzy BWM (Dong et al., 2021) and the detailed computation steps are presented in the Supplementary Information. The fuzzy weight of each aspect and the global fuzzy weights for the entire criteria system are shown in Table 5.8 and Table 5.9, respectively.

Table 5.8 Local fuzzy weight for each aspect

	AS1	AS2	AS3	AS4
Fuzzy weight	0.5657	0.2057	0.0686	0.1600

FCR=0.0615

Table 5.9 Global fuzzy weight of each criterion

AS1	**C1**	**C2**	**C3**	**C4**
Fuzzy weight	0.2182	0.1739	0.1044	0.0693
AS2	**C5**	**C6**	**C7**	
Fuzzy weight	0.0507	0.0215	0.1336	
AS3	**C8**	**C9**	**C10**	
Fuzzy weight	0.0416	0.0102	0.0167	
AS4	**C11**			
Fuzzy weight	0.1701			

Based on the calculation results in **Step 2** and the obtained fuzzy weights for the criteria system, the preference index $\pi(x_i, x_k)$ can be computed by applying Eq. (5.8) and the corresponding results are shown in Table 5.10.

Table 5.10 Preference index of each pair of comparison between the alternatives

Preference index	$\pi(S1, S2)$	$\pi(S1, S3)$	$\pi(S1, S4)$	$\pi(S2, S1)$	$\pi(S2, S3)$	$\pi(S2, S4)$
Value	0.22	0.08	0.08	0.55	0.01	0.04
Preference index	$\pi(S3, S1)$	$\pi(S3, S2)$	$\pi(S3, S4)$	$\pi(S4, S1)$	$\pi(S4, S2)$	$\pi(S4, S3)$
Value	0.61	0.20	0.14	0.55	0.16	0.08

Step 4: Calculate the leaving flow $\phi^{+}(x_i)$ and the entering flow $\phi^{-}(x_i)$ for each alternative i by using Eq. (5.9) and Eq. (5.10). The calculation results are shown in Table 5.11.

Step 5: Compute the net flow $\phi(x_i)$ based on the results of **Step 4** and Eq. (5.11) and obtain the final ranking for all the alternatives. The detailed results and the prioritization ranking are shown in Table 5.11.

Table 5.11 Final results of the net flow and ranking

Scenario	$\phi^+(\mathrm{Si})$	$\phi^-(\mathrm{Si})$	$\phi(\mathrm{Si})$	Ranking
S1	0.37	1.71	-1.34	4
S2	0.60	0.58	0.02	3
S3	0.96	0.17	0.79	1
S4	0.79	0.26	0.53	2

$i = 1, 2, 3, 4$

5.3.2 Results analysis

As shown in Table 5.11, the final ranking order of the four investigated alternatives is S3>S4>S2>S1 since the alternative with a higher $\phi(\mathrm{Si})$ is more preferred. The results suggest that S3, i.e., gasification-based treatment for syngas and steam generation, has the best overall performances on the considered indicators, followed by S4, i.e., SCWG-based treatment for gases and power generation as the second place. Scenarios 1, which only uses anaerobic digestion as the sludge treatment approach, is located in inferior position due to the unsatisfactory performance on the sludge treatment degree leading to many problems in different aspects.

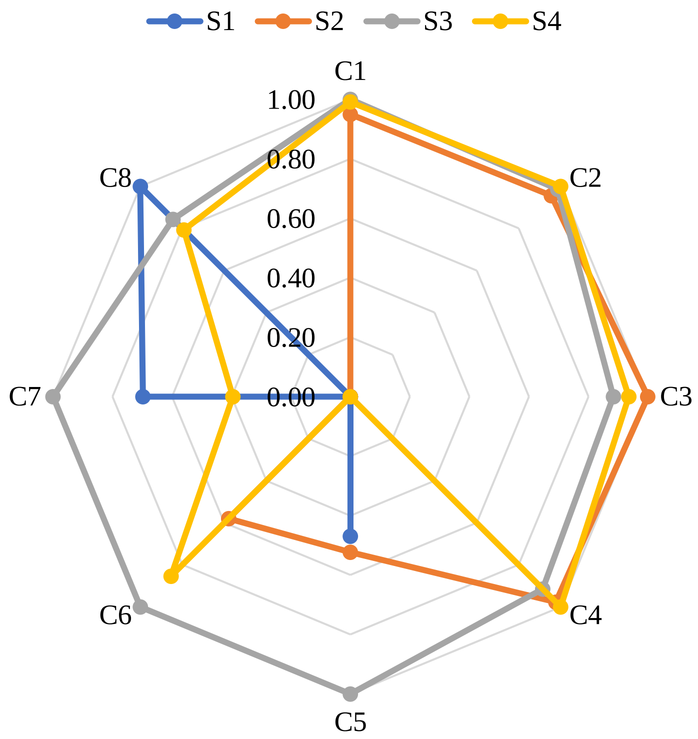
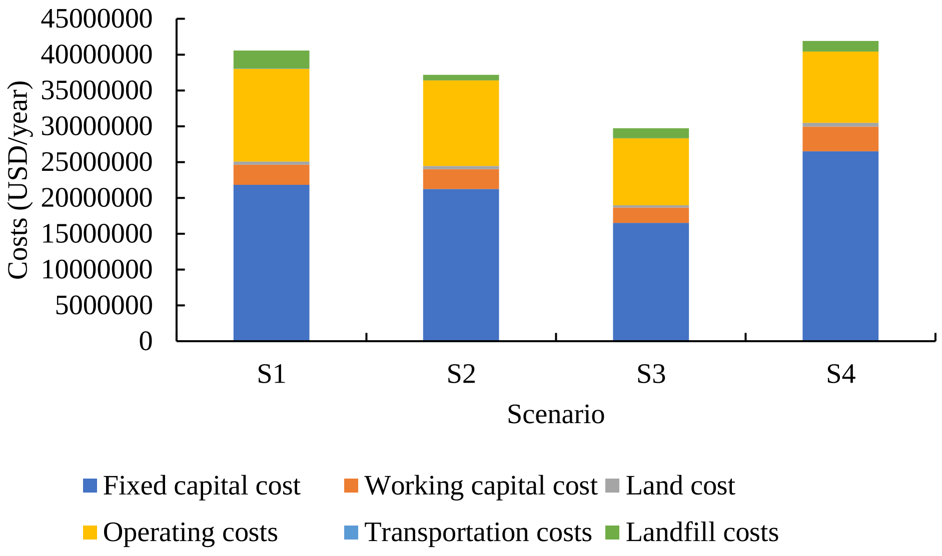
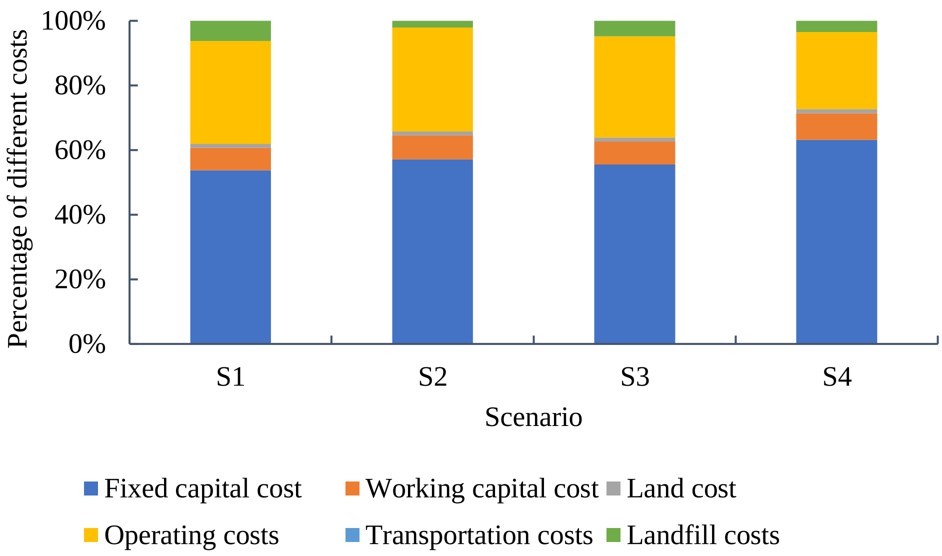


Figure 5.5 Radar map for the normalization results on the indicators with crisp numbers (C_1-C_8) of the four scenarios

A radar map (see Figure 5.5) is applied to intuitively present the advantages and disadvantages of each alternative on the criteria with crisp numbers as the performance data, that is C_1 to C_8. It is clear to see that S3 and S4 are advantageous in the presented criteria. Scenario 2 shows poor performance on C_5, C_7 and C_8, especially on C_7 and C_8 due to the high investment for the capital costs and unsatisfactory energy recovery efficiency. Although incineration possesses relatively mature technical conditions and is easy to access based on the current application scales, the relatively high operation and maintenance costs and low heating value of sewage sludge are still the major obstacles for its further promotion in developing regions. As for the Scenario 1, since it only contains anaerobic digestion as the major treatment for sewage sludge, the insufficient treatment degree leads to the poor performances on almost all the considered criteria except for the products sales and energy efficiency.



(a) Costs analysis for each scenario



(b) Percentage of different costs in each scenario

Figure 5.6 Economic analysis for the four alternatives based on the process simulation results

According to the current ranking results of the four alternatives for sludge valorization management, gasification and SCWG show many promising advantages on environmental and economic dimensions. As is shown in Figure 5.6, S3 is credited by the relatively low total investment for the entire capital costs and operating costs compared to others. Besides, it can also provide the opportunity to recover consideration amount of energy, and it is estimated that the economic value of the recovered products can be attained over 33 million USD/year. Due to the insufficient treatment degree of sewage sludge in S1, a significant expense is used for landfills. Nevertheless, anaerobic digestion as a stabilization process to promote sludge treatment can improve the energy efficiency and the economic benefits since the energy efficiency in the single process of AD can reach over 40% and the products sales are estimated to be around 26 million USD/year, which also show the potential of AD for the combination with other effective sludge treatment technologies for more sustainable management. Previous research presented with similar outcomes as well (Lam et al., 2016; Xu et al., 2014), which also indicates the reliability of the evaluation results and final decision-making results in this chapter.

5.3.3 Sensitivity analysis

Sensitivity analysis is carried out to analyze the impacts of weight variations of different criteria on the final ranking results. To investigate the influence of the weight changes of each criterion, the weight of the investigated criterion, which is so called "major criterion", is set to be 0.25. The weights of the other 10 criteria are assumed to be the same, i.e., 0.75/10=0.075. Then, 11 groups of experiments for the sensitivity analysis can be obtained. The detailed weighting assignments are shown in Table A3.16 in the Appendix and the corresponding ranking results of the 12 groups are shown in Figure 5.7, where group 0 (labeled as G0) refers to the initial ranking results of the case study and group i (i.e., Gi) refers to the experiment that investigate the i th criterion as the major criterion.

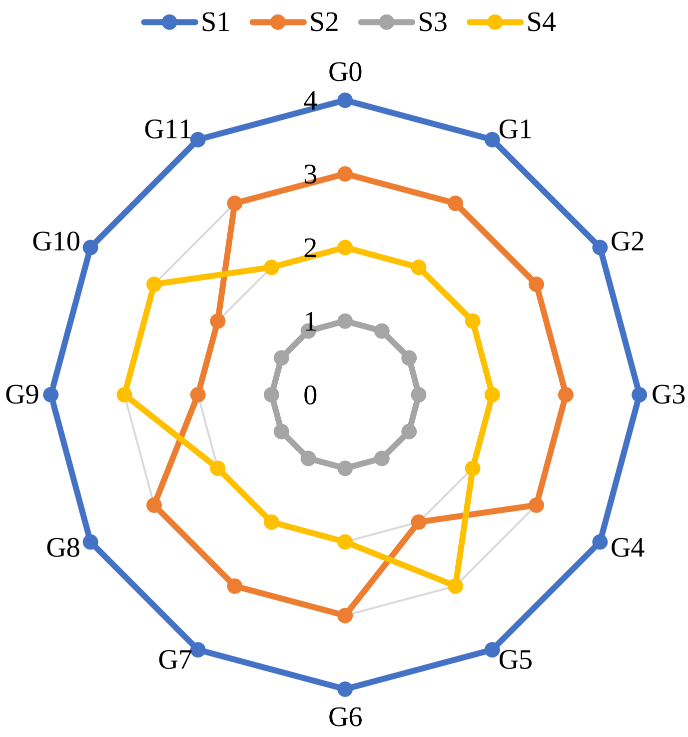
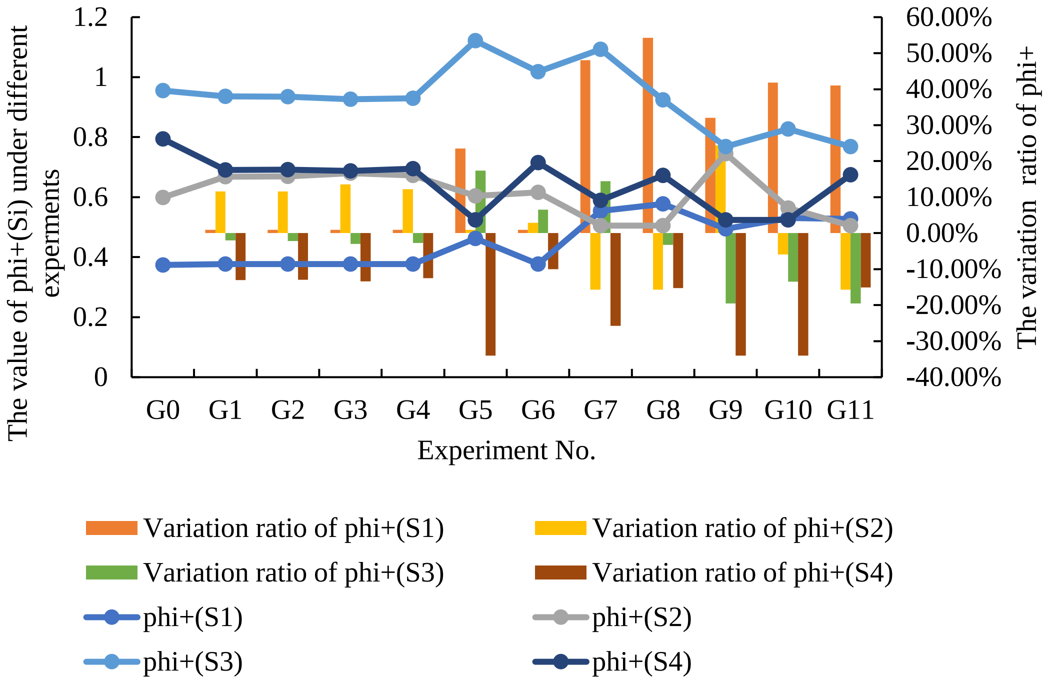
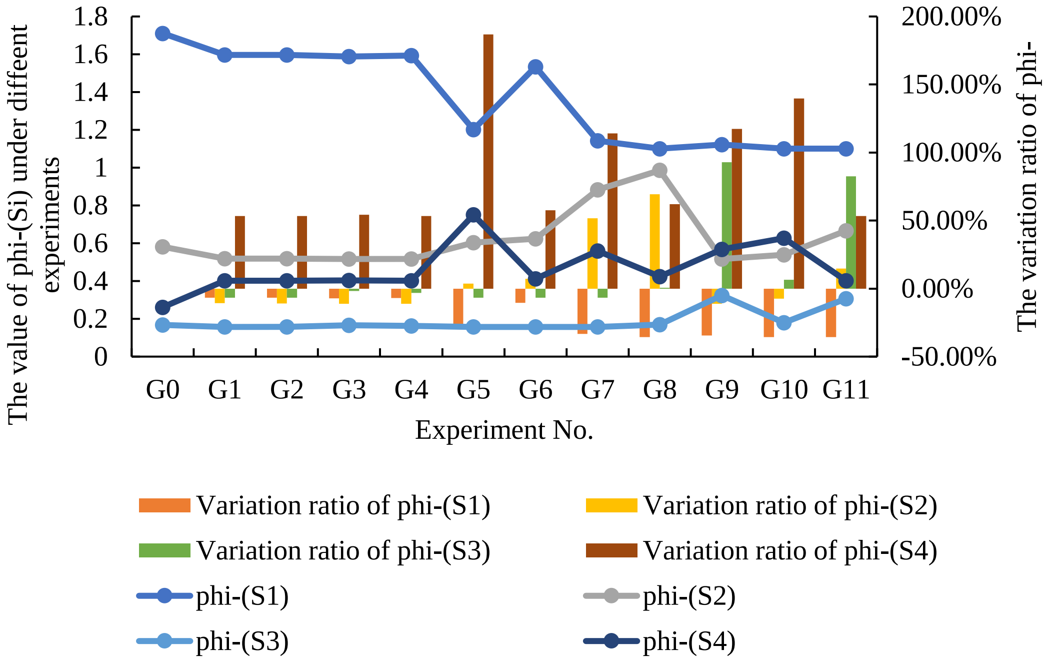


Figure 5.7 Ranking results for the sensitivity analysis including the results of the initial case study

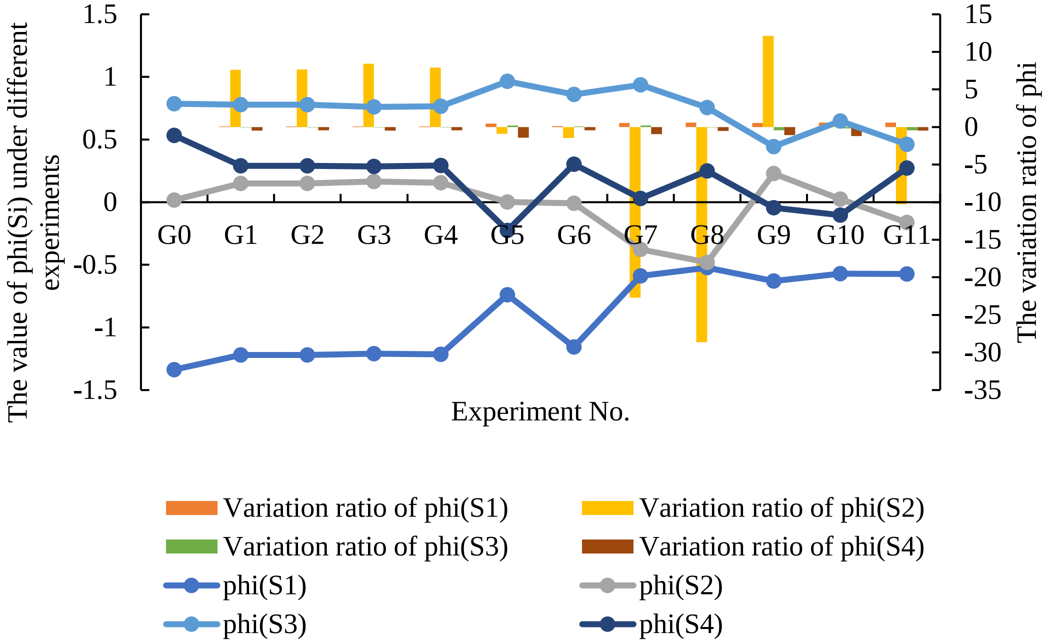
As is shown in Figure 5.7, the ranking results are relatively stable in the 12 experiments, especially for S1 and S3, which are always in the last and the first place, respectively. The rankings of S2 and S4 are sometimes swapped, but generally the rankings are still stable. Scenario 3, that is gasification, is recommended in most of the considered cases due to the promising performances on environmental and economic dimensions. Scenarios 2 will take more advantages when the technology maturity is attached to higher importance. Meanwhile, S4 is in an inferior place compared with S2 if total capital costs (C_5) is more important. To further explore the influences of the weighting variations on the ranking the provide insightful implications of the sludge-to-energy technologies, the variations of ϕ^+, ϕ^- and ϕ for each alternative are also analyzed and the results are presented in Figure 5.8.



(a) The value changes and corresponding variation of $\phi^{+}(\mathrm{Si})$ under different experiments



(b) The value changes and corresponding variation of $\phi^{-}(\mathrm{Si})$ under different experiments



(c) The value changes and corresponding variation of $\phi(\mathrm{Si})$ under different experiments

Figure 5.8 Variations of the values of ϕ^{+} , ϕ^{-} and ϕ for each scenario under different weighting assignments

Based on Figure 5.8, although the final ranking results are relatively stable, the value variations of ϕ^{+} , ϕ^{-} and ϕ are still significant especially for the indicators where the alternatives show special performances. Since $\phi^{+}(\mathrm{Si})$ represents the strengths of i th scenario over others, the increase of $\phi^{+}(\mathrm{Si})$ indicates the rising in the superiority of the i th Scenario. On the contrary, the increase of $\phi^{-}(\mathrm{Si})$ means the case against the i th Scenario increases because $\phi^{-}(\mathrm{Si})$ reveals the weakness of the corresponding scenario. According to the results shown by Figure 5.8, increasing the importance of C_5-C_7 will lead to the rising of the advantages of S3 over other scenarios to different degree, where the effect of C_5 is the most significant one. However, increasing the weights of C_9-C_{11} will result in the decrease of the superiority of S3, which also verify the lack of technology promotion and social acceptance of gasification. S4 shows disadvantages when the importance of social and technological indicators and part of economic indicators, ~~while~~ which reveals that there are still many challenges faced by SCWG due to the high requirement on the equipment and operating conditions. S2 is influenced significantly by the weighting variations for most of the indicators. It will be more preferred with the increasing weight of C_9 since it has already possessed relatively mature and compete technical conditions. In this context, S2 is also the most sensitive one (see Figure 5.8(c)) since the initial value of $\phi(S2)$ is small. S1 shows more advantages on technical and social indicators. In addition, compared with the variations of $\phi^{+}(\mathrm{Si})$, the changing of $\phi^{-}(\mathrm{Si})$ is more considerable because the initial value of $\phi^{-}(\mathrm{Si})$ is small, which makes the values of $\phi^{-}(\mathrm{Si})$ more sensitive to the weighting variations.

Besides the influences of weighting variations on the ranking results, the impact of selecting different preference rules of fuzzy PROMETHEE II method is also investigated and the corresponding ranking results are presented in Table 5.12. In this context, the selection of preference rules shows no significant influences on the final ranking. However, the values of ϕ which can indicate the overall superiority of the alternative are quite different from each other. This fact reveals that different preference rules adapting different principles to address the strengths and weakness of the alternatives, which could finally influence the evaluation outcomes, although it is not reflected in this case. Previous study has indicated the possible influence of the selection preference rules on the prioritization results (Tong et al., 2020). Despite that the choice on preference rules is usually depends on the knowledge and experience of the stakeholders, Gaussian rule is still commonly applied in the field of multi-criteria decision making since the initial statistical data usually involves random values and the rule equips the ability to address the importance of criteria in different disciplines (Tong et al., 2020).

Table 5.12 Ranking results obtained by different preference functions

Preference function	ϕ(S1)	ϕ(S2)	ϕ(S3)	ϕ(S4)	Final ranking
Gaussian rule	-1.34	0.02	0.79	0.53	S3>S4>S2>S1
Usual rule	-1.15	-0.82	0.95	1.02	S4>S3>S2>S1
Half rule	-1.23	-0.15	0.72	0.66	S3>S4>S2>S1
Linear priority rule	-1.17	-0.30	0.82	0.65	S3>S4>S2>S1
Multiclass rule	-1.41	0.00	0.86	0.56	S3>S4>S2>S1
Indifference interval linear priority rule	-1.35	-0.06	0.83	0.59	S3>S4>S2>S1

5.3.4 Uncertainty analysis

Besides the influence of selection of the preference function and weighting assignments on the final ranking results, the impacts of parameters variation are also investigated. The influence of parameter uncertainty of three economic indicators (i.e., C_5 – C_7) for S3 is analyzed by varying the value of targeted indicator within the range of [-5%, 5%]. The variation of evaluation result for S3 is chosen as an example since it is the recommended choice in the case study and some general rules can be observed from the results. Detailed results can be found in Table A3.17 in the Appendix Part III. The specific trends of changes on the value of $\varphi^{+}(S3)$, $\varphi^{-}(S3)$, and $\varphi(S3)$ are shown intuitively in Figure 5.9. According to the uncertainty analysis results, the values of $\varphi^{+}(S3)$ and $\varphi(S3)$ are influenced by the parameter uncertainty while $\varphi^{-}(S3)$ does not show any changes in this context. In terms of the amount of change and the specific values, the overall performance of S3 is stable and still keeps the most recommended place among the four alternatives, which indicates that the ranking results obtained by the proposed framework are stable and the method is robust.

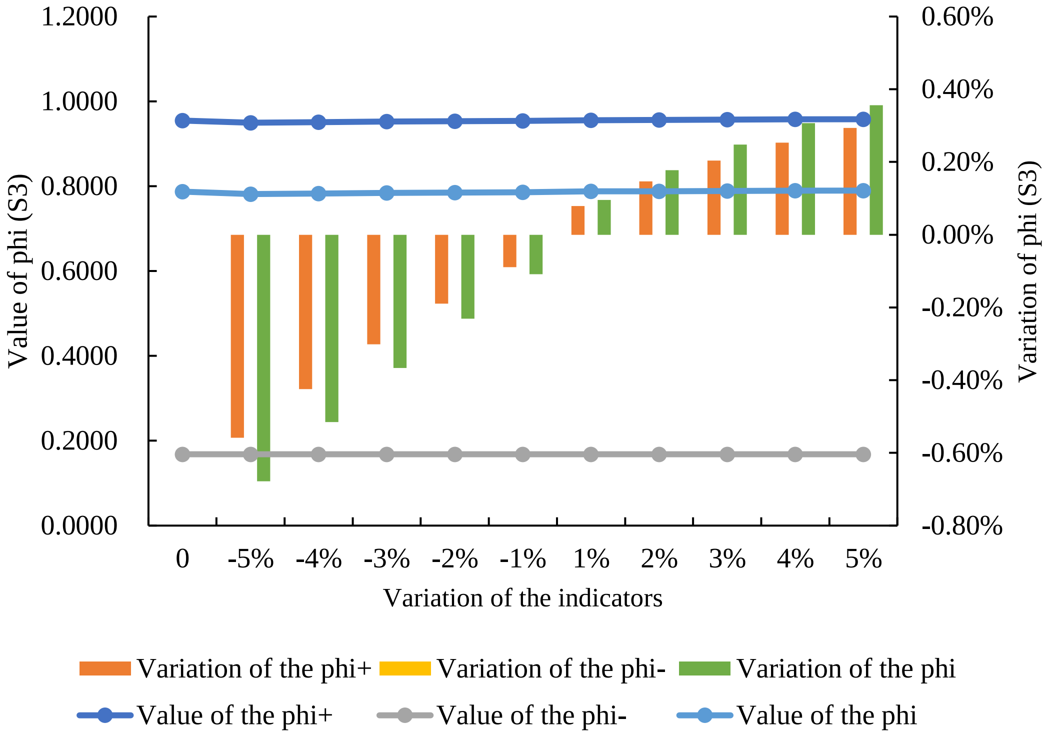


Figure 5.9 Variation trends of $\varphi^{+}(S3)$, $\varphi^{-}(S3)$, and $\varphi(S3)$ under different parameter uncertainty

5.3.5 Recommendations and implications

Based on the above discussion and comparisons, it can be found that the proposed fuzzy multi-criteria decision-making framework has the following advantages: i) it provides a framework to discuss and analyze the decision-making problem of novel industrial technologies, which are usually lack of related performance data for decision-making, at commercial scale based on the specific assumptions and process simulations; ii) it provides a relatively comprehensive decision support framework covering four sustainability pillars to discuss the overall sustainability performances of the investigated systems; iii) it can deal with the vague and fuzzy information from the simulation process and preference of decision-makers and covert the data into comparable values; iv) it can provide a complete ranking for all the alternatives and the ranking results are relatively robust and stable even facing with a certain degree of weights variations.

In addition, the ranking results of the case study can also provide useful information for the decision-makers in sludge management field, or even management for other types of waste as reference, and the major points can be summarized as follows:

- Anaerobic digestion is a commonly applied approach for sludge stabilization. It can realize energy recovery by biogas production under mild conditions with impressive energy conversion efficiency (estimated as 45% in the process simulation). However, it cannot work as a major sludge treatment technology to process the sludge separately since incomplete processing would still put pressure on subsequent disposal. Therefore, it is recommended to use together with other major treatment technologies for sludge management to improve the performance on energy efficiency, economic and environmental indicators.
- Compared with gasification and SCWG, incineration has already possessed relatively mature technical and market conditions, but it usually has higher requirements on energy supply and the corresponding equipment, which will lead to higher burdens on resources and environment. How to further improve the entire energy efficiency and reduce the total costs through improving the operating conditions or co-treatment with other high heating value feedstocks can be the

working direction for the future.

- Both gasification and supercritical water gasification have great potential application prospects, especially in terms of environment, economy and energy conversion efficiency. Gasification can provide impressive overall performances on all the considered aspects in this context and SCWG allows the existing of moisture in sewage sludge for the treatment. However, there are still some challenges faced by these newly technologies (Hosseini and Wahid, 2016; Syed-Hassan et al., 2017). Future research can focus on the improvement on the operating conditions and the promotion of the two technologies to increase the recognition and acceptance further effectively so that the valuable technologies can be more widely adopted.

Besides the contributions on sludge management decision-making and technology improvement, this paper also shows theoretical value for the related research. First of all, this framework proposed in this work combined process simulation, previous research, and the experiences of experts to generate the performance data for sustainability evaluation and prioritization ranking, which can help to address the problem of lack of related data for the emerging technologies. It breaks the previous studies only applied process simulation or experimental data to analyze the technologies at lab scale or without the discussion for entire sustainability evaluation and technology selection. Meanwhile, the framework considers not only environmental and economic indicators, but also technical and social criteria to comprehensively describe the sustainability performance of the sludge treatment technologies, and the weights can be flexibly adjusted according to the needs and preferences of stakeholders. In addition, the constructed approach can address the uncertainties caused by the vagueness of data and linguistic description provided by decision-makers through apply TFNs, and the results are verified to be stable and practical. Overall, the proposed model and case study in this work provide significant references value for the theoretical research and practice and promote the sustainable development and management of waste-to-wealth technologies.

5.4 Summary

In this chapter, a fuzzy multi-criteria decision-making framework for sustainable sludge management was constructed by combining fuzzy best-worst method and fuzzy PROMETHEE II method. Process simulation was conducted to generate the performance data for the investigated waste management technologies. A criteria system covering four sustainability pillars and eleven sub-indicators was established to evaluate the sustainability performances of the waste treatment technical routes. Fuzzy best-worst method was applied to obtain the fuzzy weights of the criteria system based on the preferences and attitudes of stakeholders and fuzzy PROMETHEE II approach was used to obtain the complete ranking for the studied alternatives. Taking sludge management as an example, a case study considering four sludge valorization technologies was conducted to verify the feasibility of the proposed framework. The final ranking of the case study was S3>S4>S2>S1, which indicated the superiority of gasification for sludge treatment with energy recovery. Sensitivity analysis was also carried out to explore the influences of weighting variations and the selection of preference rules and the ranking results kept relatively stable, which revealed the robustness and stability of the proposed decision-making framework. In addition, several suggestions and implications were provided based on the analysis results of the case study, which were consistent with the results of previous research and the practice, leading to the belief of the reliability of the proposed model.

According to the ranking results, it is recommended to vigorously develop the emerging technologies with promising potentials on environmental and economic aspects, like gasification and SCWG to further improve the technical performance and social acceptances. Incineration has been widely applied in many countries, but it still faces with challenges on the high costs, heavy environmental burdens, and unsatisfactory energy efficiency. Anaerobic digestion can work as a stabilization process to promote the sludge treatment and improve the energy conversion efficiency, while it cannot be applied separately due to the insufficient treatment degree of sludge. All these implications can provide useful information for the future sustainable development of sludge management or the management for the waste with similar features.

There are still some limitations in this study. On the one hand, this study used sewage sludge management technologies as an example to demonstrate the feasibility of the model. Further discussion on the application to other types of waste can also be conducted to extend the application scale and improve the entire decision-making framework. On the other hand, how to combine the objective information in the criteria weighting and sustainability evaluation process especially for the social and technical indicator to reduce the dependency on the subjective preferences and expertise of decision-makers is still a focus for the future work.

Chapter 6 Sustainability Prioritization of Sludge-to-Energy Technologies Under Multi-Data Conditions

The methodology framework constructed in Chapter 5 can effectively assist decision-makers to solve the problems of lacking performance data. Nevertheless, due to the limited data sources, decision-makers may also frequently face with the challenge that different data conditions (e.g., crisp numbers, interval numbers, linguistic terms and incomplete information) simultaneously exist in the same problem, which can increase the difficulty for making a suitable selection from all the alternatives. Therefore, in this chapter, a decision-making framework under multi-data conditions is proposed to solve the prioritization problem for sustainable sludge management. The investigated problem and research gaps are described in Session 6.1. The entire decision-making framework is built up in Session 6.2. Afterwards, the prioritization of four sludge-to-electricity technologies is selected as the case study and described in Session 6.3. Corresponding results are illustrated in detail in Session 6.4 and the discussion is conducted in Session 6.5. Lastly, the contributions and limitations of this work are addressed in Session 6.6.

6.1 Problem description

Uncertainty and vagueness are common in the decision-making process for sludge management, especially for emerging technologies as the alternatives. Fuzzy theory s introduced to MCDM for solving the decision-making problem with fuzzy information. for example, fuzzy Decision-Making and Trial Evaluation Laboratory (DEMATEL) method and fuzzy TOPSIS were applied as the basis for the selection of four wastewater treatment options (Dursun, 2018). However, these studies usually focused on some common sludge treatment technologies, such as landfilling, composting, and incineration. Few investigations made efforts to discuss and compare emerging technologies, especially biological sludge treatment techniques. Moreover, traditional methods only allow the decision-makers to make the choice according to the known information without the consideration for problems with incomplete information. To solve this problem, the Dempster-Shafer (DS) theory (Dempster, 1968; Shafer, 1976) of evidence was proposed to evaluate the basic probability assignment (bpa) of a decision option with an incomplete decision matrix. A Dempster-Shafer Analytic Hierarchy Process (DS-AHP) method was proposed to solve a decision-making problem directly based on the provided incomplete decision matrix (Hua et al., 2008). In addition, the considered criteria in the assessment system mostly concentrated on economic and environmental aspects. The capital costs and operational investment from the economic perspective, and some common environmental indicators in life cycle assessment (e.g., global warming potential, eutrophication potential, and land occupied) were frequently discussed, while the involving social and technical aspects in MCDM were less focused on due to being limited by the measurement and data sources (An et al., 2018; Ren et al., 2017b, 2017a).

Although there are many methods for solving the decision-making problems with incomplete and vague information, limited research applied these approaches to the sludge management field. A grey MCDM system was built up to help decision-makers process the decision making problems of sludge-to-electricity technologies with linguistic descriptions (Ren et al., 2017b). Nevertheless, this study only discussed the problem with linguistic preferences determined by the stakeholders, and incomplete information and multi-condition data were not included. The emerging biological technology MFCs for sewage sludge treatment and electricity production was also rarely analyzed.

Based on the above discussion, this chapter is aiming at filling the following research gaps:

1. It lacks a prioritization methodology which can address the decision-making problem with hybrid data conditions, including incomplete information.
2. It lacks a sustainability-based decision-making framework for sludge-to-energy technologies considering four sustainability dimensions, covering environmental, economic, social and technical aspects, not just the former two perspectives.
3. It lacks the analysis and discussion for emerging technologies which can help to provide reference information for decision-makers.

This chapter was conducted to assess and ranking four sludge-to-electricity technologies with multi-data conditions, including crisp numbers, interval numbers, linguistic terms and incomplete information. DS theory was applied as the basis for data process and prioritization and fuzzy BWM (FBWM) was applied to determine the fuzzy weights of the selected criteria according to the preferences of decision-makers, both of which were used to construct the framework of DS-FBWM. DS theory was employed since it has the ability of dealing with incomplete information and fuzzy

BWM was utilized because of the advantages in processing linguistic terms, simpler calculation process and more reliable consistency ratio. The DS-FBWM approach and Extended VIKOR method were utilized to ranking the four scenarios with incomplete information and three options with full information, respectively.

6.2 Methodology

To help with the decision-making process of sludge-to-energy technologies, a criteria system was first established to assess the sustainability performances of the selected alternatives given in Section 6.2.1. The core model for alternative prioritization and selection was described in Section 6.2.2. In this study, DS-FBWM was constructed based on the structure of DS-AHP and the principles of fuzzy BWM to obtain the final ranking of the assessed alternatives. The main calculation principles regarding DS theory were following the approach of Hua et al. (2008) to process the initial information and data, which is briefly introduced in Section 6.2.2.1. However, the weighting method applied in this chapter is the fuzzy BWM method instead of the AHP approach for deciding on the weight of each criterion, which is shown in Section 6.2.2.2. Afterwards, DS theory utilized the weights obtained from fuzzy BWM to deal with the subsequent calculations and sorting is presented in Section 6.2.2.3. The Extended VIKOR method for results validation is introduced in Section 6.2.3.

6.2.1 Criteria system

A criteria system should be built up for the sustainability assessment and selection of the sludge-to-energy alternatives. Thirteen criteria belonging to four aspects, including environmental, economic, social, and technical aspects, were considered to assess the sustainability performance of the investigated alternatives. The explanation and denotation of the criteria system are listed in Table 6.1.

Table 6.1 Criteria for sustainability assessment of sludge-to-electricity technologies

Aspect	Criteria	Description
Environmental (AS_1)[1]	Climate change (C_1)	-
	Fossil depletion (C_2)	-
	Acidification potential (C_3)	-
	Eutrophication potential (C_4)	-
	Ozone layer depletion (C_5)	-
Economic (AS_2)	Capital cost (C_6)	-
	Operation and maintenance cost (C_7)	-
Social (AS_3)	Policy support (C_8)	Policy incentives and support, cost subsides.
	Social acceptability (C_9)	Public acceptance of the technology.
Technological (AS_4)	Maturity (C_{10})	Technological maturity and application scale.
	Volume reduction (C_{11})	Degree of volume reduction.
	COD removement rate (C_{12})	Removal capacity of COD.
	Reliability (C_{13})	The degree of sludge problem solution, and the operating and maintenance ability of the technology.

Note:

1 The criteria under environmental aspect are consistent with those of Impact 2002+.

6.2.2 Multi-criteria decision-making model

6.2.2.1 DS theory

The DS theory applied in this work is based on the research of Beynon (2002) and Hua et al. (2008). Let $\Theta = \{S_1, ..., S_N\}$ denote the set of decision scenarios which is also known as the discernment frame. A basic probability assignment is defined as a mass function $m: 2^{\Theta} \rightarrow [0,1]$, which satisfies Eq. (6.1)

$$m(\varnothing) = 0 \text{ and } \sum_{S \subseteq \Theta} m(S) = 1, \tag{6.1}$$

where $\varnothing$ represents the empty set. S is a subset of Θ, and 2^{Θ} is the set consisting of all the subsets of Θ, which can be expressed as

$$2^{\Theta}=\{\varnothing,\{S_1\},...,\{S_N\},\{S_1,S_2\},...,\{S_1,S_N\},...,\Theta\}. \quad (6.2)$$

Let $V=[f(S_i,C_j)]_{N\times M}=f_{ij}$ denote the decision matrix, where f_{ij} is the evaluation information of the i th $(i=1,2,...,N)$ scenario S_i under the j th criterion C_j $(j=1,2,...,M)$. If $f_{ij}=f_{kj}$ for $\forall S_i, S_k \in \Theta$ and $S_i \neq S_k$, then both S_i and S_k belong to the same focal element (Hua et al., 2008). Here the knowledgeable scale is introduced to rate the performance of each scenario under different attributes according to the preferences of decision-makers (Beynon, 2002; Hua et al., 2008). Table 6.2 lists the knowledgeable scale applied in this work, which is based on the 5-scale approach in the research of Besynon (2002).

Table 6.2 Knowledgeable scale (adapted from (Beynon, 2002))

Knowledgeable	Rating	Knowledgeable	Rating
Extremely favorable	6	Moderately to strongly	3
Strongly to extremely	5	Moderately favorable	2
Strongly favorable	4	Acceptable to favorable	1

After transforming the original evaluation information f_{ij} into the knowledgeable numerical scale $\overline{f}_{ij}$, the preference of each scenario can be decided by $p(\overline{f}_{ij})=w_j\overline{f}_{ij}$, where w_j is the weight of j th criterion. Considering Θ is the frame of discernment containing all the scenarios, the preference of Θ is supposed to be 1 (Hua et al., 2008). Suppose A_k^j $(j=1,2,...,M;k=1,2,...,t;t<2^N)$ is the set composed by all focal elements under the criterion C_j. When different scenarios belong to the same focal element, they share the same preference.

According to the definition proposed by Hua et al. (2008), the bpa value of each focal element can be calculated as the standard normalized preference, that is

$$m_j(A_k^j) = \frac{p(A_k^j)}{\sum_k p(A_k^j)}, \forall S_i \in \Theta, \forall A_k^j \in 2^\Theta, \quad S_i \in A_k^j. \tag{6.3}$$

To obtain the bpa of all the focal elements for all the criteria, the Dempster's rule of combination is applied (Denœux, 1999; Shafer, 1976; Smets and Kennes, 1994). For two focal elements $A_k^{j_1}$ and $A_l^{j_2}$ under two different criteria C_{j_1} and C_{j_2} (i.e., $j_1 \neq j_2$, $j_1, j_2 \in \{1, 2, ..., M\}$), the bpa value of $E = A_k^{j_1} \cap A_k^{j_2}$ can be obtained using Eq. (6.4)

$$[m_{j_1} \oplus m_{j_2}](E) = \begin{cases} 0, & E = \varnothing, \\ \dfrac{\sum_{A_k^{j_1} \cap A_l^{j_2} = E} m_{j_1}(A_k^{j_1}) m_{j_2}(A_l^{j_2})}{\sum_{A_k^{j_1} \cap A_l^{j_2} \neq \varnothing} m_{j_1}(A_k^{j_1}) m_{j_2}(A_l^{j_2})} = \dfrac{\sum_{A_k^{j_1} \cap A_l^{j_2} = E} m_{j_1}(A_k^{j_1}) m_{j_2}(A_l^{j_2})}{1 - \sum_{A_k^{j_1} \cap A_l^{j_2} = \varnothing} m_{j_1}(A_k^{j_1}) m_{j_2}(A_l^{j_2})}, & E \neq \varnothing. \end{cases}$$

(6.4)

MCDM problems usually have more than two criteria. Hence, this step can first be conducted between the intersections of the focal elements under two criteria, and then repeat the combination for the intersections and the focal elements of the third criterion. The process is iterated until all the criteria are combined.

The belief measure (Bel) and plausibility measure (Pls) of the focal element which have combined all criteria together are defined as follows (Hua et al., 2008):

$$Bel(A) = \sum_{B \subseteq A} m(B), \quad \forall A \in 2^\Theta, \tag{6.5}$$

$$Pls(A) = 1 - Bel(\bar{A}) = \sum_{B \cap A \neq \varnothing} m(B), \quad \forall A \in 2^\Theta, \tag{6.6}$$

where A and B are subsets of Θ. $\bar{A}$ is the complement of A in Θ. $Bel(A)$ and

$Pls(A)$ represent the exact support and possible support to A, respectively (Hua et al., 2008). According to Eq. (6.5) and Eq. (6.6), the belief interval of A, i.e., $[Bel(A), Pls(A)]$, denoting the total amount of belief of potentially placing in A, can be obtained.

In order to get the final ranking of all the alternatives, belief interval numbers should be compared. Therefore, a comparison rule is proposed to decide on the preference degree of S_i and S_k (Hua et al., 2008).

$$P(S_i > S_j) = \frac{\max[0, Pls(S_i) - Bel(S_k)] - \max[0, Bel(S_i) - Pls(S_k)]}{[Pls(S_i) - Bel(S_i)] + [Pls(S_k) - Bel(S_k)]}. \tag{6.7}$$

Based on the calculation result of Eq. (6.7), the preference situation of S_i and S_k can be defined as follows:

(1) If $P(S_i > S_k) > 0.5$, then scenario S_i is regarded as superior to S_k, which is denoted as $S_i \succ S_k$.

(2) If $P(S_i > S_k) < 0.5$, then S_i is regarded as inferior to S_k, i.e., $S_i \prec S_k$.

(3) If $P(S_i > S_k) = 0.5$, then S_i and S_k are regarded to have the same priority, denoted by $S_i \sim S_k$.

According to the calculation results of Eq. (6.7), and the comparison rules above, the preference ranking of all the scenarios can be finally obtained.

6.2.2.2 Fuzzy BWM

In the DS theory, the preference of each scenario is decided by the numerical knowledgeable scale and the weight of the corresponding criterion. Therefore, the weights of the considered criteria should be determined before conducting the following procedures. There are various weighting methods for MCDM, such as AHP method, SWING and SIMOs (Wang et al., 2009). Best-worst method was proposed to deal with MCDM problems, which requires less comparison data and can obtain more reliable consistency ratios compared with the existing MCDM approaches (Rezaei, 2015). Considering the vagueness and uncertainty frequently occurring in decision-making processes due to the lack of complete information and professional knowledge of the relevant technologies, fuzzy best-worst method was applied to deal with the linguistic description of the preference for each criterion provided by the decision-makers (Guo and Zhao, 2017). Fuzzy BWM possesses the advantages of the best-worst method and the ability of process vague information. Hence, fuzzy BWM was selected to determine the weight of each criterion. A detailed description of the calculation principles can be found in the research of Guo and Zhao (2017). The major steps of fuzzy BWM are summarized in Figure 6.1.

6.2.2.3 DS-Fuzzy BWM

Based on the all the preliminaries of DS theory and fuzzy BWM, DS-DBWM can be constructed to solve the decision-making problems with incomplete information. The major steps of DS-FBWM are summarized in Figure 6.2. Fuzzy BWM is utilized before Step 2 to compute the fuzzy weights of all the criteria. Subsequently, Step 2 can be conducted as well as the following procedures.

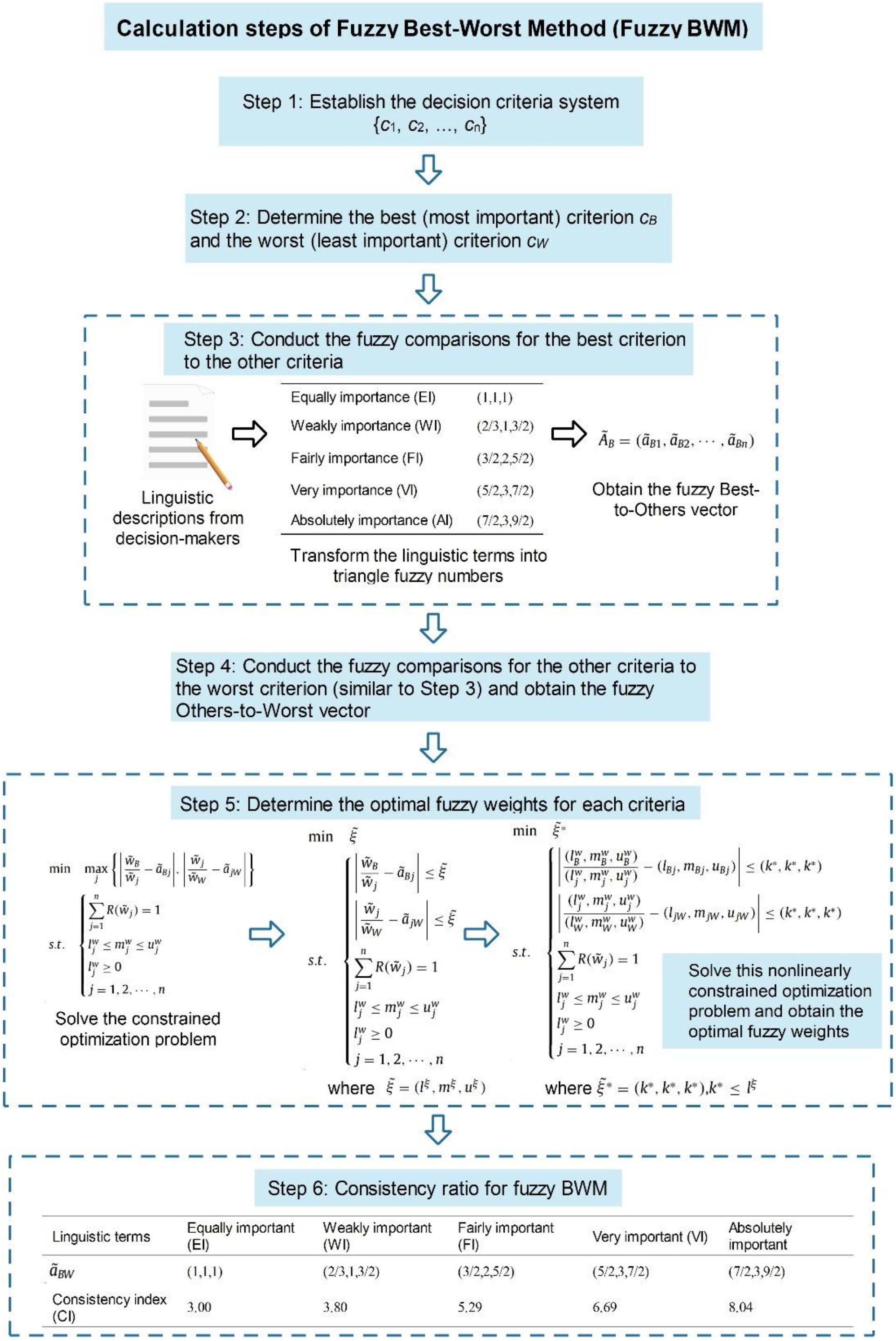


Figure 6.1 Major steps of fuzzy BWM (summarized from Guo and Zhao (2017))

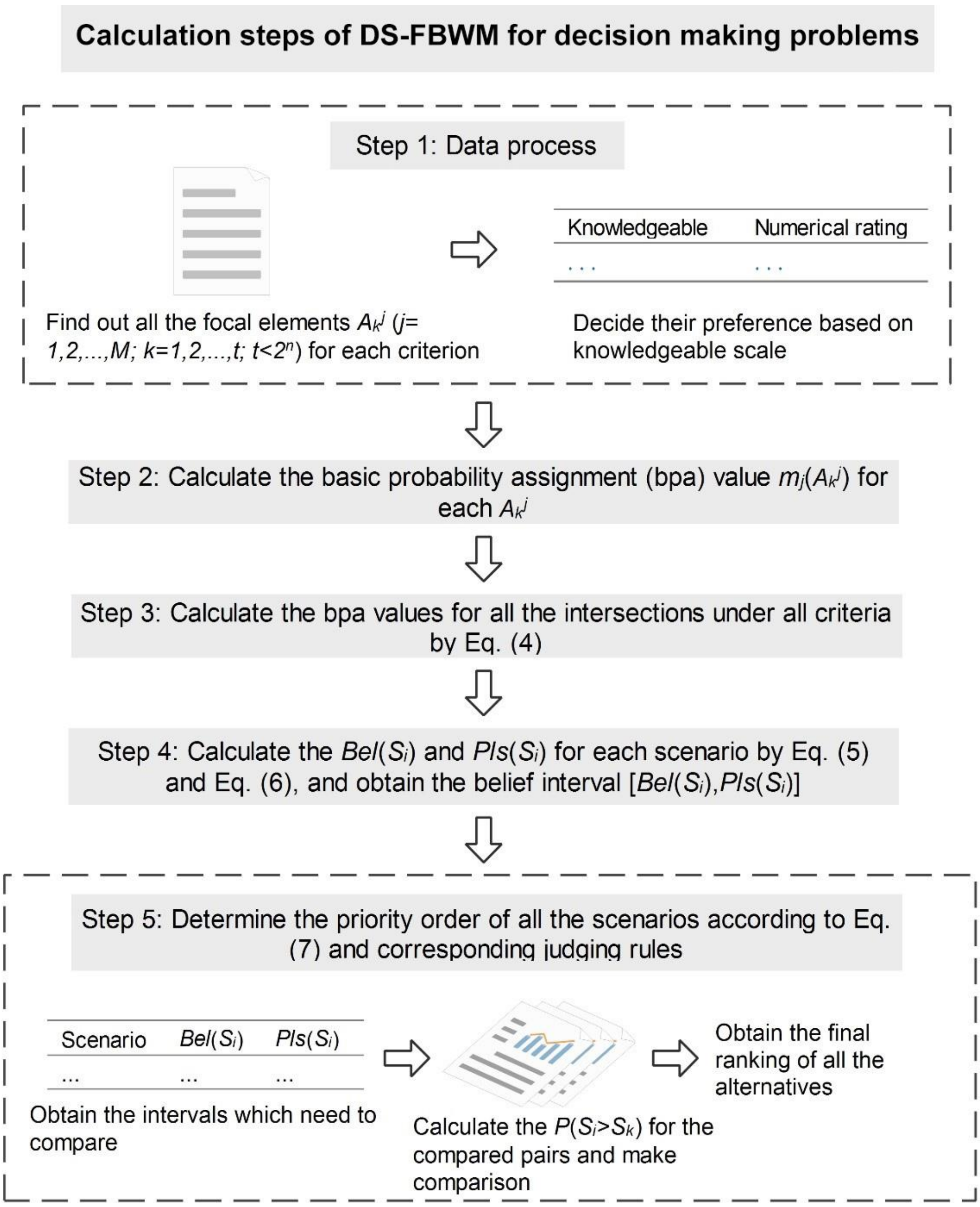


Figure 6.2 Major steps of DS-FBWM for incomplete information decision-making (summarized from Hua et al., (2008))

Calculation steps of Extended VIKOR method

Step 1: Transform other data forms into interval forms according to Table 8 and obtain the decision matrix with interval numbers

⇩

Step 2: Determine the positive ideal solution (PIS) and the negative ideal solution (NIS)

PIS: $A^* = \{f_1^*, ..., f_n^*\} = \left\{(\max_i f_{ij}^U \mid j \in I) \text{ or } (\min_i f_{ij}^L \mid j \in J)\right\} \quad j = 1, 2, ..., n$

NIS: $A^- = \{f_1^-, ..., f_n^-\} = \left\{(\min_i f_{ij}^L \mid j \in I) \text{ or } (\max_i f_{ij}^U \mid j \in J)\right\} \quad j = 1, 2, ..., n$

⇩

Step 3: Compute the intervals $[S_i^L, S_i^U]$ and $[R_i^L, R_i^U]$

$$S_i^L = \sum_{j\in I} w_j \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right) + \sum_{j\in J} w_j \left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right) \quad i = 1, \dots, m$$

$$S_i^U = \sum_{j\in I} w_j \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right) + \sum_{j\in J} w_j \left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right) \quad i = 1, \dots, m$$

$$R_i^L = \max\left\{w_j \left(\frac{f_j^* - f_{ij}^U}{f_j^* - f_j^-}\right) \middle| j\epsilon I, w_j \left(\frac{f_{ij}^L - f_j^*}{f_j^- - f_j^*}\right) \middle| j\epsilon J\right\} \quad i = 1, \dots, m$$

$$R_i^U = \max\left\{w_j \left(\frac{f_j^* - f_{ij}^L}{f_j^* - f_j^-}\right) \middle| j\epsilon I, w_j \left(\frac{f_{ij}^U - f_j^*}{f_j^- - f_j^*}\right) \middle| j\epsilon J\right\} \quad i = 1, \dots, m$$

⇩

Step 4: Compute the intervals $[Q_i^L, Q_i^U]$, i=1, 2, ...,m.

$$Q_i^L = v\frac{(S_i^L - S^*)}{(S^- - S^*)} + (1 - v)\frac{(R_i^L - R^*)}{(R^- - R^*)}$$

$$Q_i^U = v\frac{(S_i^U - S^*)}{(S^- - S^*)} + (1 - v)\frac{(R_i^U - R^*)}{(R^- - R^*)}$$

where

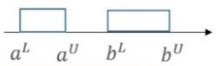
$$S^* = \min_i S_i^L, \quad S^- = \max_i S_i^U, \quad R^* = \min_i R_i^L, \quad R^- = \max_i R_i^U.$$

v represents the weight of the strategy of the "majority of criteria"

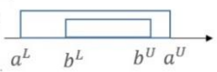
⇩

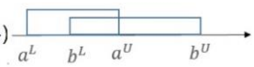
Step 5: Compare the interval numbers $Q_i=[Q_i^L, Q_i^U]$ (i=1, 2, ...,m) based on the judging rules and obtain the final ranking

Judging rules: assume that compare $[a^L, a^U]$ and $[b^L, b^U]$

(1) 
$a^U \le b^L \rightarrow [a^L, a^U]$ is the minimum interval number

(2) 
$a^L = b^L, a^U = b^U \rightarrow [a^L, a^U], [b^L, b^U]$ share the same priority

(3) 
$a^L \le b^L \le b^U \le a^U \rightarrow$ If $\alpha(b^L - a^L) \ge (1-\alpha)(a^U - b^U)$
Then $[a^L, a^U]$ is the minimum interval number, else $[b^L, b^U]$ is the minimum interval number

(4) 
$a^L < b^L < a^U < b^U \rightarrow$ If $\alpha(b^L - a^L) \ge (1-\alpha)(b^U - a^U)$
Then $[a^L, a^U]$ is the minimum interval number, else $[b^L, b^U]$ is the minimum interval number

α is the optimism level of the decision maker ($0 < \alpha \le 1$), which means that the optimist decision-maker has a higher α value than the pessimist decision maker

The interval number Q_i which is closer to 0 is regarded as a better option.

Figure 6.3 Basic steps of Extended VIKOR method for decision-making problems with interval numbers (Sayadi et al., 2009)

6.2.3 Validation method: Extended VIKOR

The Extended VIKOR method for interval numbers was applied to make comparison with the ranking result obtained based on DS-FBWM. The calculation principles applied in this work were complied with the research of Sayadi et al. (2009). Detailed computation steps can be found in their work. Figure 6.3 summarizes the major steps of the Extended VIKOR method for interval numbers. A transformation step was added before conducting this method to process the data forms since there are three different data forms in the case study.

6.3 Case study

In this study, the proposed DS-FBWM approach was applied to evaluate four sludge-to-electricity technologies under uncertainty for decision-making, which are listed as follows:

(1) Sludge incineration for electricity generation (denoted by S1) (Xu et al., 2014);

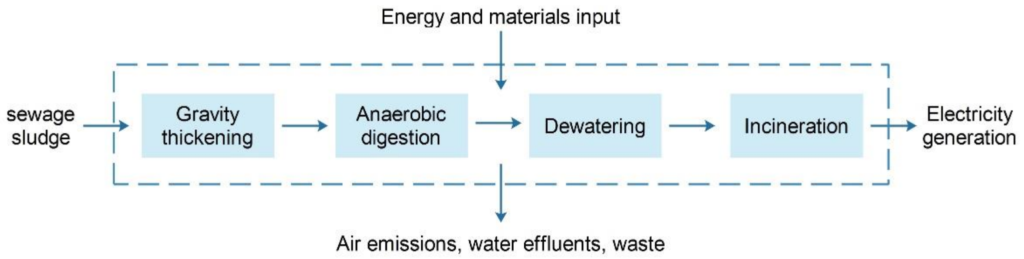
(2) Biogas generated from the anaerobic digestion process of sludge for electricity production by fuel cells (SOFC, denoted by S2) (Strazza et al., 2015);

(3) Biogas generated from the anaerobic digestion process of sludge for electricity generation by combustion gas engine (denoted by S3) (Xu et al., 2014);

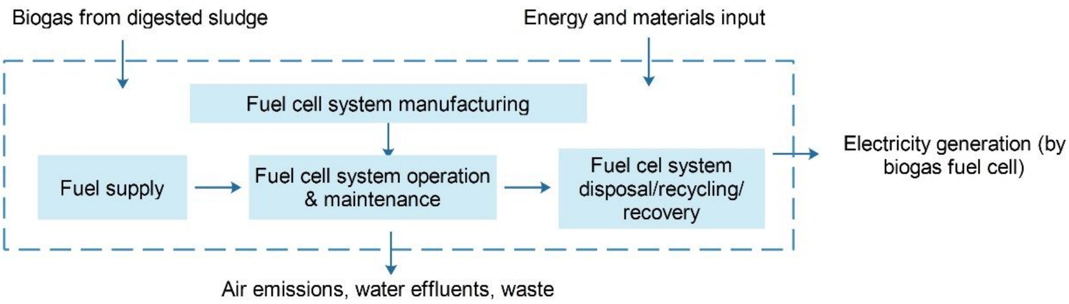
(4) Pretreated sludge for electricity generation by MFCs (denoted by S4).

As for S4, there are scarce data on the sustainability performances of MFCs for sludge treatment and electricity production. Nevertheless, there have been a few studies regarding MFCs for wastewater process with power production. The characteristics of sewage sludge, a byproduct generated from wastewater treatment process, have a close relationship with wastewater. Therefore, the data for S4 in this work were based on the related data of MFCs for wastewater treatment and electricity generation (Foley et al., 2010; Gude, 2016) in order to roughly estimate the performance of S4 under the current development status. The flowcharts of the four scenarios are shown in Figure 6.4. The reasons for selecting these four technologies are as follows: i) incineration is widely accepted worldwide and is regarded as one of the most thorough processes for sludge, but its application is still limited in China and the high cost and secondary pollution still hinder the generalization of sludge incineration for electricity production; ii) biogas fuel cells, regarded as a potential sludge-to-energy method, are actively tested, supported, and promoted for commercial application by developed countries such as Japan and America, but there are few cases in China (Su et al., 2009); iii) biogas combustion for electricity is a relatively mature approach compared with other scenarios and is widely used in rural areas; iv) MFCs for sludge treatment and electricity production is an emerging technology with many features which can promote sustainable development in the future (Gude, 2016). These four technologies have different advantages and shortcomings on different aspects. Some are rarely discussed regarding the evaluation of sustainability performance and decision-making. Hence, these four scenarios are investigated in this work to provide decision-making reference for the sludge-to-electricity technologies especially when the information is incomplete and vague.

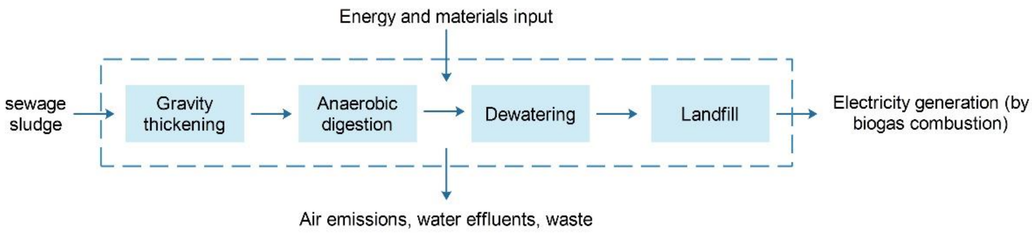
The performance data of the four alternatives were collected through literature review on the life cycle assessment of the related technologies (Foley et al., 2010; Strazza et al., 2015; Xu et al., 2014). In this work, the functional unit was 1 kWh of net electricity generation and the lifespan was supposed to be 30 years.



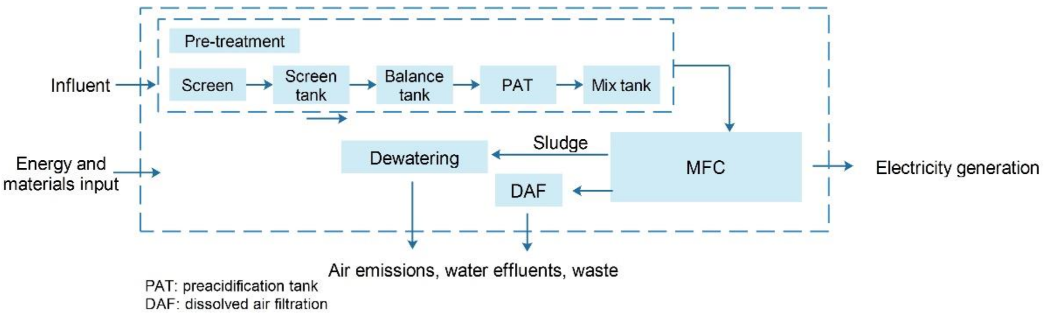
(a) S1



(b) S2



(c) S3



(d) S4

Figure 6.4 Life cycle boundaries of the four scenarios (Foley et al., 2010; Strazza et al., 2015; Xu et al., 2014)

6.4 Results

6.4.1 Criteria weighted by Fuzzy best-worst method

Since there are four aspects and thirteen criteria in the indices system as shown in Section 6.2.1, the calculation of fuzzy BWM was conducted hierarchically, i.e., the weight of each aspect w_{AS_j} $(j=1,2,3,4)$ was first computed, then the local fuzzy weight of each criterion under each aspect w'_i $(i=1,2,...,13)$ was obtained. The global fuzzy weight of each criterion w_i $(i=1,2,...,13)$ was determined by: $w_i = w_{AS_j} \cdot w'_i$, ($j=1,2,3,4$; $i=1,2,...,13$). The calculation process can be carried out step by step according to the principles, as shown in the Appendix Part IV. The fuzzy weight of each aspect and the global weight of all the criteria can be obtained and listed in Table 6.3 and

Table 6.4, respectively.

Table 6.3 Fuzzy weights of the four aspects

	AS_1	AS_2	AS_3	AS_4	CR
Weight	0.3206	0.3601	0.1152	0.2042	0.031

Table 6.4 Global fuzzy weight of the thirteen criteria

Environmental	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**
Weight	0.0922	0.0435	0.0745	0.0767	0.0337
Economic	**C_6**	**C_7**	**Social**	**C_8**	**C_9**
Weight	0.1824	0.1777		0.0766	0.0386
Technical	**C_{10}**	**C_{11}**	**C_{12}**	**C_{13}**	**Total CR**
Weight	0.0831	0.0261	0.0475	0.0475	0.0245

6.4.2 Ranking result based on DS-FBWM

According to the principle description in the Methodology section, DS-FBWM was conducted to obtain the priority order of the four alternatives. The detailed process was presented in the following.

Step 1: In the initial known information for the four scenarios, there are four different types of data. Crisp numbers mostly occur in the environmental and economic aspects. Two interval numbers also exist in the description of economic indicators for S2. Linguistic descriptions were used for social and technical aspects. Incomplete information appears in the data list of S4 due to the limited data sources (in C_3, C_4, C_5). The detailed information for the four sludge-to-electricity options is shown in Table 6.5. In this step, the focal elements for each criterion were found according to the known information. The corresponding focal elements, preference and final priority under each attribute were also obtained and are shown in Table A4.17, Table A4.18 and Table A4.19, respectively.

Table 6.5 Initial known information of the four scenarios (data are presented per functional unit)

		Unit	S1	S2	S3	[1]S4
AS_1	C_1	kg CO_2 eq	3.60	0.2	9.96	0.195
	C_2	MJ	-18.8	0.06	-41.6	-0.876
	C_3	kg SO_2 eq	-0.0190	5.07E-04	0.0040	NA

	C_4	kg PO_4^{3-} eq	-8.4271E-04	6.96E-05	-6.493E-04	NA
	C_5	kg CFC-11 eq	9.91E-08	2.18E-08	-1.059E-10	NA
AS_2	C_6	USD/kWh	0.0824	[0.1295, 0.1665]	0.1644	0.0467
	C_7	USD/kWh	0.0045	[0.017, 0.019]	0.0085	3.3592
AS_3	C_8	-	(Poor, good, poor)	(Medium, good, medium)	(Good, very good, good)	Poor
	C_9	-	[2]Medium	[3]Low	[4]High	Low
AS_4	C_{10}	-	(Good, medium, poor)	(Very poor, poor, very poor)	(Very good, very good, very good)	Very Poor
	C_{11}	-	[5]High	[6]Medium	[5]Medium	Low
	C_{12}	-	[5]High	[3]Low	[5]Low	90%
	C_{13}	-	[5,7]High	[3]Low	[5]Medium	Low

Note:

Data sources: For the criteria C_1 – C_7 of S1 and S3: (Xu et al., 2014); for the criteria C_1 – C_7 of S2: (Strazza et al., 2015); for the criteria C_1, C_2 and C_{12} of S4: (Foley et al., 2010); for the criteria C_6 and C_7 of S4: estimated from (Gude, 2016); for C_8 and C_{10} of S1 -S3: (Ren et al., 2017b).

1€=1.12USD.

[1] The performances of C_8 – C_{11} and C_{13} of S4 were estimated according to the development status of MFCs and related literature review.

[2] Medium was judged based on the situation of incineration applied in China. It was reported that incineration occupied 18.3% of the total sludge disposal. Incineration was widely recognized by the developed countries (western countries), but the application and information transparency in China is still limited (Asian Development Bank, 2012).

[3] Estimated based on the development status of biogas fuel cells. Currently biogas from digested sludge for electricity generation by fuel cell is still not practiced (Su et al., 2009).

[4] High was judged according to the reference (Tarpani and Azapagic, 2018). The electricity generated from biogas has a prepared market. Biogas combustion for electricity production is widely applied in rural area.

[5] (Asian Development Bank, 2012).

[6] The only difference between S2 and S3 is the electricity production way from biogas. The volume reduction degree should be similar.

[7] (Qin et al., 2011).

Step 2: Based on the result in **Step 1**, the fuzzy weights determined by fuzzy BWM, and Eq. (6.3), the bpa values of each focal element under each criterion was calculated, as presented in Table 6.6. Taking the bpa value of the focal element {S1} for criterion C_1 as an example, the preference of {S1} in C_1 determined by decision-makers was $3w_1$. The weight of criterion C_1 has been decided by fuzzy BWM in the last section as 0.0922.

Hence, the preference of {S1} can be obtained by $p(\{S1\}^1) = 3w_1 = 0.2766$, where the superscript 1 refers to the investigated focal element in criterion C_1. Similarly, the preferences of the other four focal elements can be calculated. Then, the bpa value of the focal element {S1} towards criterion C_1 can be determined by

$$m_1(\{S1\}^1) = p(\{S1\}^1) / (p(\{S2\}^1) + p(\{S3\}^1) + p(\{S4\}^1) + p(\Theta^1)) = 0.1161.$$

Through similar calculations, the bpa values for all the focal elements can be correspondingly obtained.

Step 3: With Dempster's rule of combination, the bpa values of all the intersections under all criteria can be obtained and are shown in Table 6.7.

Step 4: The belief measure and the plausibility measure of each scenario can be calculated based on the results of **Step 3**. Subsequently, the belief intervals were obtained, as listed in Table 6.8.

Table 6.6 The basic probability assignment value of each focal element

C_1	**Priority**	**C_2**	**Priority**	**C_3**	**Priority**	**C_4**	**Priority**	**C5**	**Priority**
{S1}	0.1161	{S1}	0.1580	{S1}	0.2134	{S1}	0.2170	{S1}	0.0259
{S2}	0.1935	{S2}	0.0790	{S2}	0.1280	{S2}	0.0868	{S2}	0.0777
{S3}	0.0387	{S3}	0.1316	{S3}	0.0854	{S3}	0.1302	{S3}	0.1294
{S4}	0.2322	{S4}	0.0263	Θ	0.5732	Θ	0.5660	Θ	0.7670
Θ	0.4196	Θ	0.6051						
C_6	**Priority**	**C_7**	**Priority**	**C_8**	**Priority**	**C_9**	**Priority**	**C_{10}**	**Priority**
{S1}	0.2053	{S1}	0.2836	{S1, S2}	0.1350	{S1}	0.0836	{S1}	0.1361
{S2}	0.1540	{S2}	0.1135	{S3}	0.2266	{S3}	0.1393	{S3}	0.2723
{S3}	0.1027	{S3}	0.2269	{S4}	0.0453	{S2, S4}	0.0557	{S2, S4}	0.0454
{S4}	0.2566	{S4}	0.0567	Θ	0.5921	Θ	0.7215	Θ	0.5462
Θ	0.2814	Θ	0.3193						
C_{11}	**Priority**	**C_{12}**	**Priority**	**C_{13}**	**Priority**				
{S1}	0.1033	{S1}	0.1664	{S1}	0.1611				
{S2,S3}	0.0620	{S2,S3}	0.0666	{S3}	0.0966				
{S4}	0.0413	{S4}	0.0666	{S2, S4}	0.0644				
Θ	0.7933	Θ	0.7005	Θ	0.6779				

Table 6.7 The bpa values of all the intersections by using Dempster's rule of combination

m_{combined}	Value
S1	0.4794

S2	0.1666
S3	0.1913
S4	0.1062
S1, S2	0.0037
S2, S3	0.0029
S2, S4	0.0044
Θ	0.0160

Table 6.8 The belief intervals of evaluated scenarios

Scenario	*Bel*	*Pls*
S1	0.4794	0.4991
S2	0.1666	0.1937
S3	0.1913	0.2102
S4	0.1062	0.1267

Step 5: Determine the final priority order of the four alternatives by applying Eq. (6.7). According to the results in Table 6.7, the belief intervals of S2 and S3 have an intersection. Hence, S2 and S3 need to be compared. Substituting the corresponding values into Eq. (6.7), gave $P(\mathrm{S3} > \mathrm{S2}) = 0.9487 > 0.5$, which indicates that S3 is superior to S2. Therefore, the final preference order of the four scenarios determined by DS-FBWM is: $\mathrm{S1} \succ \mathrm{S3} \succ \mathrm{S2} \succ \mathrm{S4}$.

6.4.3 Ranking result based on the Extended VIKOR method

The ranking for the former three alternatives, i.e., S1, S2, and S3 with full information was also obtained based on the Extended VIKOR method for interval numbers, aiming to compare with the ranking results generated from DS-FBWM. The detailed steps are described as follows:

Step 1: Transform other data forms into interval form. The transferring of crisp numbers follows this rule: $a \to [a, a]$. The linguistic description is transformed into interval numbers according to Table 6.9.

Table 6.9 The scale of interval number transformed from linguistic description (Ren et al., 2017b)

Description	Abbreviation	Interval number
Very Poor	VP	(1.5, 3.0)
Poor/Low	P/L	(3.0, 4.5)

Medium	M	(4.5, 6.0)
Good/High	G/H	(6.0, 7.5)
Very Good	VG	(7.5, 9.0)

If the performance evaluation data come from several different experts, then the final interval number can be obtained by the following equation:

$$\otimes f_{ij} = \sum_{k=1}^{L} \otimes f_{ij}^{k} / L = [\sum_{k=1}^{L} f_{ij}^{k,-} / L, \sum_{k=1}^{L} f_{ij}^{k,+} / L], i = 1, 2, ..., N; j = 1, 2, ..., M, \quad (6.8)$$

where $\otimes f_{ij}$ represents the interval number of i th scenario at j th criterion. L is the total number of participating experts and $\otimes f_{ij}^{k}$ is the opinion of the k th expert. $\otimes f_{ij}^{k,-}$ and $\otimes f_{ij}^{k,+}$ mean the lower bound and upper bound of $\otimes f_{ij}^{k}$, respectively.

Afterwards, a decision matrix with interval numbers was obtained according to the transferring principles and initial information in Table 6.5, as listed in Table 6.10.

Table 6.10 The decision matrix with interval numbers

Aspect	Criterion	S1 Lower bound	S1 Upper bound	S2 Lower bound	S2 Upper bound	S3 Lower bound	S3 Upper bound
AS_1	C_1	3.60	3.60	0.2	0.2	9.96	9.96
	C_2	-18.8	-18.8	0.06	0.06	-41.6	-41.6
	C_3	-0.0190	-0.0190	5.07E-04	5.07E-04	4.0255E-03	4.0255E-03
	C_4	-8.4271E-04	-8.4271E-04	6.96E-05	6.96E-05	-6.493E-04	-6.493E-04
	C_5	9.91E-08	9.91E-08	2.18E-08	2.18E-08	-1.06E-10	-1.06E-10
AS_2	C_6	0.8243	0.8243	0.1295	0.1665	0.16441026	0.1644103
	C_7	0.0045	0.0045	0.017	0.019	0.0085	0.0085
AS_3	C_8	4	5.5	5	6.5	6	8
	C_9	4.5	6	4.5	6	6	7.5
AS_4	C_{10}	4.5	6	3	4.5	6	7.5
	C_{11}	4.5	6	2	3.5	7.5	9
	C_{12}	4.5	6	1.5	3	7.5	9
	C_{13}	6	7.5	4.5	6	4.5	6

Step 2: Determine the positive ideal solution (PIS) f_j^* and the negative ideal solution (NIS) f_j^-, which are given in Table 6.11.

Table 6.11 The PIS and NIS of each criterion

	C_1	C_2	C_3	C_4	C_5
f_j^*	0.20	-41.6	-0.0190	-8.4271E-04	-1.06E-10

f_j^-	9.96	0.06	4.0255E-03	6.96E-05	9.91E-08
	C6	**C7**	**C8**	**C9**	**C10**
f_j^*	0.1295	0.0045	8	7.5	9
f_j^-	0.8243	0.019	4	3	2
	C11	**C12**	**C13**		
f_j^*	7.5	7.5	7.5		
f_j^-	4.5	3	3		

Step 3: Compute the intervals $[S_i^L, S_i^U]$ and $[R_i^L, R_i^U]$. The related results are given in Table 6.12.

Table 6.12 The intervals $[S_i^L, S_i^U]$ and $[R_i^L, R_i^U]$ of each scenario

	S_i^L	S_i^U	R_i^L	R_i^U
S1	3.68E-01	4.72E-01	1.82E-01	1.82E-01
S2	5.40E-01	6.78E-01	1.53E-01	1.78E-01
S3	3.01E-01	4.15E-01	9.22E-02	9.22E-02

Step 4: Calculate the intervals $Q_i = [Q_i^L, Q_i^U], i = 1, 2, 3$. The calculation results are presented in Table 6.13. According to the core principle of the Extended VIKOR method, the alternative with minimum interval number Q_i is the best choice (Sayadi et al., 2009). Detailed comparison of the interval numbers is conducted in **Step 5**.

Table 6.13 The interval Q_i of each scenario

Scenarios	Q_i^L	Q_i^U
S1	0.589011719	0.727054018
S2	0.654517155	0.973863563
S3	0	0.150733475

$v = 0.5$

Step 5: Obtain the ranking based on the judging rules. According to the results in **Step 4**, the interval Q_1 and Q_2 have an intersection. Therefore, these two interval numbers need to be compared by the judging rule. Considering the length of these two intervals, α was assumed to be 0.8. Then, the following results were obtained: $\alpha(Q_2^L - Q_1^L) = 0.0524$, $(1-\alpha)(Q_2^U - Q_1^U)$=0.0494. Since the former one is larger than the latter one, S1 is considered to be better than S2. Hence, the final ranking of the three scenarios is: $S3 \succ S1 \succ S2$.

6.5 Discussion

6.5.1 Comparison of the ranking results between DS-FBWM method and Extended VIKOR method

According to the calculation results, the ranking obtained by DS-FBWM and Extended VIKOR method are $S1 \succ S3 \succ S2 \succ S4$ and $S3 \succ S1 \succ S2$, respectively. Both methods assessed and ranked the former three scenarios, i.e., S1, S2, and S3. Scenario 2 is in the last place in the ranking results of the two methods. Based on the performance data and calculation process, this result may be caused by the immaturity of the biogas fuel cell technology. The application of biogas from digested sludge for electricity production by fuel cells in China is not widespread with a lack of experience in this domain (Su et al., 2009). Although some of the environmental aspects of S2 are acceptable and even impressive, the imbalance in other aspects makes it less prefer than the other two scenarios. Considering the potential in environmental indicators and current development tendency, biogas fuel cells for electricity generation still has potential and would benefit further research (Rillo et al., 2017). Promoting the related research and practice can be helpful to improve the maturity, reduce the total costs and make it more acceptable to the public in the future.

On the other hand, there are three major differences in the ranking results of these two methods. Analysis for the three differences are listed as follows:

- The first difference lying in the number of assessed scenarios. Four scenarios were evaluated by DS-FBWM method including Scenario 4 with incomplete information. The Extended VIKOR method only ranked the former three scenarios with complete information.

- The second difference is the core thought of processing data. Although the DS-FBWM method can deal with the situation when information is missing, it cannot make the full use of exact information. To process the option with missing information, knowledgeable scale was applied to transfer the specific values into preference ranking, which may result in the loss of generality due to subjectivity. On the contrary, the Extended VIKOR method preserves the accuracy of the known data and makes use of information as much as possible. It can process the data and rank the scenarios without the loss of generality.
- The ranking of S1 and S3 is the third difference between the results of the two approaches. Besides the additional S4 in the ranking result of DS-FBWM, the priority orders of S1 and S3 are also different. In DS-FBWM, S1 is superior to S3. However, S1 is inferior to S3 in the ranking result obtained by Extended VIKOR. Except for the difference in the core thought of processing data and calculation, the preference of the stakeholders, and the selection of indices may also lead to the occurrence of the difference. Some indices which can reflect the influence of dust and incinerated ash from incineration were not selected and investigated because of lack of data. If those indictors are considered, the priority order of S1 is worth discussion. Nevertheless, incineration in take the first place still indicates that it can be competitive with biogas from digested sludge for electricity production by combustion under certain situation, especially when policy support and ash handling are satisfactory. More efforts are expected to examine the preference order

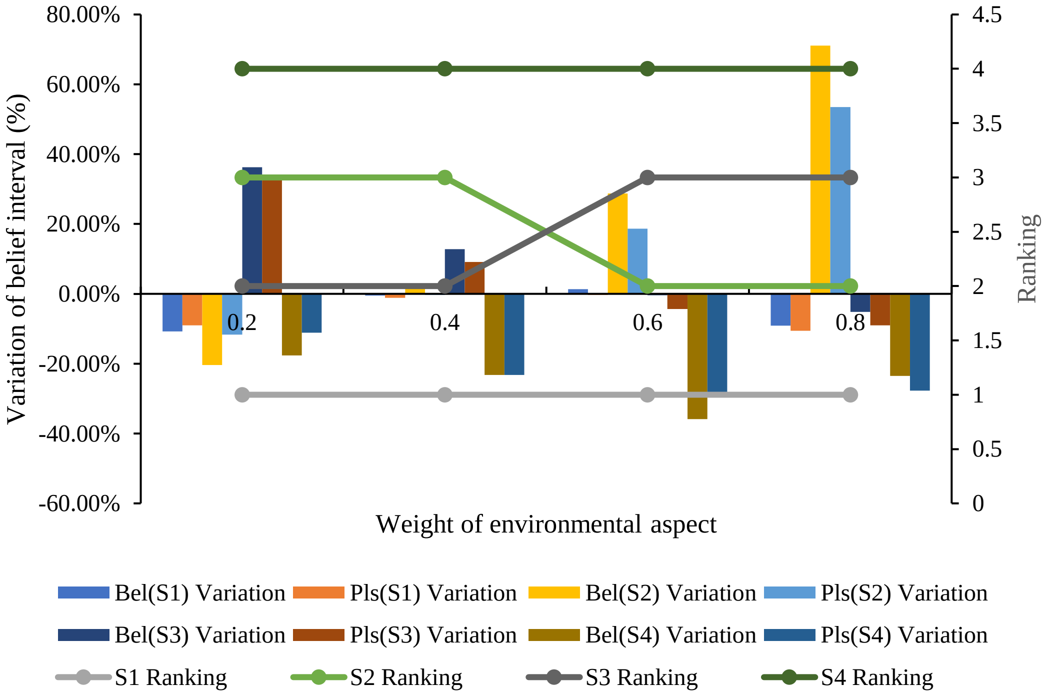
of S1 and S3 when more complete indicators are considered.

It should be noted that the ranking result of the Extended VIKOR method is also influenced by the value assignment of α. According to the calculation results, if $\alpha < 0.78$, then S2 is superior to S1. The interval length of S1 is shorter than that of S2, leading to the assignment of α as 0.8, which means a higher level of optimism. The optimism degree cannot be reflected by DS-FBWM. If the variation of α is taken into consideration, the ranking results of Extended VIKOR may have more differences compared with those of DS-FBWM, which also indicates stronger subjectivity and fuzziness in the calculation principles of DS-FBWM.

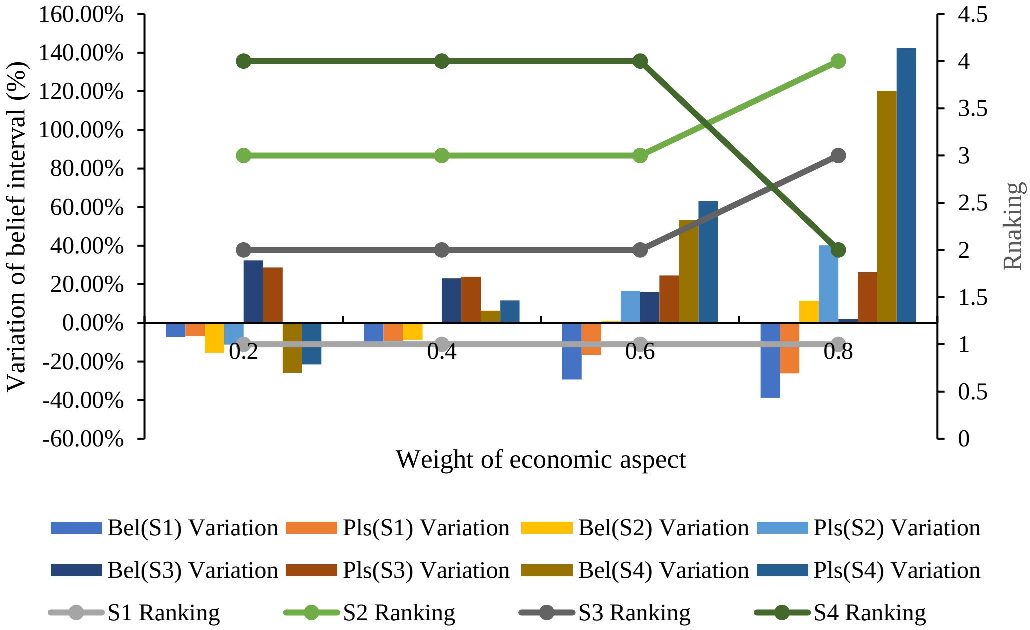
According to the above analysis, the application of these two methods can be found and related suggestions can be provided for decision-makers. When the known information is complete, both methods can be considered to help with the decision analysis. Compared with DS-FBWM, the Extended VIKOR approach can provide more exact and objective data results because there is less human intervention in the calculation process than in DS-FBWM. Therefore, it could be more reliable than DS-FBWM under the situation with complete information. However, DS-FBWM can is more flexible to deal with different types of situations especially when the information is incomplete. DS-FBWM is recommended in that case since the Extended VIKOR method does not possess the ability for processing the missing information.

6.5.2 Sensitivity analysis

Sensitivity analysis was conducted to investigate the influence of the weight variations of different aspects and criteria on the decision-making process. To study the effect of the weight change of each aspect, the local weights of all the indicators were fixed. Then the weight of the investigated aspect is set to be 0.2, 0.4, 0.6, and 0.8, respectively. Meanwhile, the weights of the other three aspects were set to be the same. Hence, four groups of weighting assignments can be obtained and each group contains 4 pieces of data records, which are shown in Figure 6.5. The ranking "1" represents the top place and "4" means the last place. The variation of the belief interval is calculated by $\frac{Bel'(S_i)-Bel(S_i)}{Bel(S_i)}$, where $Bel(S_i)$ is the lower bound of the belief interval of i th scenario in the original calculation results, $Bel'(S_i)$ is the value of sensitivity analysis. The variation of $Pls(S_i)$ can be similarly calculated.

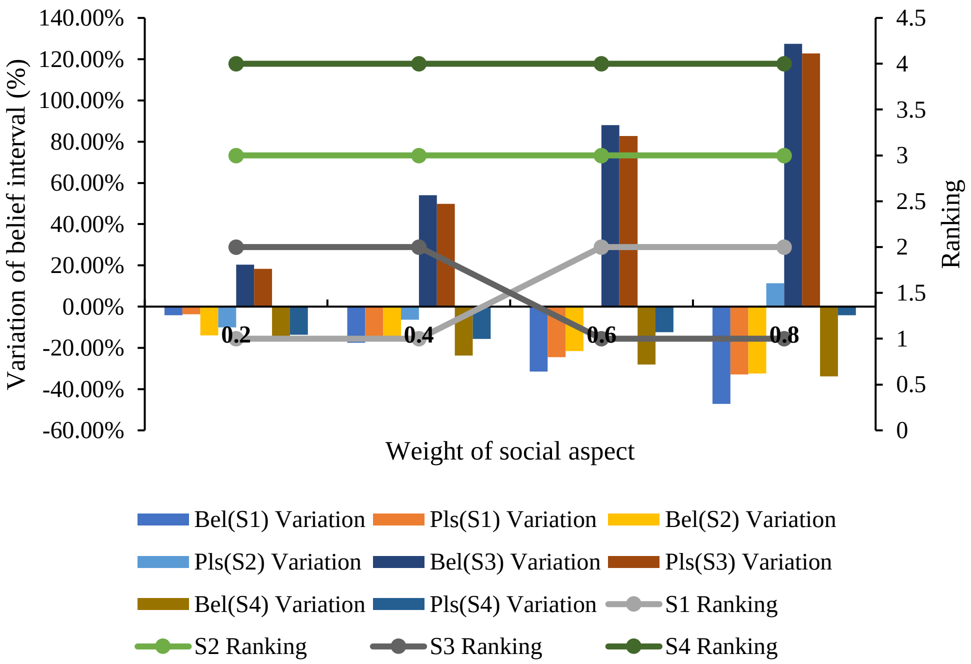


(a)



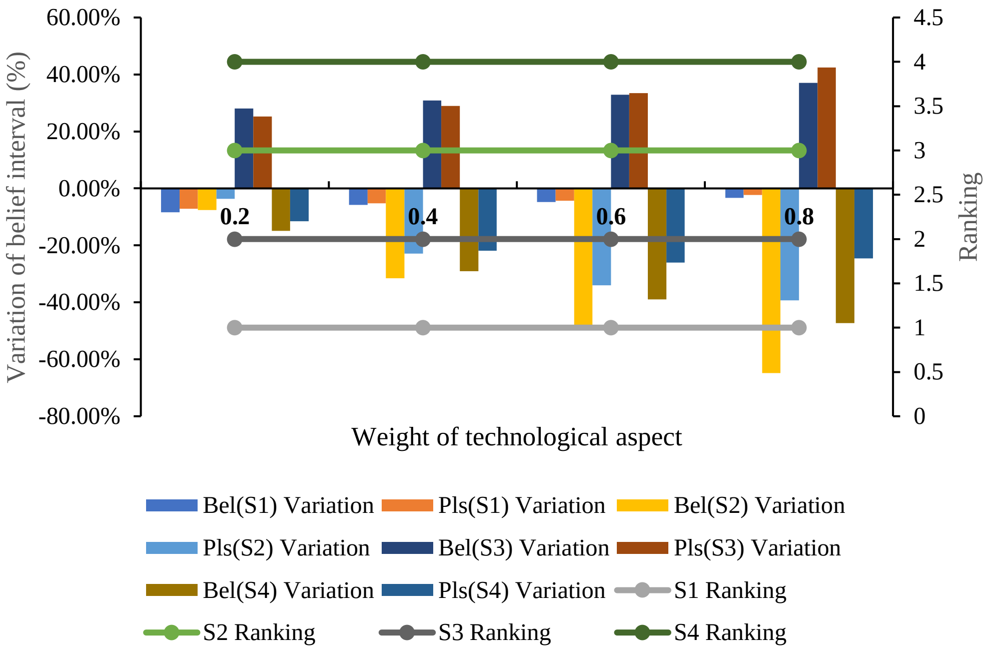
160.00%
140.00%
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
-40.00%
-60.00%
Variation of belief interval (%)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Rnaking
0.2
0.4
0.6
0.8
Weight of economic aspect
Bel(S1) Variation
Pls(S1) Variation
Bel(S2) Variation
Pls(S2) Variation
Bel(S3) Variation
Pls(S3) Variation
Bel(S4) Variation
Pls(S4) Variation
S1 Ranking
S2 Ranking
S3 Ranking
S4 Ranking

(b)



140.00%
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
-40.00%
-60.00%
Variation of belief interval (%)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Ranking
0.2
0.4
0.6
0.8
Weight of social aspect
Bel(S1) Variation
Pls(S1) Variation
Bel(S2) Variation
Pls(S2) Variation
Bel(S3) Variation
Pls(S3) Variation
Bel(S4) Variation
Pls(S4) Variation
S1 Ranking
S2 Ranking
S3 Ranking
S4 Ranking

(c)



(d)

Figure 6.5 Variations of the belief intervals when the weight of major aspect changes and corresponding ranking of the four scenarios. Sub-figures (a), (b), (c), and (d) present the situation of environmental, economic, social and technological aspect, respectively.

Figure 6.5 (a) indicates the effect of changing the weight of the environmental aspect. According to the figure, the rankings of S1 and S4 remain the same as that of initial case. The ranking of S2 increases to second place when the weight of environmental aspect is or is above 0.6, while the ranking of S3 correspondingly decreases. The variation bars illustrate that although the rankings of S1 and S4 remain stable, the belief intervals actually change to different extents. The belief interval of S4 clearly decreases when the weight of the environmental aspect increases, while the values of S1 are not sensitive to the change. This figure also reveals that biogas from sludge digestion for fuel cells to produce electricity can be competitive in the environmental perspective.

The ranking results have a big shift when the weight of the economic aspect increases from 0.6 to 0.8 (see Figure 6.5 (b)). Scenario 1 is still in the first place, though the belief interval keeps reducing as the weight of economic aspect rises. Instead of S3, S4 comes in second place when the weight of the economic aspect is 0.8, and the rankings of S3 and S2 correspondingly reduce. Considering the efficiency of electricity production, S4 is a promising option and S2 and S3 are not so preferred. However, the ranking result of the fourth situation may not be so reliable due to the missing information and the wide range of the belief intervals of the four scenarios. This fact reflects that DS-FBWM may not be suitable to a situation with extreme preferences which may lead to unreliable ranking results.

If the importance of the social aspect is or higher than 0.6, S3 is more preferrable than S1, while the rankings of S2 and S4 remain in the initial places (see Figure 6.5(c)). Hence, the obvious increase of belief intervals for S3 occurs with the weight of social aspect rising. Incineration is investment-intensive which usually requires for complete policy support and subsidies from the government. It is also less accepted by the public due to the limited apparent information and potential secondary air pollution. These barriers may impede the further promotion of wide application of incineration if there are not effective measures to deal with them.

The weight variation of the technological aspect does not have influence on the ranking result according to Figure 6.5 (d), especially the belief interval of S1 which always remains at a similar value to original result. The value of $Bel(S_2)$ continuously reduces as the weight of technological aspect increases and reaches a peak value at about 65% when the weight is 0.8. Compared to $Bel(S_2)$, the reduction of $Pls(S_2)$ is not so obvious (at most around 40%). The variation of the belief interval of S3 is relatively stable which remains at approximate 30%. Similar to the belief interval of S2, the lower and upper bounds of S4 also decrease with the increasing weight of the technological aspect. According to the data reflected from Figure 6.5 (d), both biogas fuel cells and MFCs for electricity production are weak in technological indicators due to the limited maturity, while incineration and biogas combustion for electricity generation have a longer development history and higher maturity.

To investigate the influence of the weight variations of each criterion, the weight of the major criterion is fixed at 0.25 and the weights of the other 12 criteria are assumed to be equal, i.e., 0.75/12=0.0625. The variations of the belief intervals of the four scenarios under the 13 weighting assignments are listed in Table 6.14.

Table 6.14 Variations of the belief intervals and corresponding ranking when the weight of major criterion changes

Denotation	S1		S2		S3		S4		Priority order
	Bel(S1) Variation	Pls(S1) Variation	Bel(S1) Variation	Pls(S2) Variation	Bel(S3) Variation	Pls(S3) Variation	Bel(S4) Variation	Pls(S4) Variation	
C_1	-7.03%	-8.75%	31.12%	20.72%	-22.74%	-24.48%	18.05%	7.68%	S1>S2>S3>S4
C_2	0.79%	-1.49%	-17.31%	-21.93%	49.18%	40.32%	-62.03%	-60.55%	S1>S3>S2>S4
C_3	6.15%	5.00%	-4.64%	-5.63%	15.71%	13.42%	-55.61%	-49.22%	S1>S3>S2>S4
C_4	5.33%	4.19%	-15.74%	-15.27%	27.83%	24.39%	-55.95%	-49.61%	S1>S3>S2>S4
C_5	-20.26%	-20.03%	5.83%	4.73%	67.92%	61.82%	-50.74%	-43.65%	S1>S3>S2>S4
C_6	3.80%	2.51%	-11.83%	-12.75%	6.98%	4.86%	-18.96%	-19.52%	S1>S3>S2>S4
C_7	-0.57%	-0.09%	-12.88%	-7.18%	22.55%	23.29%	-35.66%	-26.40%	S1>S3>S2>S4
C_8	-11.26%	-10.31%	-9.53%	-6.23%	50.36%	44.90%	-45.27%	-40.64%	S1>S3>S2>S4
C_9	-9.22%	-9.77%	-18.55%	-14.65%	51.26%	45.77%	-40.83%	-32.32%	S1>S3>S2>S4
C_{10}	-8.82%	-9.37%	-29.45%	-25.36%	63.97%	57.37%	-48.57%	-40.86%	S1>S3>S2>S4
C_{11}	0.79%	-0.31%	-13.88%	-10.24%	14.58%	15.63%	-38.57%	-35.62%	S1>S3>S2>S4
C_{12}	3.74%	2.62%	-21.42%	-17.48%	7.48%	8.38%	-37.81%	-34.61%	S1>S3>S2>S4
C_{13}	0.20%	-0.89%	-23.09%	-19.40%	14.97%	12.29%	-44.13%	-36.09%	S1>S3>S2>S4

In the 13 assigned situations, all the rankings are the same as the original ranking result, i.e., $S1 \succ S3 \succ S2 \succ S4$. According to the presented data in Table 6.14, S1 is insensitive to almost all the criteria except for C_5, which decreases about 20%. S2 has advantages in C_1 and C_5 and the former one is more obvious. Improving the importance on other criteria makes S2 less preferred. As for S3, the only weakness is C_1 which can cause around 20% reduction of the belief interval of S2. Attaching more importance on the other 12 criterion makes S2 have higher priority to different extents, especially on C_2, C_5, C_8, C_9, and C_{10} (increase above 40%). Similar to S2, S4 also performs well when the weight of C_1 is increased but is disadvantaged on the other criteria. However, S4 has much wider variation than S2. The variation range of S2 is about 5%-30%, while that of S4 is 8%-60% (absolute values). Hence, from the perspective of ranking, the method is not sensitive to the weight changing of each criterion. Nevertheless, with respect to the belief intervals, i.e., the preferred extent, S2, S3 and S4 are all sensitive to the weight changing of the criteria, especially for the four criteria in environmental aspect (C_2-C_5), and the criteria in social and technical aspect.

6.6 Summary

This chapter developed a new method based on DS theory and fuzzy BWM, called the DS-FBWM framework, and applied it to assess and rank the sustainability performances of four sludge-to-electricity technologies: incineration, biogas from digested sludge for electricity production by fuel cells, biogas from digested sludge to generate electricity by combustion, and MFCs, where part of the information of MFCs is missing. DS-FBWM can deal with the decision-making problem with incomplete information. Four aspects and thirteen criteria were selected to form a criteria system and fuzzy BWM was used to decide the weight of each criterion. The ranking results of DS-FBWM indicated that sewage sludge incineration for electricity production has relatively high priority and MFCs is at the inferior place under the current development status. The Extended VIKOR method was utilized to rank the former three scenarios with complete performance information and compared with the ranking result of DS-FBWM. Biogas combustion for electricity generation is preferable than incineration in the ranking result of the Extended VIKOR method. The difference may be resulted from the diversity of the core computing thought. DS-FBWM is a relatively subjective method which transfers the exact information into knowledgeable scale according to the preferences of the decision-makers, leading to the underutilization of the known information. However, it can provide necessary reference for the decision-making problem with incomplete information. In future work, a new method can be developed to solve the decision-making problem with missing information which can make full use of the known data.

Sensitivity analysis revealed that improving the weight of the environmental aspect can increase the priority of S2. MFCs (i.e., S4) would become more preferred if the economic aspect is attached to higher importance. S3 can be more competitive when the weights of the social and technological aspects improve. These results also indicated the strengths and weaknesses of these technologies. Incineration performs acceptably in the set situation of this work, but it is not widely accepted by the public due to the possible secondary pollution which is not fully reflected by the selected indicators, and still requires more government support. Considering the social acceptance and technological conditions, digested biogas combustion for electricity generation may be a more suitable choice with prepared markets and wide demanding. Biogas fuel cells and MFCs are both environmental-friendly especially on the climate change and they may become cost-effective if they can be fully developed in the future. All in all, related research and effective measures are still expected to improve current management for sludge-to-energy technologies. More reports and data from practical application are needed to study the performance of the technologies so that more reliable ranking results can be provided as a decision-making reference.

Chapter 7 Sustainability-Oriented Multi-Stakeholder Decision-Making Analysis for Sludge-to-Energy Strategies based on Game Theory

Chapter 6 provides a methodology framework to solve the decision-making problems under hybrid data conditions. However, decision-makers also need to consider the situation where conflicting interests of different groups of stakeholders are involved in the decision-making process. Traditional multi-criteria decision-analysis methods may not directly address the decision-analysis problems considering the interactions between stakeholders. In this chapter, a group decision-making framework is constructed to deal with the decision-making problem considering the interactions between stakeholders. The studied problem and research gaps are described in Session 7.1. The proposed method framework is constructed in detail in Session 7.2. In Session 7.3, a case study for sludge valorization strategies is analyzed to verify the established methodology framework. Results and discussion are presented in Session 7.4. The contributions and limitations are revealed in Session 7.5.

7.1 Problem description

Multi-criteria decision-making (MCDM) methods can help with the decision-making process with the consideration of multiple criteria. There are plenty of multi-criteria decision analysis approaches which can be applied to analyze the trade-off and assist the decision-makers 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 actual decision-making process because the process not only requires the decision-makers to consider multiple criteria, but also the interests of multiple groups involved, which are usually conflicting. 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 during the process, and the residents may consider more about the odor and job creation such social influence (Soltani et al., 2016). In order to face with the challenges above, game theory with the ability of addressing the influence of interactions between stakeholders and dealing with the conflicting interests is introduced into the decision-making process to help the decision-makers reach an agreement on their “sustainable” goals. Game theory can describe the interactive behavior of the participants and analyze the situations where the behaviors of decision-makers can not only affect their own benefits or loss but also those of others. It can provide a thinking approach to resolve such kind of decision-making problems (Aplak and Sogut, 2013).

Many efforts have been conducted on using game theory and MCDM for decision-making problems in many different disciplines. 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 find out 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 in 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).

According to the above literature review, game theory combined with MCDM methods can be further improved or extended and applied in different domains, including 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 investigate 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 sewage sludge.

As mentioned above, the propose of this chapter is to fill the following research gaps:

1. It lacks a decision-making framework to solve the group decision-making problem with the consideration of conflicting interests and the interactions between stakeholders for sludge management field.
2. It lacks discussion on the social impacts for the decision-making process of sustainable sludge management.

Hence, the chapter is conducted to build up a decision analysis framework which combines game theory and MCDA methods for solving sludge management problem. Sustainability index (SI) of different strategy, which address the overall performance on the four sustainability dimensions, can be generated based on the evaluation results and the preferences of the involved stakeholders. An optimal strategy which can be accepted by the all the players can be found according to the proposed methodology framework. Decision analysis results can provide some suggestions on how to improve the other alternatives. A case study on sludge management was carried out to verify the feasibility of the proposed framework. The case study considered the situation of two-play game which can be further extended into multi-player game under complicated situation.

7.2 Methodology

In this section, the constructed framework is introduced in detail. The methodology framework is presented in Figure 7.1 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 7.2.1 and Section 7.2.2, respectively. Criteria system for the sustainability evaluation is also constructed in Section 7.2.3 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 7.2.3. Weighting method for the criteria system is introduced in Section 7.2.3.1. Then, according to the performance data and weights of criteria, the integrated sustainability index (SI) can be obtained by using MCDM method, which is described in detail in Section 7.2.3.2. The integrated sustainability index is the basis of payoff matrix for the further game theory analysis, which is presented in Section 7.2.3.3. Section 7.2.4 describes the step for mutual agreement which can help the stakeholders reach a consensus on the ultimate selection.

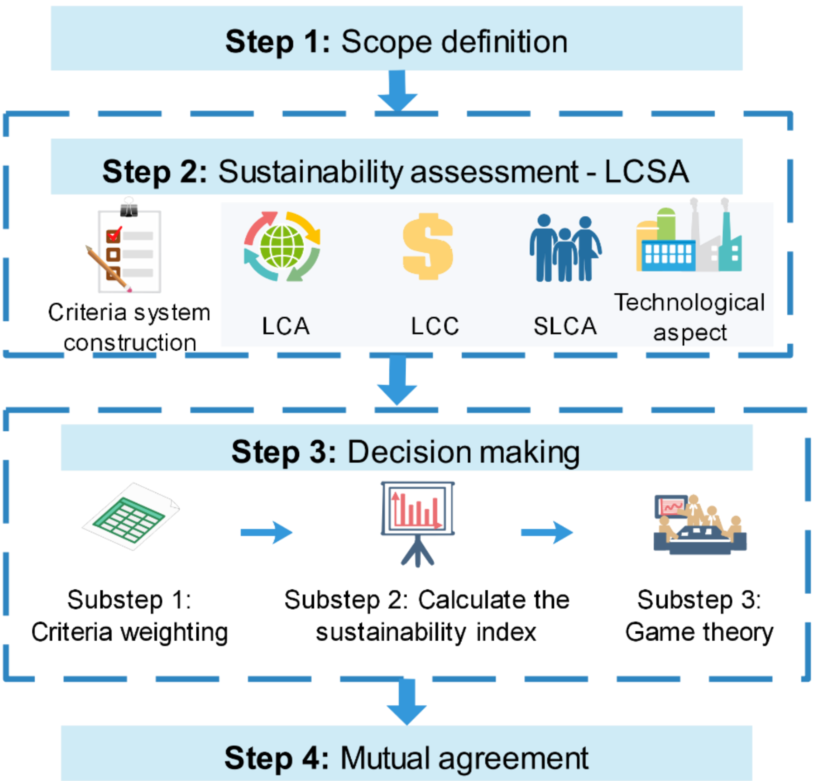


Figure 7.1 Methodology framework of this research

7.2.1 Scope definition

Reliable sustainability assessment is necessary for conducting convincing decision-making analysis in sustainability management field. LCSA is used to evaluate the sustainability performance of alternatives, According to the international standard (Ciroth et al., 2011), there are four major steps for sustainability assessment, as shown in Figure 7.2.

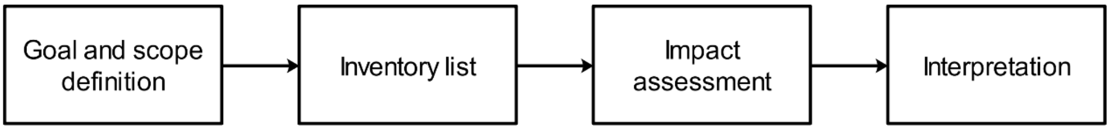


Figure 7.2 The flowchart of the basic steps for LCSA (Ciroth et al., 2011)

In this stage, the related preliminaries should be clearly identified, such as system boundaries for LCSA, stakeholders, and alternatives. Table 7.1 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 based on the it (Soltani et al., 2016). All in all, the scope definition should be clarified specifically according to the investigated system and decision-making problem.

Table 7.1 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 objective of the target system which can provide a reference to the relationship between the corresponding inputs and outputs	-

	(Cluzel et al., 2013; ECOIL, 2006).	
Involved stakeholders	The considered interested parties participate in the decision-analysis problem.	$\{P_1, P_2, \cdots, P_k\}$, 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.
……	……	……

7.2.2 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., 2017b). Eleven criteria covering four aspects were applied in this work. More detailed information for each criterion are presented in Table 7.2. Criteria system can be constructed based on the specific requirements of stakeholders and the focused problem. Although the indicators of the criteria system in this context are different from those in the former chapters, the core though is still to analyze the concerned indicators to obtain the overall performance of the alternatives.

Table 7.2 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 (AS4)	Odors control (C_8)	The ability of controlling or eliminating odors.
	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 7.3.

Table 7.3 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. (7.1) - (7.3).

$$l_q = \sum_{t=1}^{T} l_q^t / T \tag{7.1}$$

$$m_q = \sum_{t=1}^{T} m_q^t / T \tag{7.2}$$

$$u_q = \sum_{t=1}^{T} u_q^t / T \tag{7.3}$$

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 q th 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 t th 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 7.3. Then, based on Eqs. (7.1) - (7.3), 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 (7.4) (Guo and Zhao, 2017).

$$a_q = \frac{l_q + 4m_q + u_q}{6} \tag{7.4}$$

where a_q is the defuzzied performance data of the q th 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 $(3+4\times5+7)/6 = 5$.

7.2.3 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 7.2.3.1, Section 7.2.3.2, and Section 7.2.3.3, respectively.

7.2.3.1 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 7.3. 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.

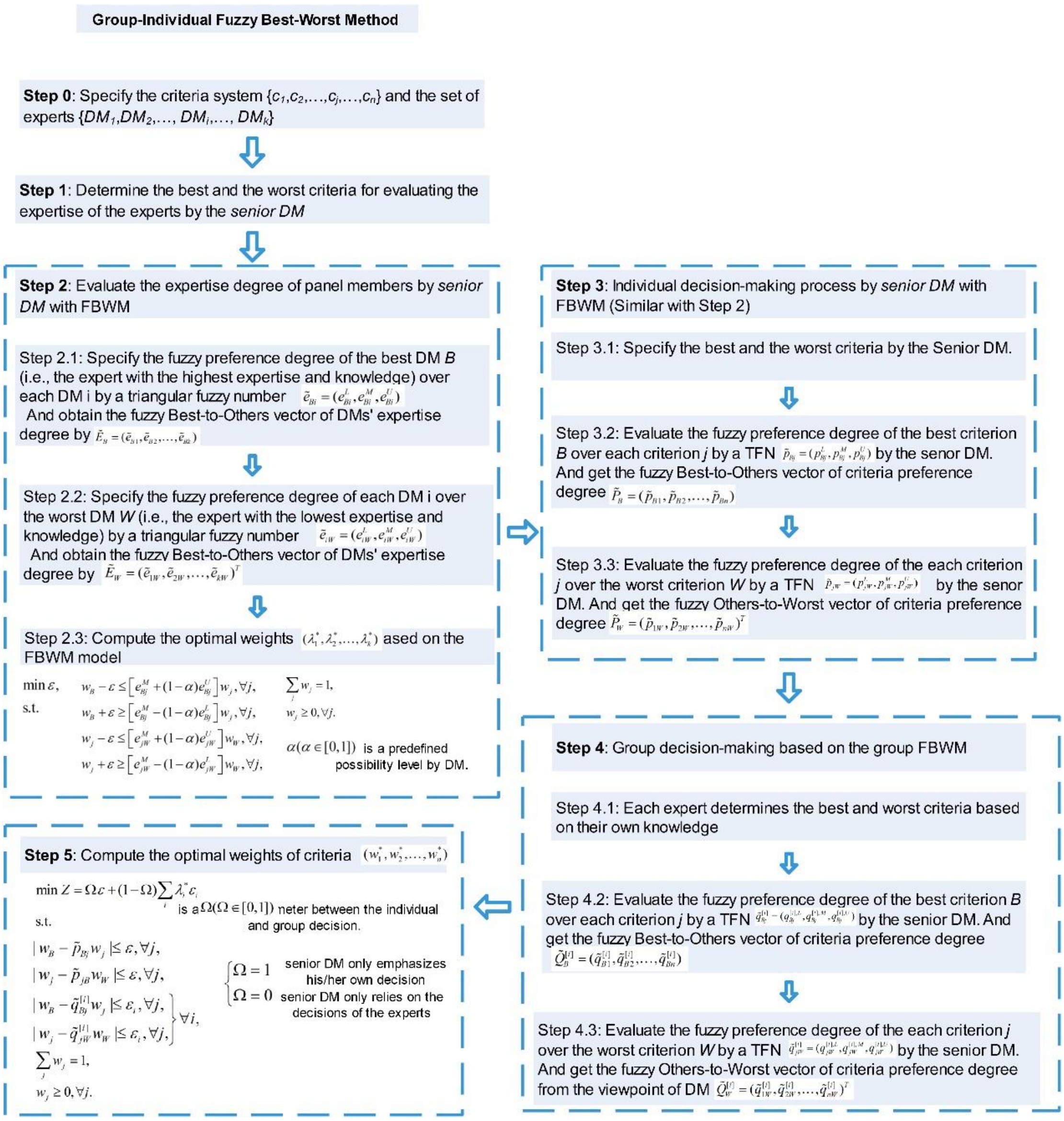


Figure 7.3 Basic step description of the GI-FBWM (Hafezalkotob and Hafezalkotob, 2017)

7.2.3.2 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

7.4. Normalization step can be conducted by Eq. (7.5) and Eq. (7.6) according to the category of the specific criterion.

$$\text{Beneficial criterion: } a_q^j = \frac{b_q^j - b_{\min}^j}{b_{\max}^j - b_{\min}^j} \tag{7.5}$$

$$\text{Cost criterion: } a_q^j = \frac{c'^j_{\max} - c'^j_q}{c'^j_{\max} - c'^j_{\min}} \tag{7.6}$$

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 range 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 7.4 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. (7.7) (Soltani et al., 2016),

$$\mathrm{SI}_j^i = \sum_{q=1}^{m} w_q a_q^j,\ j = 1, 2, \ldots, k,\ i = 1, 2, \ldots, n_j. \ , \tag{7.7}$$

where w_q is the weight of the q th 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. (7.7), 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.

7.2.3.3 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:

$$u_1(s_1^*, s_2^*) \geq u_1(s, s_2^*),\ \forall s \in S_1 \tag{7.8}$$

$$u_2(s_1^*, s_2^*) \geq u_2(s_1^*, s),\ \forall s \in S_2 \tag{7.9}$$

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.

7.2.4 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.

7.3 Case study

In this session, 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.

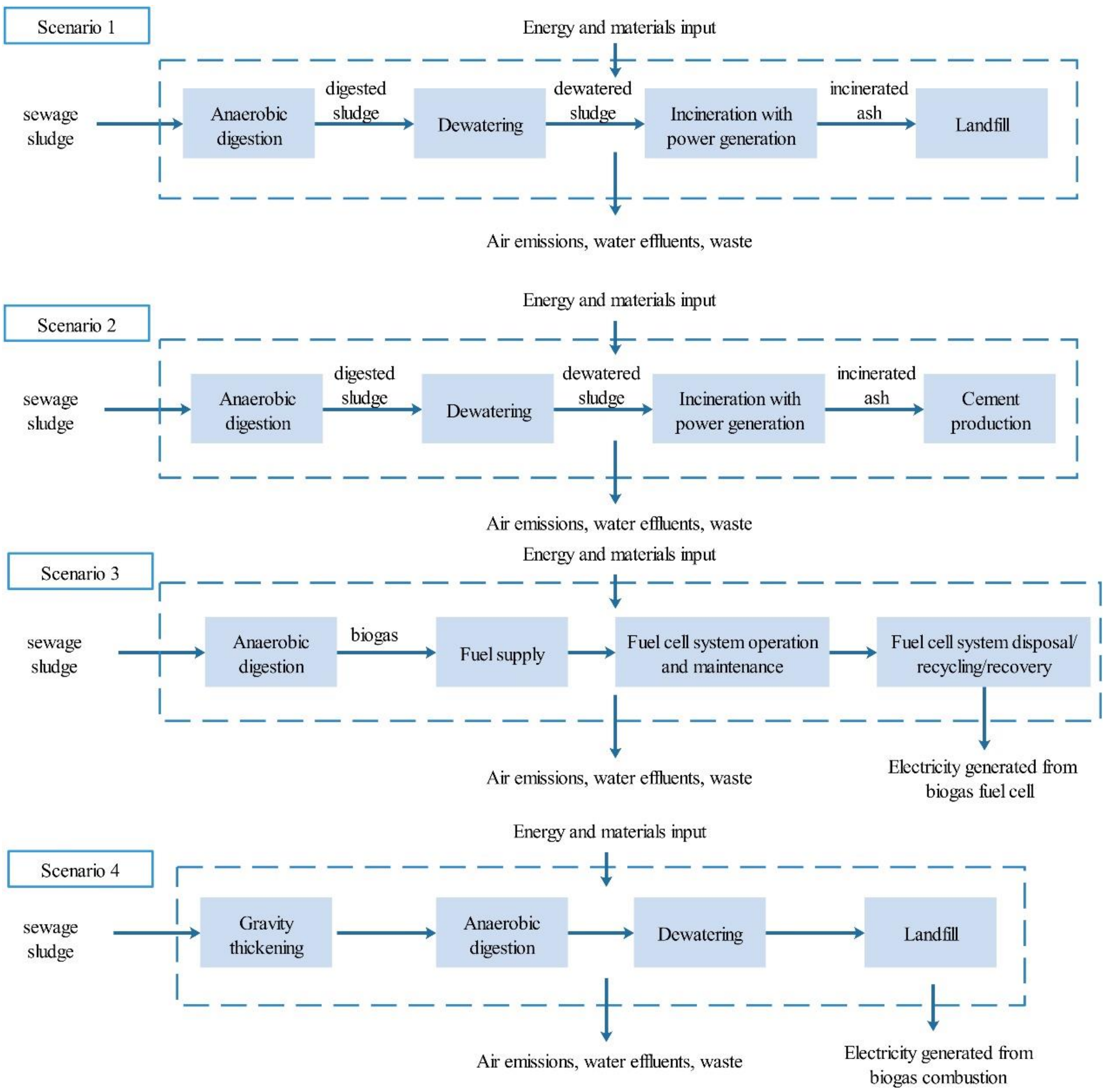


Figure 7.4 The scope of four sludge treatment scenarios considered for LCA in the case study (Lam et al., 2016)

System boundaries of the investigated four scenarios in this research are shown in Figure 7.4. 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 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). The stakeholders considered include 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 7.2. 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 7.3). In this case study, the experts were selected based on their working experience and were assumed with the same weights, which means that their opinions were regarded with equal importance. Some studies may also weight the experts by considering their professionalism (Hafezalkotob and Hafezalkotob, 2017), which is not a focus here in this study.

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.

7.4 Results and discussion

7.4.1 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 A5.1 in the Appendix Part V. According to the estimated results in Table A5.1 and Eq. (7.5) and Eq. (7.6), normalized environmental impacts can be obtained and are presented in Table A5.2. 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 A5.3 and the normalized results are presented in Table A5.4. 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 A5.5 and Table A5.6 in the Appendix. By Eqs. (7.1) - (7.3), the integrated evaluation results can be obtained and are listed in Table A5.7. Afterwards, the TFNs were defuzzied by Eq. (7.4) to prepare for the next step and the corresponding results are shown in Table A5.8. Normalized results can be subsequently obtained based on the above calculation (see Table A5.9). The results presented by Table A5.9 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.

7.4.2 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., 2017b; 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 descriptions are presented in the Appendix. The weighting results from the perspective of STF manager are shown in Table A5.20 - Table A5.22. The weighting results from the viewpoint of government manager are shown in Table A5.30 - Table A5.32. 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.

7.4.3 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 7.5.

Table 7.5 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)	$\boxed{(0.73,0.65)}$
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 7.5, 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 results, S3 can bring relatively satisfactory benefits to environment and society. 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.

7.4.4 Mutual agreement

The tipping fee means a suggested amount that can convince the government to keep a consistent choice with that of STF, i.e., that is prefer S3 to S4, and making the STF still select S3 in the context 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 can be paid to the government, both players will give priority to S3. The possible value of tipping fee can be obtained according to above analysis.

$$0.73 - 0.054x > 0.32 \rightarrow x < 7.59 \tag{7.10}$$

$$0.62 + 0.16x > 0.65 \rightarrow x > 0.19 \tag{7.11}$$

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.

7.4.5 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 A5.33 and

Table A5.34, respectively. More detailed weighting assignment for the other three aspects with respect to STF can be similarly obtained and are presented in Table A5.35 - Table A5.40. 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 A5.41 – Table A5.44.

Based on the sustainability assessment results and the weighting assignment of each group, sensitivity analysis results can be obtained and are shown in Figure 7.5 and Table A5.45 for STF, and Figure 7.6 and Table A5.46 for the Government, respectively. The value changes of SI with respect to STF under the influence of weighting changes are investigated and shown in Figure 7.5. Since the preferences on different indicators for the Gov were fixed, the outcome of payoff was the same as the original selection (0.6491 for S4). However, the SI of STF is different with the initial result as the weights changing. Based on the results, when the value of SI is larger than that of the Gov, STF will be the dominate role for the final decision, and STF should pay a certain amount of tipping fee to convince the Gov to keep the same choice with them. Figure 7.5 also reveals that the percentage of SI's change of the STF is not as significant as that of the Gov, within 20% as absolute value.

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.

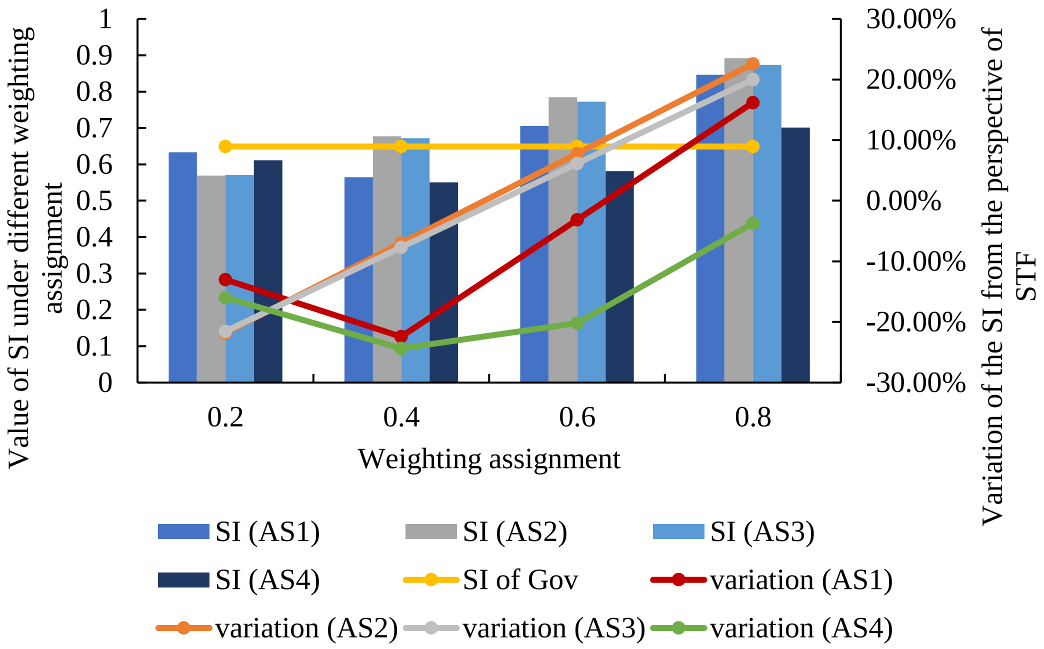


Figure 7.5 Variation of the SI of STF under different weighting for the preferences of STF. SI (AS1) refers to the value of sustainability index of the STF's choice when the weight of AS1 is assigned to be the specific value. The meaning of other aspects can be obtained in the similar way. Variation (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 A5.46 in the Appendix 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.

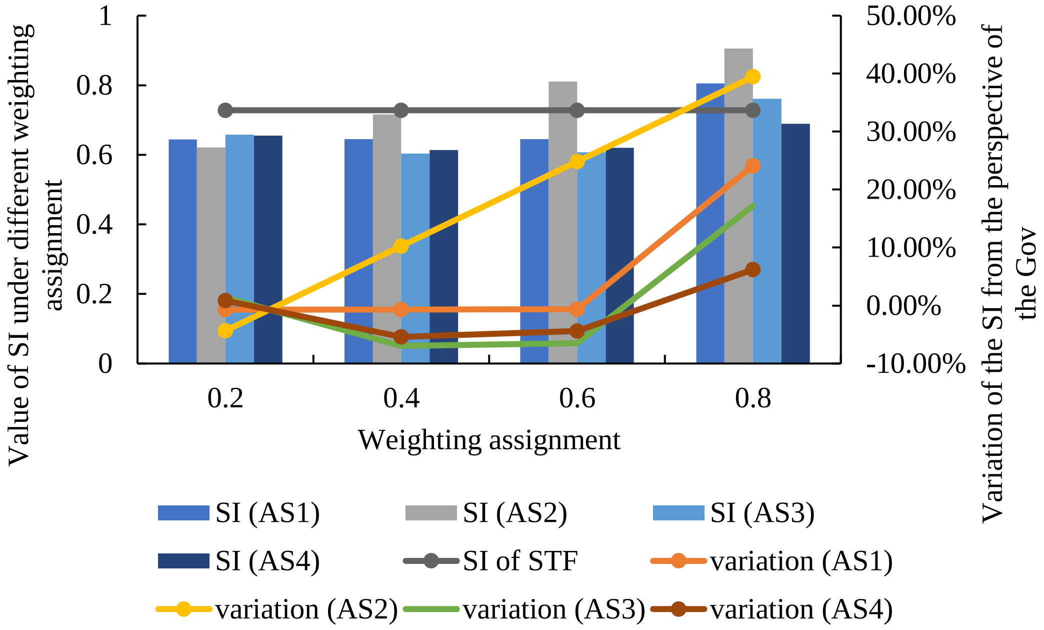


Figure 7.6 Variation of the sustainability index (SI) of the Government under different weighting assignments from the perspective of the Gov

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 A5.47. 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 A5.1 in the Appendix Part V. Detailed results can be found in

Table A5.48 and

Table A5.49. 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 A5.2 in the Appendix. Detailed results are provided in Table A5.50. 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 A5.55 – Table A5.59 in the Appendix Part V. The final recommendations can be obtained based on the weights and performance data in the initial case study (see Table A5.59). 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.

The feasibility, rationality, and reliability of the constructed methodology framework on solving the multi-criteria decision analysis problem with conflicting interests of involved stakeholders have been demonstrated by the case study and corresponding analysis. In this context, S3 or S4 was more preferred as the final selected strategy. Although S3 was the final selection after mutual agreement, S4 can also be considered and chose by the two players through the similar process. In that case, the Gov should provide additional tipping fee to the STF to convince them and come to an agreement. Similar technique route recommendations were also obtained by existing research (Liu et al., 2020b; Ren et al., 2017b). 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. The stability of decision analysis results was indicated by sensitivity analysis which were guaranteed by the check and balance of different stakeholders, leading to the belief of the robustness of the proposed methodology framework.

7.4.6 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 Figure 7.6. 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 7.6 The strengths and the weaknesses of the proposed framework

Strengths	Weaknesses
● Diverse criteria and conflicting interests of different parties can be considered. ● Impact of the interactions between stakeholders can be addressed. ● Fuzzy information from the experts' judgement can be processed. ● Performances on the four sustainability pillars can be evaluated. ● Result with relatively high stability and can be accepted by both players.	● Social impact is considered as the third sustainability pillar not as a stakeholder involved in the decision-making process. ● Weighting and the evaluation for social and technical indicators rely on the preferences, experience and knowledge of the stakeholders.

7.5 Summary

In this chapter a game theoretic-based MCDM framework for sludge management was constructed. Eleven indicators covering four perspectives were selected to evaluate the sustainability performances for the strategies. An individual and group fuzzy BWM was used to integrate the preferences of different parties and decide the fuzzy weights. 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. The constructed framework was applied to a specific case to demonstrate the feasibility.

Four technology alternatives were selected as the valorization strategies. STF and the Gov were assigned to be the two players in the case study. 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 residues. The influence of social aspect was taken into account by the sustainability assessment, but the impact could be different with the interactions with residues 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.

Chapter 8 Urban Sludge-to-Energy Supply Chain Management for Circular Economy

The formers chapters have constructed a methodology framework covering sustainability evaluation and decision-making under complex conditions. However, it is still necessary to integrate the entire process and discuss how to design a proper supply chain for sustainable sludge management. In this chapter, a supply chain design model based on a mixed-integer programming approach is proposed to solve the supply chain design and optimization problem for sustainable sludge management. The investigated problem and research gaps are presented in Session 8.1. Then the optimization model is established in detail in Session 8.2. A case study based on the data conditions and context in Hong Kong is conducted to apply the proposed approach in Session 8.3. In Session 8.4, the results are discussed and analyzed to evaluate the feasibility and reliability of the constructed model. Lastly, the contributions and limitations are summarized in Session 8.5

8.1 Problem description

Growing concern on sustainability and sustainable development drives people to seek for more clean and renewable energy, which also leads to the growing attention on sludge-to-energy (STE) technologies, especially during the recent two decades. Hence, how to select the major treatment technology, design the industrial chain and supply chain according to the regional characteristics aiming to achieve harmless treatment, or even to maximize the benefit of the treatment, is a core concern about the problem of the current environmental experts and stakeholders.

Many efforts have been conducted to explore the possible methods and approaches for solving the problem of supply chain design and optimization. A lignocellulosic biofuel supply chain was designed by a mathematical model with the ability of processing time-staged, multi-commodity, production/distribution system, prescribing facility locations and capacities, technologies and material flows (An et al., 2011). Biomass element life cycle analysis (BELCA) was developed and applied to solve the planning problem of biomass supply chain (Lim and Lam, 2016). A two-stage optimization model for the sustainable WTE supply chain design was constructed from macro and micro two perspectives to explore the optimization of supply network (Lam et al., 2013). Bioethanol supply model, mathematical programming models and multi-criteria decision-making (MCDM) framework have been utilized to optimize the WTE supply chain (Pan et al., 2015). Seuring (2013) presented a review for the quantitative methods, which emphasized the application of life cycle assessment (LCA), equilibrium models, MCDM, and analytic hierarchy process (AHP).

Although there are some studies investigating the possibility, potential and performance of WTE supply chain design as well as constructing optimization models to solve the problem, current research still has much room for improvement, especially on STE supply chain management. Researchers found that bio-heating, incineration, and co-digestion were frequently discussed owing to the generation of various types of biofuels (Pan et al., 2015), which means that the studies on other technologies, such as aerobic digestion, are still very limited. Meanwhile, only specific types or mixture of waste or biomass transferred into a target form of energy or valuable products were frequently discussed. Some papers analyzed the supply chain which applied a specific biomass as the feedstock, such as the waste from tequila industry (Murillo-Alvarado et al., 2015), wine (Malindretos et al., 2016), forestry waste (Paulo et al., 2015), and municipal solids waste (MSW) (Santibañez-Aguilar et al., 2013). Some articles directly proposed a framework for the general biomass supply chain which may process different types of waste simultaneously. Sharma et al. (2013) presented the biomass types among over 30 studies regarding biomass supply chain design and revealed that multiple biomass types occupied around half of the reviewed articles. They also figured out that the end products involving in biomass supply chains were usually the treatment products, such as biofuels (biogas, bioethanol, and bio-oil), and bioelectricity (Sharma et al., 2013). Another study revealed that in the three dimensions of sustainability, social aspect was the one that addressed the least compared with economic and environmental dimensions (Seuring, 2013). Besides, the study conducted for a specific country also indicated the major challenges existing in the development of current biomass supply chain domain. A review summarized the research and development of biomass and bio-waste supply chains for bio-energy and biofuels production in the context of India and the results showed the major challenges that need to be overcome for future included feedstock supply, efficiency, export of output energy and the government policy (Ghosh, 2016).

According to the above literature review, three major research gaps can be found as follows.

- Most supply chain design research focused on a general category or a specific type of biomass or waste. Currently, there is no study investigating the supply network design for sludge-to-energy according to our best knowledge.
- The studied technologies were limited to several thermochemical technologies, while other emerging technologies and biological technologies are less discussed.
- Economic benefit was attached to the highest importance during supply chain design. The analysis considering the balance between other sustainability pillars, like environment and economy was limited, and social aspect was even rarely mentioned.

Therefore, this chapter aims to fill the above research gaps by constructing an optimization model based on mix-integer programming for the supply chain design problem of sludge management with the consideration of both economic benefits and environmental impacts. A case study was analyzed for the sludge-to-energy supply chain design in Hong Kong by applying the proposed model, which covers four technical routes. As far as the authors know, this work is the first study to investigate the supply chain design problem of sludge management, which can provide important reference for related decision-making and promote the sustainable development of sewage sludge management.

8.2 Mathematical model

In this section, an optimization model based on mixed-integer programming approach is constructed considering three layers related with sludge generation and treatment. The optimization problem is first addressed in Session 8.2.1. Then the model is established and explained in Session 8.2.2. Some STE technologies that can be investigated by the model are briefly introduced in Session 8.2.3 to indicate the adaptable scale of this model.

8.2.1 Problem statement

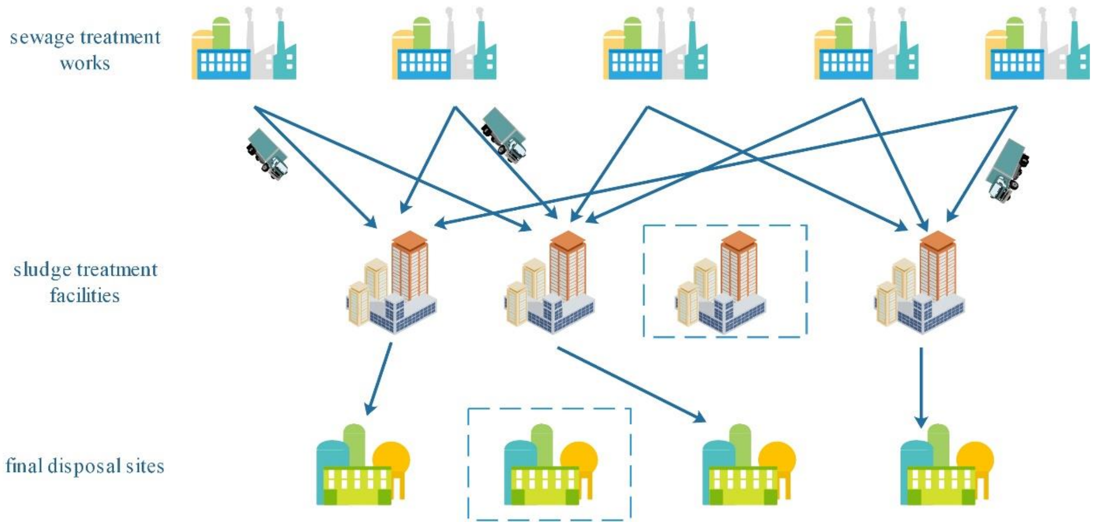


Figure 8.1 The network topology of the supply chain for sludge valorization utilization (the boxed components represent the facility or final disposal site that are not selected for construction or application)

The proposed model aims at solving a supply chain design problem with three levels, which is shown in Figure 8.1. The three levels in order are sewage treatment works, sludge treatment facilities (STFs), and final disposal sites. In the model, the form of recovered energy is determined as the technology is identified. Hence, selecting the most suitable energy form or products is excluded in the research scope. The recovered the energy and recycled materials are directly transferred into the market value to offset the corresponding input. Therefore, the generated benefits and required investment are also determined when the technical route is confirmed. The following questions can be solved by the proposed model.

(1) Where should the new sludge treatment facility be built when there are multiple alternative locations?

(2) How to distribute the sludge generated from sewage treatment works to the STFs?

(3) Which sludge treatment technologies should be selected when there are different alternative sludge treatment technologies?

(4) Which landfill site should be selected when there are multiple alternative final disposal sites?

The problems include location selection, technology selection, and arrangement of sludge treatment. In order to solve the above problems, a mixed-integer programming model is established, which is described in detail in the Section 8.2.2.

8.2.2 The proposed model

In this section, a mixed-integer programming model for the supply chain of sludge sustainable management is presented by minimizing the total life cycle cost. The objective function can be expressed as follows.

$$\min z = FC + TC - R \tag{8.1}$$

$$FC = \sum_{j \in S} \sum_{t \in FT} \left(w_{jt} (C_t \sum_{i \in M} x_{ij} + sign(\sum_{i \in M} x_{ij}) CC_t) \right) \tag{8.2}$$

$$TC = Q \cdot \left(\sum_{i \in M} \sum_{j \in S} x_{ij} \cdot d_{ij} + \sum_{j \in S} \sum_{k \in T} y_{jk} \cdot d_{jk} \right) \tag{8.3}$$

$$R = \sum_{j \in S} \sum_{t \in FT} \left(w_{jt} R_t \sum_{i \in M} x_{ij} \right) \tag{8.4}$$

Objective function (8.1) aims to minimize the total costs of the entire supply chain for sludge management. Formulas (8.2) - (8.4) refer to the capital costs, transportation costs and revenues for the supply chain system, respectively. w_{jt} $(j \in S, t \in FT)$ is a decision variable to determine whether the specific technology should be selected in the supply chain, which can only take value from 0 or 1. x_{ij} means the amount of dewatered sludge transported from wastewater treatment plant i ($i \in M$. M is the set of wastewater treatment works) to the j th ($j \in S$) sludge treatment facility. y_{jk} refers to the amount of sludge residues transported from the j th sludge treatment facility to the k th final disposal site. Both x_{ij} ($i \in M, j \in S$) and y_{jk} ($j \in S, k \in T$) are continuous variables. $sign(\sum_{i \in M} x_{ij})$ is the indicator which reveals that whether there is a sewage treatment work $i\,(i \in M)$ transporting sewage sludge to sludge treatment facility $j\,(j \in S)$. In Eq. (8.2), if the value of $\sum_{i \in M} x_{ij}$ is positive, then sludge treatment facility j should be constructed and the construction expenses should be considered. C_t and CC_t are the operating cost and the capital cost for construction of the t th ($t \in FT$. FT is the set of type of sludge treatment facilities, which is also refer to the sludge treatment technique routes) type of sludge treatment facility, respectively. d_{ij} is the distance between the i th sewage treatment works and the j th sludge treatment facility (STF). Q is the unit cost of fuel for the considered transportation mode. d_{jk} is the distance of the sludge treatment facility with the j th ($j \in S$) technique route to the selected landfill site k . The first item in Eq. (8.3) ($Q \cdot \sum_{i \in M} \sum_{j \in S} x_{ij} \cdot d_{ij}$) describes the transportation costs from wastewater treatment plants to the sludge treatment facilities, while the latter ($Q \cdot \sum_{j \in S} \sum_{k \in T} y_{jk} \cdot d_{jk}$) describes the corresponding costs from sludge treatment facilities to the final disposal sites. The total revenues generated from sludge treatment is estimated by the earnings generated from per functional unit and the total amount of sludge treated by the corresponding technology (see Eq. (8.4)).

The constraints of the optimization system majorly include the mass constraints and the environmental requirement constraints, which are introduced in detail by Eqs.(8.5) - (8.17).

$$RQ_i = \sum_{j \in S} x_{ij}, \forall i \in M \tag{8.5}$$

Constraints (8.5) reveal that the amount of sludge generation in the wastewater treatment plant i, that is RQ_i, should be equal to the total amount of sludge transported from the plant to the STFs for the further treatment, i.e., $\sum_{j \in S} x_{ij}$.

$$sc_i \geq \sum_{j \in S} x_{ij}, \forall i \in M. \tag{8.6}$$

Constraints (8.6) indicate that the capacity limitation of the wastewater treatment plant i, that is sc_i, should be no less than the total amount of sewage sludge transported to the sludge treatment facilities, i.e., $\sum_{j \in S} x_{ij}$.

$$\sum_{t \in FT} w_{jt} \alpha_t \cdot \sum_{i \in M} x_{ij} = \sum_{k \in T} y_{jk}, \forall j \in S \tag{8.7}$$

The constraints (8.7) indicate the relationship between the amount of treated sewage sludge $\sum_{i \in M} x_{ij}$ and ash or residues $\sum_{k \in T} y_{jk}$ generated after the specific treatment. The total amount of residues generated in the j th STF is determined by the total quantity of received sludge and the transferred coefficient of the corresponding technology applied in the facility.

$$\sum_{t \in FT} w_{jt} = sign(\sum_{i \in M} x_{ij}), \forall j \in S \tag{8.8}$$

Constraints (8.8) show that the STF j should be constructed and adapt one type of sludge treatment technical route once there is a sewage treatment work transporting sludge to the STF j. Otherwise, there is no need to construct or select a technology for the facility.

$$sign(\sum_{j \in S} x_{ij}) \geq 1, \forall i \in M \tag{8.9}$$

Constraints (8.9) indicate that there is at least one sludge treatment facility receiving the sludge transported from the i th wastewater treatment plant.

$$\sum_{k \in T} sign(y_{jk}) \leq 1, \forall j \in S \tag{8.10}$$

Constraints (8.10) reveal that there is at most one final disposal site k receiving the residues from STF j.

$$\sum_{j \in S} w_{jt} \leq 1, \forall t \in FT \tag{8.11}$$

Constraints (8.11) point out that one technology route can only be selected by one sludge treatment facility.

$$\sum_{t \in FT} w_{jt} \leq 1, \forall j \in S \tag{8.12}$$

According to the constraints (8.12), one sludge treatment facility can only adapt one treatment route.

$$\sum_{j \in S} y_{jk} \leq tc_k, \forall k \in T \tag{8.13}$$

Constraints (8.13) are still the capacity constraints which reveal the limitation given by the maximum capacity of the final disposal site tc_k should be no less than the total amount of residues transported in it, i.e., $\sum_{j \in S} y_{jk}$.

$$\sum_{i \in M} \left(\sum_{t \in PT} w_{jt} EF_t \cdot x_{ij} \right) \leq ER_j, \forall j \in S \tag{8.14}$$

Except for the mass constraints, some other conditions such as the emissions limitations restricted by the regulations can also be considered as the constraints to improve the completeness of the model. Meanwhile, some industries may also emphasize the importance of total generated profits from the sewage sludge treatment process, which can also be added to address the performance of the supply chain for sludge management. Constraints (8.14) provide the relationship of the emission requirements and the emission of each technology. In Eq. (8.14), the sludge treatment facility j has established connection with the t th type of scenario. It can be regarded as the total emissions from the j th sludge treatment facility adapting the t th scenario of sludge treatment technique route should be no more than the mission requirement of the t th technique route, which has been selected by the corresponding STF.

$$\sum_{t \in FT} w_{jt} = sign(\sum_{k \in T} y_{jk}), \forall j \in S \tag{8.15}$$

Constraints (8.15) indicate that only once sludge treatment facility j is in use can the residues be transported from the facility to the landfill site.

$$x_{ij} \geq 0, \forall i \in M, \forall j \in S \tag{8.16}$$

$$y_{jk} \geq 0, \forall j \in S, \forall k \in T, \tag{8.17}$$

Nonnegativity restrictions for the decision variables are described in Eqs. (8.16) - (8.17).

8.2.3 Applicable scale

Once the basic features and necessary data for the STE technologies in the investigated region are available, these technologies can be considered as the alternatives for the supply chain design. Considering the structure of the supply chain model and the common process for sludge treatment and disposal, the technical route should at least include the major treatment method and disposal approach. For example, sewage sludge generated from wastewater treatment plant is transported to the treatment facilities for the main treatment including thickening, digestion, dewatering, and incineration. Afterwards, the residues are transported to the disposal sites for post-treatment (Hong et al., 2009). Such a process is a complete technical route for sludge management. Therefore, a wide range of technologies can be considered and investigated by the model, such as incineration, gasification, pyrolysis, and anaerobic digestion, as long as the corresponding parameters of the entire process are accessible. In addition, there is no strict limitation on the final valuable products generated or recycled from the treatment process as long as it can be converted into the corresponding economic value. Hence, waste heating and steam, biofuels, and electricity recovered from the sludge treatment process can all be considered as the valuable products in the model, leading to a relatively wide applicable scale of this model.

8.3 Case study

8.3.1 Sludge management in Hong Kong

Sewage sludge is classified into special waste in Hong Kong, which is characterized by high content of chloride owing to the utilization of seawater for flushing in (Leong et al., 2010). Meanwhile, Hong Kong is a city with large population and limited area, leading to a high population density. All these factors result in the caution and limitations in the selection of sludge management technologies in Hong Kong.

After the sludge generated from the sedimentation tanks during the sewage treatment process, primary sludge is collected and then transported to the aeration tanks for the secondary treatment. Afterwards, the treated sewage and activated sludge are separated in the final sedimentation tanks. Parts of the activated sludge is sent back to the aeration tank to maintain adequate micro-organism population for the subsequent biological treatment, while the remaining part, which is also called surplus activated sludge, is sent for thickening and digestion. Digested sludge is firstly dewatered to reduce the moisture content before transporting to the landfill sites. The basic process is illustrated by Figure 8.2, which is exampled by the flowchart of Shatin Sewage Treatment Works (Drainage Services Department, 2009a). The preliminary processing of sewage sludge that precedes the main treatment may be slightly different in different sewage treatment works, but this is the general working flow in the sewage treatment works of Hong Kong.

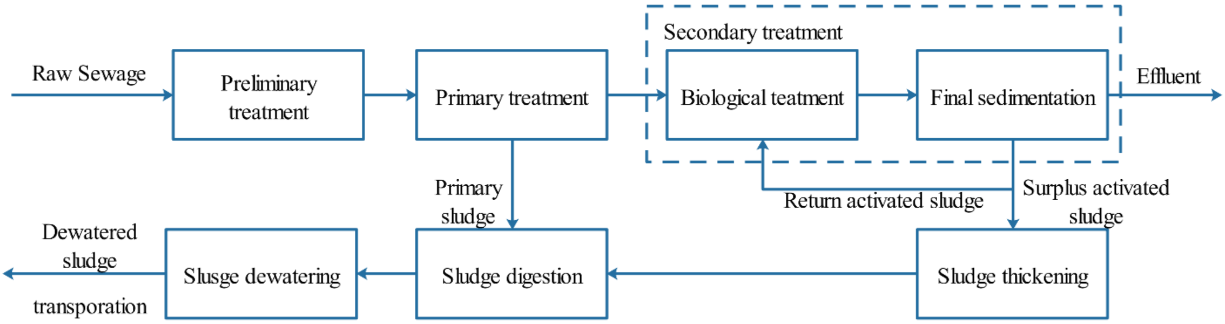


Figure 8.2 Flowchart of the basic processes for sewage treatment in Shatin Sewage Treatment Works (modified from (Drainage Services Department, 2009a))

According to Figure 8.2 and reports of sewage treatment works (Drainage Services Department, 2009a), wastewater is discharged to Victoria Harbour to help solve the red-tide problem. The dewatered sludge was usually transported to the landfill sites for final disposal. However, this approach cannot dispose the harmful components in the sludge effectively. It could bring many potential threats to the environment and human health. The components with recovery value and the potential for energy regeneration are ignored. Moreover, disposing large quantities of dewatered sludge at landfills would accelerate the saturation rate of landfills and affect the stability of landfills (Drainage Services Department, 2017). This is a serious problem for Hong Kong due to the very limited land resources.

In order to solve the problem, a sludge treatment facility called "T▪PARK" was constructed and applied to process the dewatered sludge from major sewage treatment works after commencement, which helps reduce large amount of dewater sludge for directly landfill disposal. Figure 8.3 reveals the tendency and total quantity variation of received dewater sludge by STF.

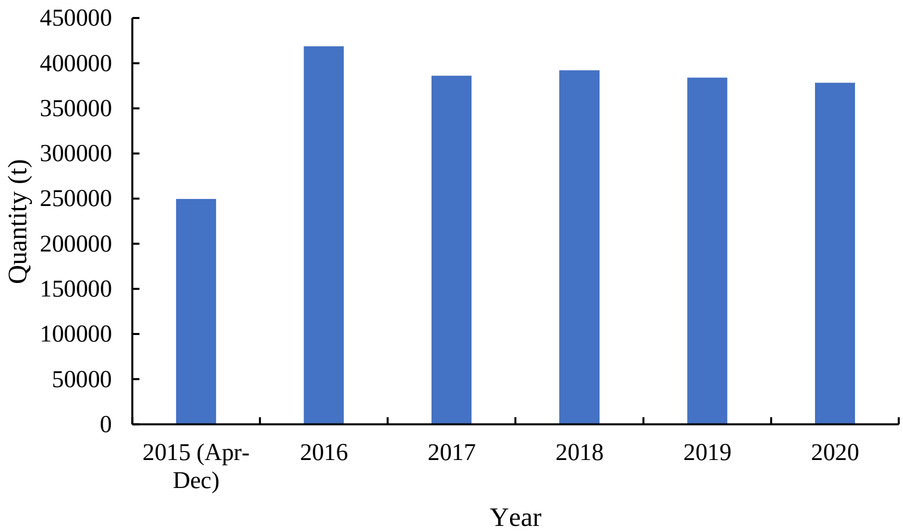


Figure 8.3 Sewage sludge collected by the T▪PARK (Environmental Protection Department, 2021a)

The sludge treatment facility uses fluidized bed incineration technology as the major approach for sludge management and the incinerated ash is collected for landfill. Although it shows some advantages in sludge management, is it the most suitable alternative for the entire STE supply chain design? Whether the current supply chain can be further optimized or improved? These questions are the major focuses of this case study. The questions proposed in the Methodology section can also be addressed.

8.3.2 Specific assumptions and data sources

Four sludge-to-energy treatment scenarios were investigated in this study and the basic flowchart and system boundaries considered in environmental assessment are shown in Figure 8.4. The main treatment of both Scenario 1 (S1) and Scenario 2 (S2) are incineration (Lam et al., 2016). The difference between the former two technical routes lies in final disposal. Incineration is followed by the landfill in S1, while cement production is the follow-up step of incineration in S2. The major treatment of Scenario 3 (S3) is gasification (Hong et al., 2009). Hydrothermal-pyrolysis technology (HPT) is the essential approach for sludge treatment in Scenario 4 (S4) (Xiao et al., 2018). These four technical routes four sludge valorization utilization are selected because the following reasons.

i) Incineration is regarded as the most thorough sludge treatment method and has been adapted by many developed countries and regions (Zhao, 2018). However, incineration usually requires a considerable amount of energy input and effective measures for the flue gas process. The sustainability and applicability to a specific region are still needed to discuss and investigate.

ii) Gasification and hydrothermal-pyrolysis are relatively new technologies which may have not been applied in a wide scale for sludge management, but they still show many advantages and huge potential for the energy regeneration and sludge treatment (Syed-Hassan et al., 2017; Xiao et al., 2018). Hence, it is necessary to study the potential of applying these advanced technologies in the supply chain of sludge management.

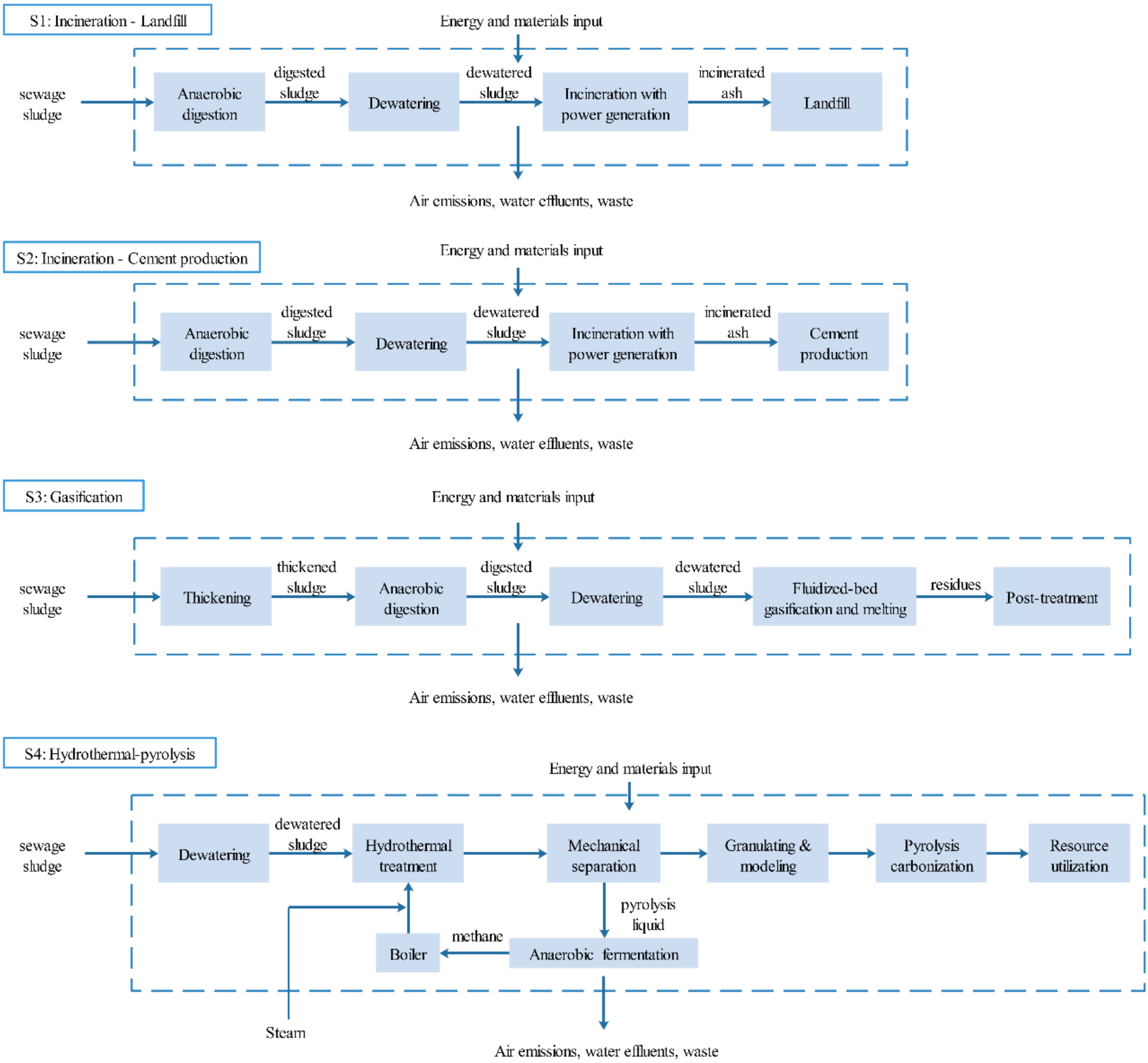


Figure 8.4 System boundaries of the investigated scenarios in the environmental assessment in this research. S1 and S2 were modified from the work of Lam et al. (2016). S3 and S4 were drawn based on the work of Hong et al. (2009) and Xiao et al. (2018), respectively.

In this case study, the considered environmental indicator was the emission of greenhouse gases (GHG) since climate change is an important growing concern for sustainable development. The service year of sludge treatment facilities was supposed to be 20 years. The horizon of the supply chain network in this work is one day. The regulation on carbon emission of the local governmental is estimated based on the recording data for the carbon emissions during the decade and the goal for the future in order to realize better sustainable development (Council for Sustainable Development, 2021). The emission requirements are not estimated based on the technology type in the case study. Some cities may have strict emission requirements on the sludge treatment plant with specific technology. In that case, the parameter of emission requirement can be determined by the emission standard on the plant. But in the context of this chapter, the emission requirements were roughly estimated by the emission goal of the government. Equivalent carbon emission of each scenario was estimated according to the environmental life cycle assessment results from the related references (Hong et al., 2009; Lam et al., 2016; Xiao et al., 2018). System boundaries of environmental impact and economic aspect were actually the same. The functional unit was selected to be 1 dry ton of sewage sludge. In the case study, the process of thickening and dewatering do not present obvious contribution to the carbon emission. Hence, the carbon emissions from these two processes are omitted, which are not presented by Figure 8.4, but actually the costs for thickening and dewatering are considered in the economic analysis. Besides, the costs of sludge generation are not considered. Only the costs and benefits generating during the major treatment were investigated.

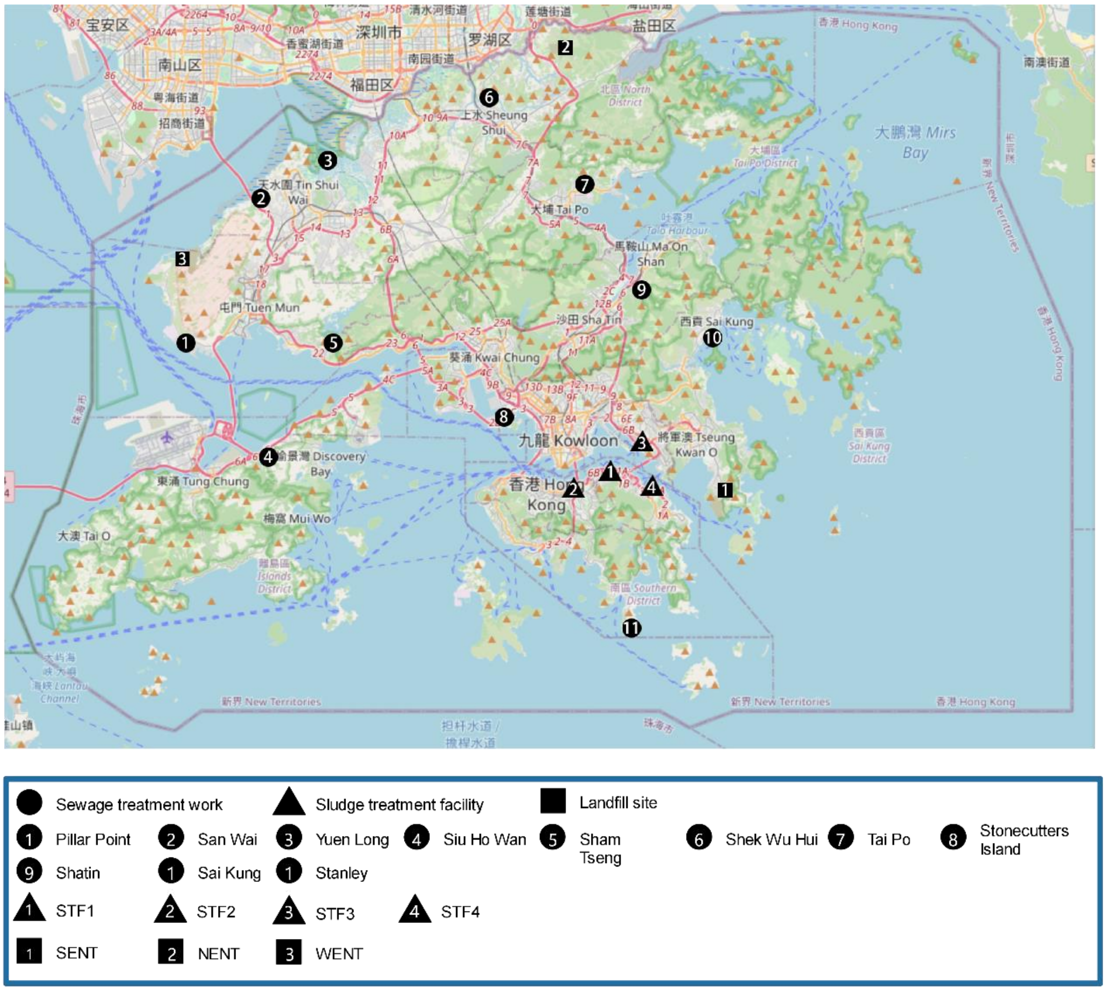


Figure 8.5 Sketch map of position distribution of the sewage treatment works, alternative sludge treatment facilities, and landfill sites. The base map was provided by OpenStreetMap (2021).

The rough position distribution of the facilities in the three layers is shown in Figure 8.5. There are eleven major sewage treatment services considered in the supply chain network. Related information of the sewage treatment services is presented in Table 8.1. Data of daily average amount of sludge generation were applied in the case study.

Table 8.1 Basic information about 11 major wastewater treatment works in Hong Kong

No.	Name	Longitude	Latitude	Daily average amount of sludge generation[12]	Capacity[12]
1	Pillar Point[1]	113.9557	22.3683	80.51	116.50
2	San Wai[2]	113.9939	22.4506	116.50	116.50
3	Yuen Long[3]	114.0374	22.4705	7.58	33.15
4	Siu Ho Wan[4]	114.0066	22.3154	85.24	85.24
5	Sham Tseng[5]	114.0759	22.3677	2.65	8.05
6	Shek Wu Hui[6]	114.1314	22.5124	38.36	44.04

7	Tai Po[7]	114.2022	22.4600	44.99	56.83
8	Stonecutters Island[8]	114.1505	22.3302	663.00	1136.57
9	Shatin[9]	114.2250	22.4098	118.39	161.01
10	Sai Kung[10]	114.2847	22.3779	3.79	10.42
11	Stanley[11]	114.2283	22.2150	4.17	5.49

Note:

The latitude and longitude information were collected from Baidu Map (Baidu, 2021).

1 Reference: (Drainage Services Department, 2009b).

2 Reference: (Drainage Services Department, 2019a).

3 Reference: (Drainage Services Department, 2009c)

4 Reference: (Drainage Services Department, 2016)

5 Reference: (Drainage Services Department, 2009d)

6 Reference: (Drainage Services Department, 2009e)

7 Reference: (Drainage Services Department, 2009f)

8 Reference: (Drainage Services Department, 2009g)

9 Reference: (Drainage Services Department, 2009a)

10 Reference: (Drainage Services Department, 2009h)

11 Reference: (Drainage Services Department, 2009i)

12 Daily amount of sludge generation of each sewage treatment work is estimated based on the data record of each plant and the relationship between the wastewater generation and daily sludge generation in Hong Kong. About 2.8 million m^3 wastewater (Environmental Protection Department, 2016) and 1326 t sludge are generated in HK in one day (Drainage Services Department, 2017). Hence, it is estimated that 2110 m^3 wastewater can generated 1 ton of sludge.

There is a one-to-one correspondence between the scenarios and the sludge treatment facilities. Four alternative locations are selected and related information are presented in Table 8.2. Alternative positions and capacity are assumed parameters which can be adjusted according to the actual situation. Some important process data regarding the four scenarios are shown in

Table 8.3. It should be noted that the differences between S1 and S2 include the difference on the final disposal approach of sludge residues as well as the function of sludge treatment facilities. The incinerated ash will be transported to the landfill site in S1, while the residues in S2 will be applied for cement production in sludge treatment facility (Lam et al., 2016).

Table 8.2 Basic information and assumption for the possible position of four sludge treatment facilities

Denotation	Longitude	Latitude	Capacity (t/day)
STF1	114.2159	22.2955	500
STF2	114.1911	22.2848	500
STF3	114.2347	22.3102	500
STF4	114.2423	22.2864	500

Note:

The latitude and longitude information were collected from Baidu Map (Baidu, 2021).

Table 8.3 Parameters of different sludge treatment routes considered in this research

No.	C_t [1]	CC_t [2]	α [3]	R_t [4]	EF_t [5]	ER_t [6]
Unit	USD/t DS	USD/day	-	USD/t DS	kg eq CO_2/t DS	t eq CO_2/day
S1	440.7599	2359.5890	0.1654	0	0.0242	1671.9633
S2	20.9586	2359.5890	0.1654	0	0.0241	1671.9633
S3	426.5585	25.2895	0.2759	0	0.0198	1671.9633
S4	214.8800	485.4064	0.2200	30.592	0.0527	1671.9633

S1: incineration + landfill; S2: incineration + cement production; S3: gasification; S4: HPT.

DS Dry solids of sludge

1 Operating cost C_t for each scenario is estimated based on the references (Hong et al., 2009; Lam et al., 2016; Xiao et al., 2018).

2 Construction cost CC_t is converted to daily cost according to the total investment and service year. 1 year=365 day.

3 α for S1 and S2 is obtained according to the data on the amount of sludge incineration and corresponding incinerated ash for landfill (Drainage Services Department, 2017). The values for S3 and S4 are from research of Zhu et al. (2015) and Mills et al. (2014).

4 The profit R_t generated from S1 to S3 has been considered in the total operating cost of the corresponding costs, while the data for S4 was provide in the reference(Xiao et al., 2018).

5 Emission factor of CO_2 equivalent for each scenario is estimated based on the LCA results provided in the references (Hong et al., 2009; Lam et al., 2016; Xiao et al., 2018).

6 All the scenarios share the same requirement on carbon emission because the emission requirement for sludge treatment industry was regarded as a whole. It is not separated by the type of sludge treatment facility and the adapted technique route, which is used to describe the property of the specific t th type of sludge treatment facility.

EF and ER are more related to the technique route and the local conditions (especially for ER). Since the j th constructed STF can select the t th type of sludge treatment technique route, it can also be regarded as t th type of sludge treatment facility, or STF j with technique route t.

1 RMB=0.16 USD

1 HKD=0.13 USD

1 JPY=0.0092 USD

The sale price of electricity is 1.108 HKD/kWh (Lam et al., 2016), which is 0.14 USD/kWh.

The construction cost of S1 and S2 was assumed to be the same since the main technology is consistent. The investment was estimated based on the total investment for the facility (Luo, 2010), the division of zones (Environmental Protection Department, 2022), and the capacity setting. Construction cost of the STF with S3 (gasification) was estimated based on the data provided by Hong et al. (2009) and the investment for adapting S4 was calculated based on the data in the research of Xiao et al. (2018). The requirement on carbon emission was roughly estimated based on the carbon emission goal and corresponding proportions. According to the records, carbon emissions equivalent per capita should be less than 4.5 t and the population in Hong Kong was about 7.5 million in 2019. Hence, the total carbon emissions equivalent is about 40.5 million tons. Meanwhile, there is about 6% emissions coming from waste and others. It is roughly estimated that sewage sludge treatment occupies around one quarter of the waste treatment in Hong Kong (EPD, 2018).

It is assumed that the transportation mode applied in this supply chain network was truck with a load of 20 t (Lam et al., 2016). Unit cost for transporting 1 ton of dewatered sludge for 1 km, that is Q, is supposed to be 0.4778 USD/(km·t) (Lam et al., 2016). Three landfill sites, including SENT (the South New Territories Landfill), NENT (the North New Territories Landfill), and WENT (the West New Territories Landfill), were considered in the case study, which are responsible for the sanitary landfill work for the different kinds of waste in Hong Kong. The basic information of the landfill sites is presented in Table 8.4.

Table 8.4 Basic information about three landfill sites considered in the case study

No.	Landfill site	Longitude	Latitude	Daily capacity (t)
1	SENT[1]	114.2906	22.2838	1339.8292
2	NENT[2]	114.1806	22.5480	627.2609
3	WENT[3]	113.9393	22.4216	2207.9583

Note:

The latitude and longitude information were collected from Baidu Map (Baidu, 2021).

1 (Environmental Protection Department, 2021b)

2 (Environmental Protection Department, 2021c)

3 (Environmental Protection Department, 2021d)

The daily capacity of each landfill site is estimated based on the total received amount of waste and the proportion of sewage sludge in the special waste.

The results can be obtained by substituting the relevant data into the proposed model for calculation, which are presented in detail in the next section.

8.4 Results and discussion

8.4.1 Optimal decision results between the Sewage Treatment Works and Sludge Treatment Facilities

The decision variables between the first and the second level were firstly figured out, including the transported amount of sludge between each sewage treatment service and alternative sludge treatment facility, and the selection of construction position of the sludge treatment facility. The detailed results are shown in Table 8.5. According to the results, constructing three facilities with capacity of 500 t/day can already satisfy the current demand of sludge daily treatment, since there is no sewage treatment work transporting sludge to the fourth possible position of sludge treatment facility. Among the constructed three STFs, the former two plants are full-load operation while the third one is not operating at full capacity, which means that the current supply chain design still can receive more sludge if the amount of sludge generation grows. Under this circumstance, the transportation cost between the first- and the second-level can be accordingly calculated as listed in Table 8.6.

Table 8.5 Amount of sludge transported from the i th sewage treatment work to the j th alternative position of sludge treatment facility (Unit: t)

Sewage treatment works	STF1	STF2	STF3	STF4
1	0	80.51	0	0
2	0	116.50	0	0
3	7.58	0	0	0
4	0	85.24	0	0
5	0	2.65	0	0
6	38.36	0	0	0
7	2.00	0	42.99	0
8	447.90	215.10	0	0
9	0	0	118.39	0
10	0	0	3.79	0
11	4.17	0	0	0
Total	500	500	165.18	0

Table 8.6 Transportation cost between sewage treatment works and sludge treatment facilities (USD/day)

Sewage treatment works	STF1	STF2	STF3	STF4
1	0.00	1596.56	0.00	0.00
2	0.00	2437.07	0.00	0.00
3	154.68	0.00	0.00	0.00
4	0.00	1258.25	0.00	0.00
5	0.00	30.41	0.00	0.00
6	748.86	0.00	0.00	0.00
7	27.86	0.00	555.79	0.00
8	2655.29	1075.00	0.00	0.00
9	0.00	0.00	1001.36	0.00
10	0.00	0.00	26.32	0.00
11	28.69	0.00	0.00	0.00
Total	3615.37	6397.28	1583.48	0.00

In this stage, the technical routes are still not confirmed. The final disposal site selection and the most suitable technical route under the assumptions are obtained after the total optimal costs can be calculated, which are addressed in the next subsection.

8.4.2 Global optimal solution of the supply chain design for sludge management

According to the calculation results, the entire supply chain design for sludge-to-energy management can be determined as follows and the supply network is also shown in Figure 8.6.

1) Three sludge treatment facilities should be constructed on the three former alternative positions, that is STF1, STF2, STF3, respectively. STF4 was not selected.

2) The selection of technique route for sludge treatment by each STF was S4, S2 and S3, respectively. S1 was not selected.

3) Landfill site 1, that is SENT, was chosen to receive the residues from all the sludge treatment facilities.

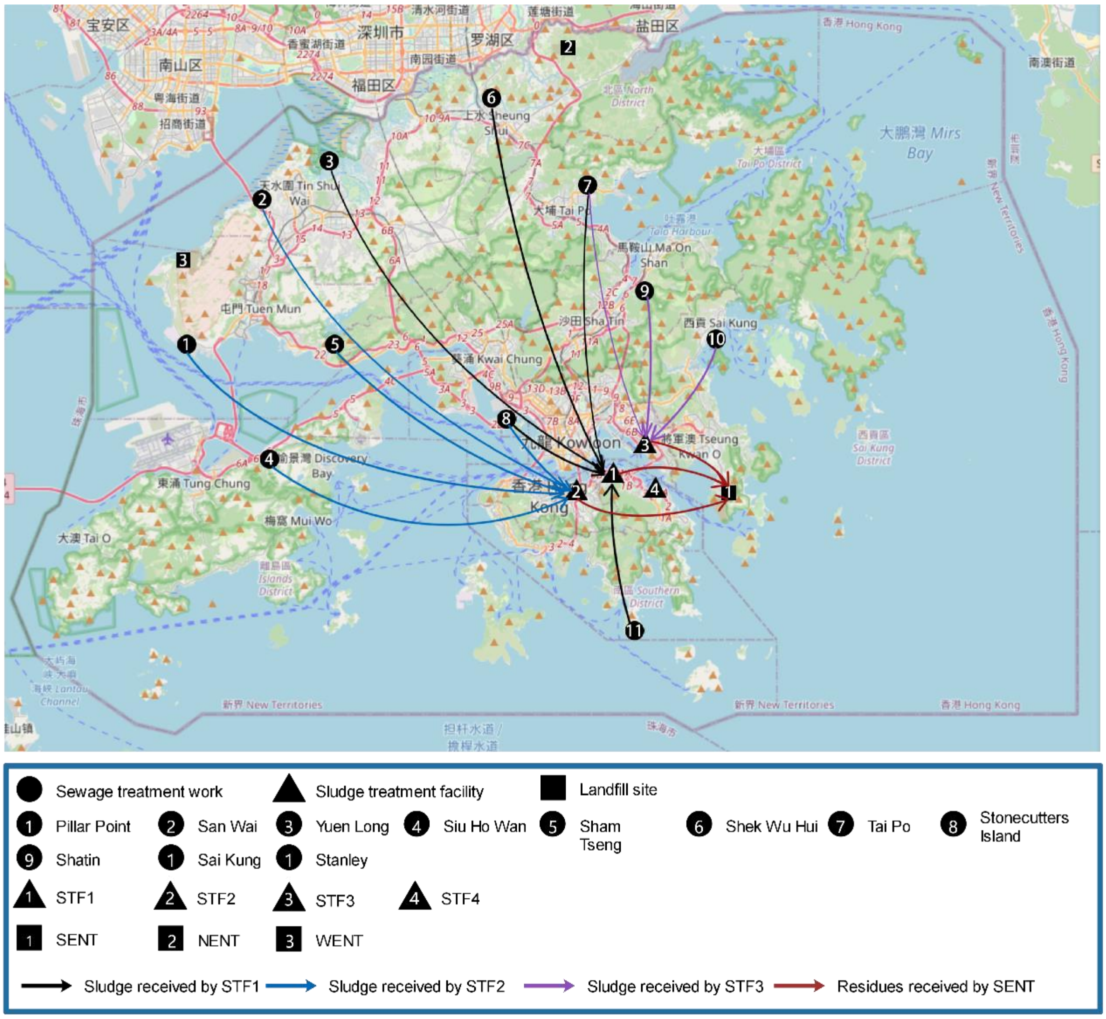


Figure 8.6 Sketch map of the optimal supply network of sludge management in the case study. The base map was provided by OpenStreetMap (2021).

Under the optimal situation, the total daily cost for sludge treatment was estimated to be 188428 USD/day, which is shown in Figure 8.7. The expenditures of each sludge treatment facility and the corresponding cost for each part are also presented. The total costs for STF1, STF2, and STF3 were 96901, 19236, and 72281 USD/day, respectively. The cost contribution for each different process is illustrated in Figure 8.8. According to the calculation results, sludge treatment took the majority part for the total costs, especially in STF1 and STF3, both around 95%. The expense on sludge treatment for STF2, however, only contributed 55% for the total costs. This is owing to the higher transportation cost and relatively low total treatment costs, where the revenues have been considered in the operating costs of STF2. Although STF3 was not full load operated, the cost for sludge management played a dominate role in the total cost due to the relatively high operating cost and extremely low expenses on construction and transportation. Hence, the overall contribution of sludge treatment costs, considering the entire situation in the three constructed sludge treatment facilities, still occupied the dominant position, by about 90%.

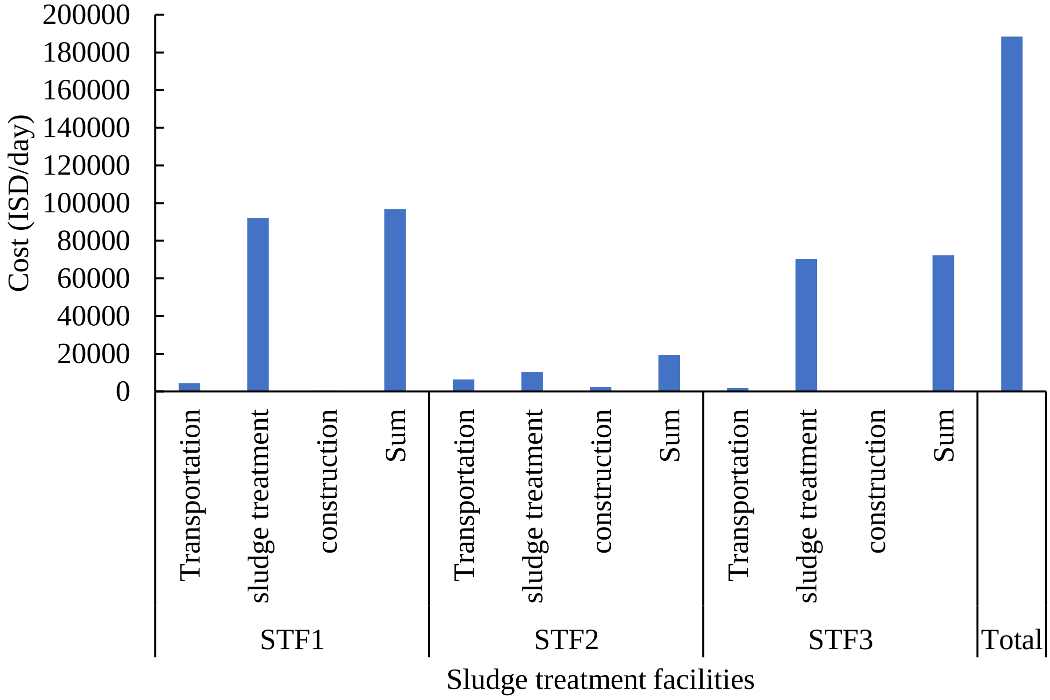


Figure 8.7 Optimal cost for each sludge treatment facility under the assumed situation

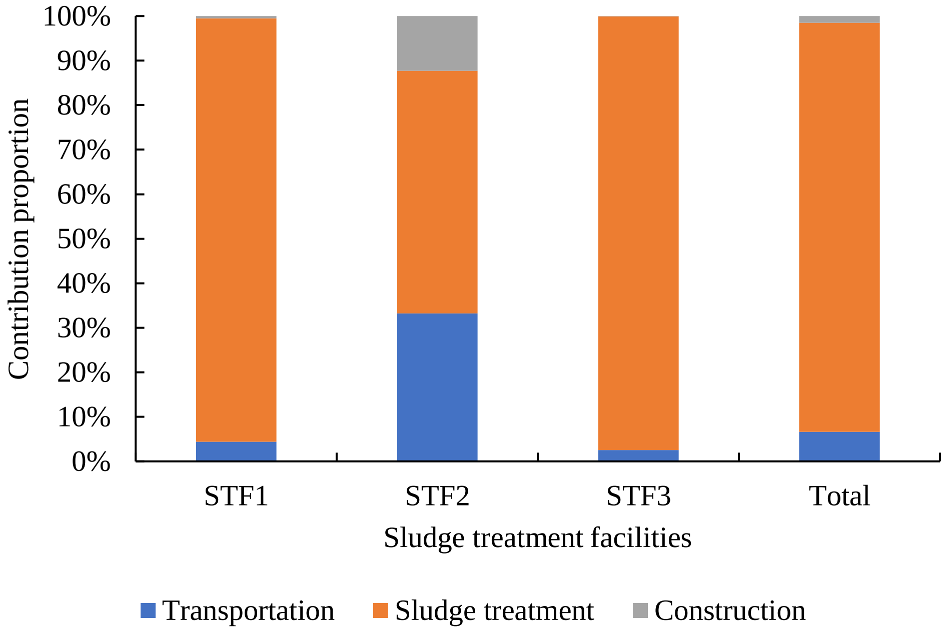


Figure 8.8 Contribution percentage of each part in the total cost for different sludge treatment facilities

8.4.3 Sensitivity analysis

The presented case study discussed the situation where only different types of technical routes can be selected by different sludge treatment facilities. This assumption was made based on the considerations that sometimes an advanced technology may require expensive equipment, extensive area, and additional energy supply at the construction stage and the municipality may be limited by the total budget for sludge treatment. It takes time for sludge treatment facilities to become profitable. Meanwhile, the assumption for “a similar technology cannot be used for all sites” is majorly set for the study of the situation where a region cannot afford multiple facilities with advanced technologies. The above assumption can be expressed as a constraint if there is a limitation on the budget for the sludge management system investment. The main consideration in the initial stage of investment is the construction cost for the sludge treatment facility. Hence, the limitation on the initial budget for sludge management system investment can be expressed as Eq. (8.18).

$$\sum_{j \in S} \sum_{t \in FT} w_{jt} \cdot CC_t \leq LC \tag{8.18}$$

where LC refers to the limited budget for the initial investment of sludge treatment facilities construction for the specific region. $\sum_{j \in S} \sum_{t \in FT} w_{jt} \cdot CC_t$ calculates the initial investment for the constructed sludge treatment facilities. This constraint can be added to the model to consider more complicated situation, which can be further discussed in the future work.

Sensitivity analysis was conducted to investigate the results under the situation where the different sludge treatment facilities can choose the same sludge treatment technical route, but they still can only choose one scenario. The influence of parameter variation, including amount of sludge generation and the capacity of sludge treatment facility, was also analyzed in this section.

8.4.3.1 Case 0: Same type of sludge treatment technology can be selected

When the same type of sludgy management route can be selected by different sludge treatment facilities, constraints (8.11) should be deleted from the original model while the others keep the same. By constituting the corresponding data into the model, optimization results can be similarly obtained. Case 0 worked as a contrast solution with the original case as well as the following two cases to investigate whether choosing the same technology can provide a better supply network design alternative. According to the optimization results, the arrangement for sludge transportation amount from sewage treatment works to each sludge treatment facility was the same as the results of initial case study (see Table 8.5), which indicated that the transportation plan between the first level (sewage treatment services) and the second level (sludge treatment facilities) put no influence on the selection of sludge treatment technology. In this stage, the objective was to find out the transportation plan which can achieve the minimum transportation costs between the two levels. All the STFs selected S2 for sludge major process. The summary and comparison of major results of original case and case 0 are shown in Table 8.8.

8.4.3.2 Case 1: Full-load operation of all the sewage treatment services

The situation where the total amount of sludge generation increased to the capacity of sewage treatment facilities was discussed. The eleven sewage treatment works were supposed to be full-load operation, while the other parameters were consistent with those in the case study. Corresponding capacity of each sewage treatment service can be found in the Table 8.1.

According to the model, four sludge treatment facilities were all constructed since the total amount of daily sludge generation is about 1700 t. In this situation, the optimal result can be obtained through the assignment shown in Table 8.7. Detailed optimization results are provided and can be referred in the Appendix Part VI (Table A6.1 and Table A6.2). The major results compared with other cases are listed in Table 8.8. Similarly, the situation of choosing the same type of sludge treatment technology was also analyzed and all the facilities still selected S2.

Table 8.7 Technical route selection of each sludge treatment facility in Case 1

	STF1	STF2	STF3	STF4
Adapted scenario	S4	S2	S3	S1

8.4.3.3 Case 2: Larger capacity of sludge treatment facilities

In this case, the capacity of sludge treatment facilities was supposed to be 1000 t/day and the other parameters were the same as initial assumptions. Transportation arrangement is shown in Table A6.3 and the corresponding transportation costs are presented in Table A6.4 in the Appendix Part VI. According to the results, there are only two sludge treatment facilities under operation (STF2 and STF3), because two sludge treatment facilities can satisfy the demand for the daily sludge generation and treatment. Scenario 2 was chosen by STF2 and Scenario 4 was adapted by STF3. Still, if the same type of technology can be selected, both facilities will use S2 as the sludge treatment technology. The optimization results of case 2 can be found in Table 8.8.

8.4.3.4 Optimization results comparison

The main optimization results of initial case study, case 1 and case 2, and their corresponding results of case 0 in sensitivity analysis, are collected and presented in

Table 8.8.

Table 8.8 Summary and comparison of the major optimization results of different cases (Unit: USD/day)

	Initial case study		Case 1		Case 2	
	Original model[a]	Case 0[b]	Original model[a]	Case 0[b]	Original model[a]	Case 0[b]
Total costs	188428	43095	460441	63729	65610	40327
TC	12478	11596	18625	17115	11367	11187
STC[c]	173080	24420	436587	37176	51398	24420
Construction costs	2870	7079	5230	9438	2845	4719

Note:

a Original model refers to the model that all the sludge treatment facilities can only select different sludge treatment technical route.

b Case 0 means the situation where the STFs in the corresponding case can select the same type of sludge treatment technologies.

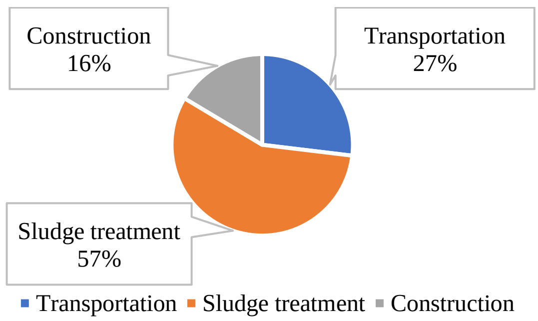
TC Transportation costs

c *STC* Sludge treatment costs with the consideration of-revenue but exclude construction costs for STF (*FC*-*R*-construction costs).

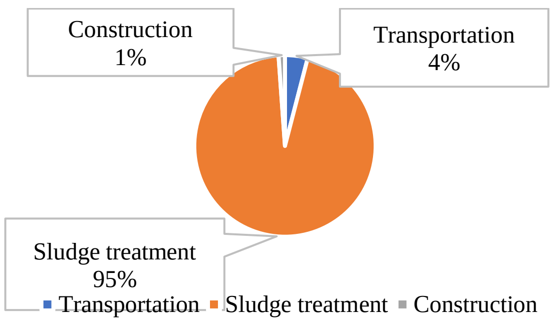
Based on the calculation results, several important conclusions can be drawn as follows.

- The optimization results of case 0 are significantly lower than the situations where sludge treatment facilities cannot select same sludge management technologies. If the same technology can be adapted by different sludge treatment facilities, the most advantageous alternative will be employed by all of them, that is S2 in this context.
- When the construction amount of sludge treatment facilities increases, the total costs also increase considerably.
- Increasing the capacity of sludge treatment facility can contribute to the reduction of total investment for sludge management.

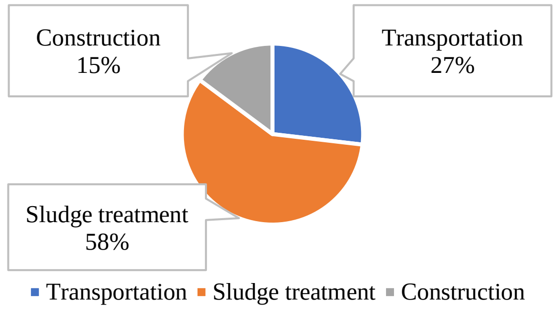
Compared with the original case study and Case 1, Case 2 provided with a relatively centralized management for the sludge management. Hence, it can be concluded that centralized management with suitable technology and a proper capacity for the daily treatment would contribute a lot on reducing the total costs for sludge management. Results also revealed that the majority of the total investments coming from the part responsible for sludge treatment no matter in case 0 or the original model. The proportions of transportation and construction are less significant compared with that of operation costs, especially for the original model. On the contrary, the percentage contribution of construction and transportation can nearly reach a half, as it is shown in Figure 8.9.



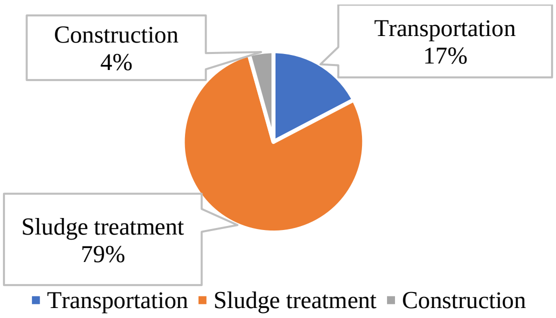
(a) Initial case study by the assumptions of Case 0



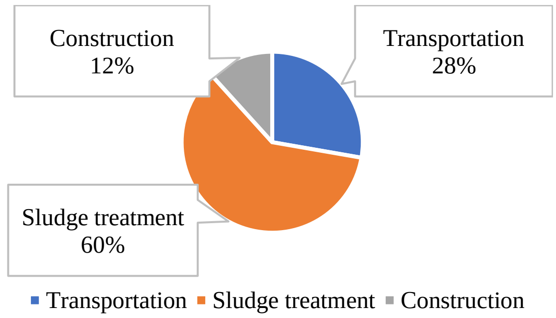
(b) Case 1 by the original model



(c) Case 1 by the assumptions of Case 0



(d) Case 2 by the original model



(e) Case 2 by the assumptions of Case 0

Figure 8.9 Proportion contribution of different costs under different situations

8.4.4 Implications

Results of case study verify the feasibility of the proposed model for solving the optimization problem of supply chain design for sludge-to-energy. The model can also be adjusted flexibly according to the requirement of the decision-makers to add some constraints, like the related regulations on emissions. Sensitivity analysis showed the flexibility of the model on adjusting the conditions and assumptions. Meanwhile, the optimization results obtained by different cases can provide valuable reference for decision makers in supply chain design for sludge management, which can be listed as follows.

- The costs of centralized treatment for sludge were lower than the total costs of several dispersed sludge treatment facilities for receiving and treating sludge. Considering the current assumptions, more sludge treatment facilities means higher costs for construction, especially when the advanced instrument and the facility require a fairly high cost of input. It could be more cost-effective to design a sludge treatment facility with a suitable daily capacity for the region to centrally treat all sludge generated in this area.
- Appropriate improvement of the daily capacity for sludge processing in the STF can also reduce the total cost if the conditions of plant and equipment permit. Sometimes the endless increase of daily processing capacity may bring great pressure to the equipment and facility as well as increase the costs. Detailed interactions and influences are still expected to be discussed in the future work.
- Adapting a suitable and cost-effective sludge-to-energy technology can contribute a lot to the reduction on the total costs, especially for the developed region with the accessibility for the technology and can afford the investment for the construction, operation, and maintenance. If it is less possible to build a centralized sludge treatment facility, adapting the same and more efficient technology in constructed plants can also benefit.

In this study, the optimal results suggested incineration followed by cement production is a more cost-effective approach for sludge valorization management. Although the capital cost of incineration for construction is the highest among all the options, it still shows many advantages for energy recovery and materials regeneration. On the one hand, there is considerable amount of energy recovery during the incineration process, where the waste heat can be reused to supply the energy for the total process, which can greatly offset the substantial amount of operating cost. On the other hand, despite the lowest construction of S3, the total operating cost is still close to the entire operating cost of S1 after considering the generated benefits. Scenario 4 indicates the similar situation. In spite of the relatively low operating cost and construction cost, the benefit is not so considerable, which may reveal the improvements for such technique are still expected, like optimizing technical conditions to reduce the cost, and improving the energy recovery efficiency. In addition, the sludge residues generated in the incineration process can be applied for cement production, which can not only eliminate the transportation expenditure for transporting the ash to another plant for final disposal, but also create considerable value as producing useful construction materials. It can avoid the soil pollution under proper process for the construction material production as well. Therefore, S2 is regarded as a suitable technical route for sludge management in Hong Kong.

Currently, the major sludge treatment technology in Hong Kong is the type of Scenario 1. Sanitary landfill is the main approach for the post treatment of residues. However, the result of this research suggests that employing cement production for the incinerated ash can significantly improve the total benefits as well as reducing the harmful environmental impact. This result was also consistent with the analysis of the research presented by Lam et al. (2016). In the study of Lam et al. (2016), detailed discussion for several sludge management technologies was conducted from the viewpoint of environmental life cycle assessment and life cycle costs, which provided persuasive evidence that incineration followed by cement production is a promising approach for sludge valorization utilization. As for the supply chain design, the sludge treatment facility in the practice is basically the same with the obtained optimal selection. The major difference is that there is only one STF in Hong Kong which is responsible for treatment of all the generated sludge in this city. Providing more STFs may bring convenience for the transportation if the investigated region covering a larger area. All in all, the result shows relatively high consistency with previous study and reality from different aspects, which reflect that the proposed methodology framework has enough flexibility and reliability for solving relevant problem.

8.5 Summary

In this chapter, an optimization model was proposed to solve the supply chain design problem for sludge valorization management. Four sludge-to-energy technical routes were considered as the alternatives. A case study based on the data and conditions in Hong Kong was conducted to verify the feasibility of the proposed model. Sensitivity analysis was also carried out to discuss the changing of the results under different assumptions. The optimization results indicated the feasibility of the constructing model for solving such kind of supply chain design problem and provided some valuable reference for the related management and decision-making. When different type of sludge treatment technology can only be selected by different sludge treatment facilities, the priority of the scenarios in descending order is S2, S4, S3, S1. If the same technology can be adapted in the different plants, S2 will be preferred by all the sludge treatment facilities. The results have a certain overlap with the current sludge supply chain design in Hong Kong, which also indicated the reliability of the optimization results obtained by the constructed model. However, it does not mean the results have not reference value for the current supply chain design in Hong Kong, since the adapting technical route in Hong Kong is similar to S1, not S2, which is more competitive in the context, leading to the necessity for the further improvement of sludge management in the city.

Some implications can also be obtained based on the optimization and sensitivity analysis results. Firstly, centralized management can contribute to the cost reduction for sludge treatment in the urban area since decentralized management may face with higher construction costs for new facilities. Secondly, suitable improvement on the daily capacity for sludge treatment in the STF can also help to cut down the expenses, which is correlated with the first implication. It should be noted that the capacity should be a little bit larger than the maximum demand of sludge treatment in the area, but it cannot be increased without limit because the expenses on the equipment and construction may can also increase significantly. In addition, adapting a cost-effective sludge treatment route would contribute a lot to the cost reduction and energy recovery. Sometimes centralized management may be limited by the local conditions, then permitting the different sludge treatment facilities employing the same cost-effective technology is also helpful for the sustainable supply chain management of sewage sludge. The implications obtained in this research are not only limited to the sludge management field, but it may also be applicable to the other types of biomass and waste with similar features, which could be a future working direction to demonstrate the feasibility.

The technology development status, regulations, and conditions can be highly depending on the investigated region, which usually requires the specific research to be conducted for the specific area. However, the cases presented and discussed in this chapter are still valuable because the results provided some general trends which reveal several universal laws of variation and also indicate the advantages of some sludge management technologies. Nevertheless, there are still some limitations in this research. The constructed model used a single objective function aiming to achieve the minimum total costs for sludge management with the consideration of environmental emissions, but there are at least three sustainability pillars can be included, that is environment, economic and society. In the different versions of the definition for sustainability, culture and technology may also be considered. Generating an overall index to reflect the entire sustainability performance of the constructed supply chain can contribute a lot to the sustainable development of sludge management. Future research may consider proposing a novel index or develop a multi-objective programming model to address the overall sustainability performance of the sludge-to-energy supply network and further provide a more comprehensive insight of the management system.

Chapter 9 Conclusions and Future Work

This chapter presents a summary of the project, covering the major contributions and limitations of the current research. Working direction for the future work is also proposed to guide the further development of relevant study.

9.1 Conclusions

This project constructed a systematical decision-support framework for sustainable sewage sludge management with life cycle thinking, covering sustainability evaluation for the alternatives, sustainability-oriented prioritization under different data conditions, and supply chain design. Proposed methods and models were verified through comprehensive case studies. Corresponding implications and suggestions were provided to guide the future sustainable management of sewage sludge.

Aiming to know about the development state-of-arts and the features of different sludge management technologies, a comprehensive literature review of sludge valorization technologies was conducted to preliminary understand the current development status of sludge treatment technologies, including biological processes (anaerobic digestion, fermentation, and MFCs) and thermochemical process (incineration, pyrolysis, gasification, and SCWG). Basic reaction process and core principles, influencing factors and the main products generated during the treatment process as well as their yields were introduced. According to the literature review, a qualitative assessment between the common techniques was also carried out to enhance the understanding of the techniques. Results showed that anaerobic digestion followed by incineration can still provide attractive performances on environmental and economic effect currently. However, with the development of the emerging technologies, such as microbial fuel cells, hydrogen production from sludge pyrolysis, gasification and SCWG, their strengths on the environmental and economic perspectives could be grow, especially on environmental impacts. All these facts reveal the necessity of continuing to promote the development of sludge-to-energy technologies in order to realize sustainable management of sewage sludge and contribute to the sustainable development of the entire society.

To address the energy flow and footprints of major elements of sludge management alternatives, a life cycle composite footprints index was proposed covering energy, water, and the footprints of other concerned elements. Fuzzy BWM and fuzzy AHP were applied to generate the fuzzy weights of the criteria and further to obtain the overall scores of the investigated alternatives. A case study with six sludge-to-energy scenarios was conducted to evaluate the sustainability performances by using the proposed composite index from the perspectives of energy efficiency, carbon missions and water consumptions. The impact of weighting changes was investigated by sensitivity analysis. Uncertainty analysis was also conducted to investigate the impact of parameters changing. Results indicated the feasibility of proposed index to evaluate the sustainability performance of sludge-to-energy alternatives and revealed the advantages and shortcomings of the evaluated scenarios, which could facilitate the development of sludge treatment technologies as well as sustainable sludge management.

To deal with the problem of lacking data in sustainability evaluation and uncertain preferences and descriptions in decision-making process for sludge management, a decision-analysis framework was established based on process simulation and fuzzy MCDA methods. Process simulation provides basic performance data of the investigated alternatives for sustainability assessment. Four dimensions of sustainability were considered as the criteria system for the overall performance evaluation, including eleven sub-indicators. Fuzzy weights of the criteria were decided based on the preferences of stakeholders by using fuzzy BWM. Afterwards, a complete ranking for all the alternatives can be obtained according to the evaluation results and corresponding weights by applying fuzzy PROMETHEE II approach. A case study which investigated four sludge valorization technologies was conducted to demonstrate the feasibility of the proposed framework. Results suggested that gasification was more preferred in this context, followed by supercritical water gasification with energy recovery, which is also a promise method for sustainable sludge management. Sensitivity analysis was also carried out to study the influences of weighting changes and the choice on preference rules on the final ranking. Results indicate the robustness and stability of the constructed framework. Insightful suggestions and implications can also be provided based on the analysis results, which can contribute a lot to the sustainable management of sewage sludge.

In order to solve the decision-making problem with multi-data conditions in the context of sludge management, a new decision-making framework called DS-FBWM was constructed based on Dempster-Shafer theory and fuzzy best-worst method. The considered hybrid data conditions include crisp numbers, interval numbers, linguistic descriptions, and missing information. Four dimensions in sustainability and thirteen criteria were considered to form the criteria system for the performance assessment. DS theory was applied to address the missing information and fuzzy BWM was employed to calculate the weights according to the preferences of stakeholders. A case study with four sludge-to-electricity technologies was analyzed by the proposed framework, including sludge incineration with power generation, biogas from sludge digestion for electricity generation by fuel cells, MFCs for sludge treatment with electricity production. Extended VIKOR method for interval numbers was also utilized to validate the ranking results of the proposed model. Results suggested sludge incineration for electricity generation is preferred under the context and MFCs is inferior due to the current development status. By comparing of the ranking results between the proposed model and the extended VIKOR method, the feasibility, flexibility, applicability of the proposed method can be validated for solving the decision-making problem under multi-data conditions, especially the situation with incomplete information.

A group decision-making framework was developed based on game theory and MCDA methods to solve the decision-making problem with multiple criteria and conflicting interests for sustainable sludge management. Besides environmental and economic aspects, which were frequently discussed in the previous studies, social and technical indicators were also covered in the criteria system for the performance evaluation. In the proposed model, an individual and group fuzzy BWM was utilized to obtain the weights of criteria, which is a flexible approach to both individual and group decision-making. Based on the performance data and preferences of different stakeholders, payoff matrix can be obtained for the further analysis. A case study with a two-player game was investigated to verify the feasibility and reliability of the proposed model. Each player has the same four sludge valorization technical routes as the alternative strategies. Results revealed that biogas for electricity generation through fuel cells can be attractive when the environmental impacts are emphasized. The influences of weighting changes and parameters' uncertainty on the decision analysis result were explored by sensitivity analysis. According to the analysis results and discussion, the proposed model showed a relatively great robustness and stability, which can also provide a useful suggestion for the different groups of decision-makers and help them to reach a final consensus.

To develop a sustainable supply chain for sludge valorization management, an optimization model was built up based on a mixed-integer programming model for the supply chain model with a three-layer topological structure. Aiming at minimizing the expenditure of the overall system, the generation of the sewage sludge and treatment demands as well as the requirements on the emissions are considered as the constraints. Sludge distribution from sewage treatment services to the sludge treatment facilities, technical route selection, and construction location selection can be solved by the proposed model. Four sludge-to-energy technical routes were considered as the alternatives in the case study of Hong Kong. Based on the specific data conditions and assumptions in the city, results showed that selecting a most cost-effective sludge management technical route and conducting centralized management in a suitable facility with proper daily treatment capacity would contribute to the total costs reduction. Sensitivity analysis was also conducted to discuss the impact of assumptions changing. Both the optimization results and outcomes of the sensitivity analysis indicated the feasibility and reliability of the constructed model for supply chain design problem, which also provide some useful suggestions and implications for the better sustainable development of sludge management in Hong Kong based on the current situation. The flexibility of the model also provides the possibility for the application in the similar field for sustainable supply network design.

In terms of the overall structure and content, this project provides a relatively complete and comprehensive framework to support sustainable management of sludge valorization technologies. Starting with literature review, the state-of-arts of the current sludge management technologies were investigated, including the traditional techniques as well as the emerging technologies. According to the literature review, several important research problems were pointed out and research objectives were correspondingly set to address the problems. Firstly, a composite footprint-index which can reflect the performance of sludge-to-energy technologies from the perspective of energy recovery and environment. The proposed index can not only provide important reference information for decision-making, but also can promote the improvement and optimization of the sludge treatment process. Then, in order to deal with the sustainability evaluation and decision-making problem facing with data insufficient situation, a fuzzy MCDA method based on process simulation with life cycle thinking for performance assessment was established. With this framework, data insufficiency problem for emerging technologies can be effectively solved and the process simulation results can be regarded as important data reference for technology improvement and decision-making. Besides the problem of initial data insufficiency, multi-data conditions are also common in the practice of decision-making process. To deal with this kind of problem, DS-FBWM was developed which can handle the decision-making problems with crisp numbers, interval number, linguistic terms, and missing information. The proposed methodology framework can significantly promote development of sustainable decision-making process and provide useful reference information under uncertainty. More complicated situation may occur when there are different groups of stakeholders with conflicting interests involved in decision-making process. Therefore, a decision-making approach of individual and group MCDA combined with game theory was proposed to process decision-making problems with multi-stakeholders. It has the ability to flexibly obtain the overall opinions of an entire group of stakeholders and help the involved players to reach a consensus on their final selection of sludge management technology. Finally, aiming at minimizing the daily costs, a supply chain design and optimization model was developed for sustainable sludge valorization technologies management. The established model can solve the problems of technique route selection, transportation amount arrangement, and location selection with the consideration of sewage sludge treatment demands and requirement on environment emissions. The model can provide suggestions and references for better sustainable management of sludge valorization technologies from a more macroscopic point of view. All in all, these approaches can provide effective solutions to solve different decision-making problems flexibly and also indicate meaningful reference information and implications for the future development of the related research and industry through various case studies in the practice. The cases can not only verify the feasibility, applicability, and reliability of the proposed models, but also provide profound insights to guide the practice and application in sustainable sludge management. Therefore, this research can contribute to the development of the related studies for the researchers and sustainable development for the policymakers by the suggestions and implications.

9.2 Limitations and future work

Although many complicated scenarios have been discussed in this research, there are still some limitations in this work which can be considered as working directions for the improvement in the future work. The limitations mainly reflect in the following two perspectives.

1. It lacks the analysis for the dynamic life cycle assessment as the basis for the decision-making framework. Current research focuses on the static analysis without considering the temporal effects, especially for the environmental emissions, which could further influence the result of decision-making. In the future, a dynamic life cycle assessment approach could be constructed and integrated into the decision-support framework to help the decision-makers deal with the problem when considering the temporal effects.
2. It lacks the dynamic analysis for long-term decision making, although the project

has investigated the situation where the interactions between stakeholders are considered by game theory. Since the technology selection usually involves with long-term application of the specific technology, it is necessary to discuss the influences of different uncertainty regarding to the criteria weightings, which indicates the variations on preferences. A dynamic MCDM framework could be developed in the future to address the sludge management problems with the consideration of different possible states that can affect the preferences of the stakeholders to promote the entire long-term decision-making process.

3. It lacks the consideration of other sustainability pillars for the supply chain design and optimization, such as social and technical aspects. Although a programming model is constructed which covers costs and benefits analysis and emission requirements, it is still necessary to further explore the overall sustainability performance in order to achieve better sustainable management of sludge supply chain. An overall index with the consideration of various sustainability aspects can be constructed as the objective function to address the entire sustainability performance for the supply chain as a future working direction. Multi-objective programming model can also be considered as an approach to solve the problem and improve the related research on sustainable supply chain management.

Besides the above limitations, how the outcomes can be applied in the real world is another necessary problem to be further discussed. The major contributions of this research include different decision-support frameworks which can be utilized under various complex situations and provide important reference information for scientific decision-making. Generally, the application and promotion of the outcomes in this research can start from the upper level of policy and development direction for the government from a macroscopic perspective. The decision-making results can provide reference for policy making of the government which can be work as the guideline for the enterprises to implement specific treatment process. With the support and guidance of the policy, cooperation relationship with sludge treatment enterprises can be established. Based on the constructed process simulation model, sustainability assessment approaches, and decision-making frameworks, reference information on technology selection and scheme optimization can be provided for the industries. Pilot application can be firstly conducted before wide-scale application to collect and enrich the industry database of sludge treatment technologies, especially for the emerging technologies. The feedback of the practice will be combined with process simulation results to adjust and improve the accuracy and reliability of the entire model. The improved model and enriched database can be the basis for the further promotion and application in more related facilities and enterprises.

In addition, since the decision-making process usually involves with different parties of stakeholders, another issue should be investigated is about how the findings of this research can benefit them. To solve this problem, a few challenges should be first identified, which have been listed as follows:

- The first challenge is the information gap and expertise gaps between researchers and decision-makers. It is necessary to discuss how to make the research outcomes quickly recognized and accepted by the decision-makers who may not possess the same level of professional background knowledge as the scholars.

- How to obtain the necessary information from stakeholders effectively and accurately and provide the desired results to them.

For the first challenge, a figure which can illustrate the entire framework of the methodology in a terse and concise way can contribute to the understanding of the outcomes of this research. Some key nodes and links can be shown in the figure which can help them to have a clear idea on the major steps. Detailed descriptions on the principles and calculation may not be the focus, and the importance can be attached to the results obtained by the methods and whether they are satisfactory. The reliability, risks and related benefits are also their concerned. The focused points of stakeholders and decision-makers should be introduced and explained in detailed.

The solution for the second challenge is similar to the first one and the key point is to make stakeholders clear that what conclusions and results they can obtain by providing what kinds of information to the framework. A possible to solve this problem is to construct an interaction platform based on a database with enormous amount of industrial data for sewage sludge treatment processes. This platform can provide decision support according to the industrial data and the preferences and technical information provided by the users (stakeholders or decision-makers). And the different groups of stakeholders can be directed to different interface for the information input and decision recommendation based on their interests and preferences. The stakeholders can choose the most suitable option from the list presented in the platform which can describe their needs most aptly. Afterwards, the platform will analyze according to the requirements of users and database and generate recommendations for decision-making. Possible benefits and influences can also be obtained to provide more reference information and evidence for the decision-makers. Constructing such an interaction platform is a possible and effective way to improve the efficiency of decision-making as well as the promotion of the methodology frameworks established in this research. Future work may consider the feasibility and specific measures for the construction of such a platform as well as other possible approaches to solve the problems for generalization.

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Appendices

Contents

Appendix Part I: Overview of the concepts of sustainability, sustainable development, sustainability assessment methods and the application on sludge management

Table A1.1 Brief description of different category of sustainability evaluation methods

Category	Definition	Remarks
Individual/set of indices	The methods that use a single or a set of indices to address the sustainability perfromance on different aspect (Angelakoglou and Gaidajis, 2015).	- Also be regarded as key performance indicators (KPIs) if the indicators are choosed according to predefined organizational objectives and applied for progress evaluation on the major aspects of the investigated systems.
Composite indicators	The methods that diverse indicators are combined and used in a defined methodology as sub-indices or a signle index for sustainability evaluation (Angelakoglou and Gaidajis, 2015).	- Involving steps include normalzation, weighting, and aggregation. - The maajor calculation process could be subjective. Uncertainty and sensitivity analysis are usually combined to healp improve the robustness of the methods (Singh et al., 2009).
Socially responsible investment (SRI) indicators	The methods based on the indeces which are frequently applied by external staeholders to evaluate sustainability performance for the concerned customers-industries (Angelakoglou and Gaidajis, 2015). SRI may also be defined as a type of investment discipline or style which is attached with more importance on social or environmental aspect (Russell, 2008).	- It can work as social indicators to address the social and economic sustainability performance and be combiend with composite indices (Angelakoglou and Gaidajis, 2015). - SRI indicators can help to promote ethical and socially concerned issues, such as environmental sustainability, social justice, and corporate ethics (Russell, 2008).
Energy and materials flow analysis (EMFA)	The methods address sustainability performance through quantifying the material and/or energy flows of the investigated systems (Angelakoglou and Gaidajis, 2015).	- Can be futher classified into material flow analysis (MFA) and energy flow analysis (EFA) (Angelakoglou and Gaidajis, 2015). - The principle of this category of methods is the law of investigation of mass and energy to evaluate the flows of concerned materials and energy.

		- The combination of EMFA and LCA can improve accuarcy and relevance
Environmental accounting	The methods address sustainability performance through converting the environmental costs and benefits to economic value (Angelakoglou and Gaidajis, 2015; Willet et al., 2019).	- The category of methods can contribute to the evaluation process if the monetization of ecosystem services is relatively complete and can be fully captured (Willet et al., 2019). - Lack of obligatory independent assessment can limit the reliability and quality of the assessment results obtained from EA (Willet et al., 2019). - Can be combined with other methods and further improve the effectiveness (Gómez-Baggethun and Ruiz-Pérez, 2011).
LCA & MCDM	LCA refers to the methods that invlove life cycle thinking (Angelakoglou and Gaidajis, 2015). MCDM methods can assess the examined alternatives under multiple conflicting criteria.	- LCA shows the advantage on providing a comprehensive and stuctured evaluation on the enironmental impacts and benefits. However, it fails to assess different systems in different scale and region and is also easy to be limited by other conditions beyond geographic system boundaries (Willet et al., 2019). - MCDM or MCDA is a powerful tool to conduct ranking and sustainability evaluation for diverse systems due to the flexibility and ability of dealing with the interactions and dialogue between stakeholders (Cinelli et al., 2014).

Table A1.2 Brief description of different sustainability assessment methods

Category	Assessment approach	Description
Indicators set	IChemE Sustainable Development Progress Metrices (IChemE)	Provide measurement for sustainability performance of industrial facilities in different scales by a set of indicators .
	Indicators of Sustainable Production (ISP)	Based on a group of major amd supplemental indicators which can contribute to the measurement of sustainable production systems (Veleva and Ellenbecker, 2001).

	Sustainability Assessment Framework for Industries (SAFI)	Provide general guidance for the selection on assessed criteria aming at reliable and objective sustainability evaluation (Labuschagne et al., 2005).
Composite indicators	AIChE Sustainability Index (AIChE SI)	Evaluating the sustainability performance of an industry based on seven sustainability-oriented categories (Angelakoglou and Gaidajis, 2015).
	BASF Method (BASF)	A cradle-to-grave assessment which investigates the environmental behavior and influence on human health and ecosystems stability (Saling et al., 2002).
	Compass Index of Sustainability (COMPASS)	Evaluating the sustainability of investigated industry through four aspects, inclufing nature (N), economy (E), society (S) and well-being (W) (Angelakoglou and Gaidajis, 2015).
	Compliment Index (COMPLIMENT)	A comprehensive method for sustainability assessment which combines LCA, multi-criteri analysis and evironmental indicators (Hermann et al., 2007).
	Other methods	More summarization on composite indicators can be found in the previous reviews (Angelakoglou and Gaidajis, 2015; Singh et al., 2009).
Socially responsible investment indicators	Dow Jones Sustainability Index (DJSI)	Pre-defined sustainability criteria are applied to evaluate sustainability performance of the industries according to a best-in-class method (RobecoSAM, 2013).
	FTSE4Good Index (FTSE)	A method to evaluate the performance on industries which satisfy the globally accepted responsibility standards and find out the industries with outstanding performance on environmental aspect (Angelakoglou and Gaidajis, 2015).
	OEKOM Corporate Rating (OEKOM)	A method to evaluate and prioritize industries based on their environmental and social sustainability performance (Angelakoglou and Gaidajis, 2015).
Energy and matters flow analysis	Material flow analysis: ecological footprint (EF), material inputs per service and ecological rucksack (MIPS), substance flow analysis (SFA), etc.	1. EF method assesses the requirement of theoretical area in global hectares for consumed resources production and wastes assimilation (Wackernagel and Rees, 1996). 2. MIPS method assesses the possible environmental influence of the useful output of a product with respect to its material and energy input (Moll and Schmidt-bleek, 1998; Schmidt-Bleek, 2001). 3. SFA method detects and monitors the flows of substances that put considerable impact on environmental and heal risks during their production and consumption process (Brunner, 2012; Huang et al., 2012).

	Energy flow analysis: cumulative energy demand (CED), embodied energy (EE), emergy analysis (EA)	1. CED method evaluates the performance of the investigated system based on the estimation of the direct and indirect energy consumption throughout the entire life cycle (i.e., extraction. treatment and disposal) (Huijbregts et al., 2006). 2. EE method evaluates the sum of the direct and indirect energy consumption for the production of a specfic product/service (Brown and Herendeen, 1996; Brown and Ulgiati, 2004). 3. EA method estimates the energy consumption of one kind (usually refer to the solar energy) in transformation to produce a product/service including direct and indirect way (Brown and Ulgiati, 2004).
Environmental accounting	Cost-benefit analysis (CBA)	A method provides specific calculation procedure to examine the benefits and costs of the investigated process or project (Hanley and Spash, 1993; Poveda and Lipsett, 2011).
	Contingent valuation method (CVM)	A survey-based approach which evaluates the willingness to pay or accept for environmental improvements or environmental quality reduction (Poveda and Lipsett, 2011; Venkatachalam, 2004).
	Environmental management accounting (EMA)	A general method which evaluates environmental and economic performances through assessing environmental costs accounting and physical environmental flows analysis (Angelakoglou and Gaidajis, 2015; Gibassier and Alcouffe, 2018).
Life cycle sustainability analysis (LCSA) & MCDM	Signle aspect/generic framework: Briges to sustainability (BRIDGES), Carbon footprint (CF), Ecosystem Damage Potential (EDP), Life cycle sustainability dashboard (LCSD), USES-LCA.	1. BRIDGES: a general assessment framework to evaluate environmental, economic and social sustainability performance covering multiple life cycle stages. It emphasizes the importance of resource scarcity, overabundance and possible influence (Beloff et al., 2004). 2. CF: an estimation method of greenhouse gases emissions expressed in CO_2 equivalents (Pandey et al., 2011). 3. EDP: a model can assess the impact on ecosystems resulted from land occupation and land transformation (Koellner and Scholz, 2008, 2007).

	4. LCSD: a method with general guidelines for the revision to benchmark the products' sustainability (Traverso et al., 2012). 5. USES-LCA: a method of impact evaluation of exotoxicity and human toxicity on both midpoint and endpoint levels (Huijbregts et al., 2000; Van Zelm et al., 2009).
Multi-impact assessment (CML 2001, Eco-Indicators 99, EDIP 2003, EPS 2000, IMPACT 2002+, LIME, ReCiPe, TRACI)	1. CML 2000, IMPACT 2000 and ReCipe are frequently used in evaluation for renewable energy (Campos-Guzmán et al., 2019). 2. Climiate change, acidification and photooxidants formation are three often considered ondicators for renewable energy assessment (Campos-Guzmán et al., 2019). 3. CML 2001 replied a midpoint approach based on the standards of ISO 14040, while Eco-indicator 99 folows an endpoint method (Campos-Guzmán et al., 2019). 4. EDIP 2003: a midpoint method concerntrated on damage assessment. 5. EPS 2000 evaluates five impact categories on midpoint and endipoint. 6. Impact 2002+ combines IMPACT2002, Eco-indicator 99, CML and IPCC approaches considering both midpoint and endpoint.
Life cycle costs (LCC) & social life cycle sustainability assessment (SLCA)	LCA, LCC, and SLCA address the sustainability performance on environment, economy, and society, respectively (Ciroth et al., 2011; Colantonio, 2009; Sala et al., 2013b).
MCDM (Multi-attribute decisio- making, MADM; Multi-objective decision-making, MODM)	1. MADM focuses on the decision-making problems with finite alternatives while MODM considers more than two alternatives. 2. Criteria: technical, economic, environmental, social (Campos-Guzmán et al., 2019)(Wang et al., 2009).

3. Weighting methods: subjective weighting methods, objective weighting methods, and combination of both (Wang et al., 2009).

4. Multi-criteria decision analysis: elementary methods, unique synthesizing criteria methods, and the outranking methods (Cinelli et al., 2014; Wang et al., 2009).

5. Frequently applied methods: AHP and related combination or improved methods, TOPSIS, VIKOR (Campos-Guzmán et al., 2019).

6. Combined with other theory or tools: fuzzy theory (Abdullah, 2013; Mardani et al., 2015a), Data Envelopment Analysis (DEA), grey relation analysis, etc. (Renganath and Suresh, 2017).

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Appendix Part II: Life Cycle Energy-Carbon-Water Nexus Analysis of Sludge-to-Electricity Technologies

I. Case study

Table A2.1 Characteristics of sludge treated by different step (Hong et al., 2009)

Characteristic		Value	Unit
Water content in	Injected sludge	99	% w/w
	Machine thickened sludge	96	% w/w
	Gravity thickened sludge	98	% w/w
	Dewatered sludge	80	% w/w
	Composted sludge	40	% w/w
	Dried sludge	10	% w/w
	Incinerated and melted residues	0	% w/w
Digestion rate		50	% w/w

Table A2.2 Energy and materials consumed during each sludge treatment process (Hong et al., 2009) (presented by functional unit)

	Unit	Machine thickening	Anaerobic digestion	Dewatering	Compost	Drying	Incineration[a]	Electric melting[b]	Gasification & melting[c]
Electricity consumed	kWh	179	223	70	70	118	304.8	95.2	372.9
Electricity generation[d]	kWh		72.7				928.5		1.3×10^3
Heat consumed	kWh					1.6×10^3			
Natural gas consumed	m^3						46.5		
CO_2 emissions	g		4.5×10^5				3.7×10^5		

a: Equipment for incineration was fluidized bed.

b: Electric melting was applied to treat incinerated ash.

c: Facility for gasification was fluidized bed. This process was directly used to treat sludge.

d: Electricity was generated from biogas and waste heat.

Data Source

Related data were collected from previous literature. Inventory data were directly obtained from the records of Hong et al. (2009). The greenhouse gases emissions and water consumptions in the process of electricity generation from coal combustion were collected from a previous paper (Chang et al., 2015). The data of lower heating value of sewage sludge and carbon content were from an estimation work (Cooper et al., 1999). Gas consumption from the reference (Hong et al., 2009) was regarded to be natural gas (NG) and the corresponding lower heating value was selected to be 47.141 MJ/kg ("Lower and higher heating values of gas, liquid and solid fuels," 2011). Water consumptions and CO_2 emissions during the process of natural gas production was supposed to be 9 L/GJ NG (Clark et al., 2013) and 1.301 kg/GJ NG (Burnham et al., 2012), respectively. Lower heating value of standard coal equivalent was collected from a general report as 29.307 MJ/kg coal equivalent (ce) (Standardization Administration of the People's Republic of China, 2008). In addition, direct CO_2 emissions and water generation from natural gas (gas-field gas) combustion were calculated according to the equivalent coefficient of standard coal (Standardization Administration of the People's Republic of China, 2008). As for the CO_2 emissions from standard coal combustion, it was calculated to be 2.54 t CO_2/t ce, that is 86.669 kg CO_2/GJ ce (Tu and Liu, 2014). Assumed that the standard coal equivalent consists of 5% H element and the moisture is 5%, then the water generation from the full combustion of coal can be obtained as 500 kg/t ce, that is 17.061 kg/GJ. Data regarding the coal production was calculated based on the previous records (Fan, 2017). Carbon dioxide was regarded as a kind of energy carrier with a capacity of 6.28 MJ/m^3 (Standardization Administration of the People's Republic of China, 2008) and the density of CO_2 was supposed to be 1.977 kg/m^3.

Fuzzy Best-Worst Method

Table A2.3 The linguistic terms of the fuzzy preferences of the best criteria to the other two criteria

Criteria	Energy recovery	Carbon emissions	Water consumptions
Best criteria - Energy recovery	Equally importance	Fairly importance	Very importance

Table A2.4 The linguistic description of the fuzzy preference of the other criteria to the worst criteria

Criteria	Worst criteria – Water consumptions
Energy recovery	Very important
Carbon emissions	Weakly important
Water consumptions	Equally important

II. Sensitivity analysis

Table A2.5 Weights assignment of Group A

	A1	A2	A3	A4	A5	A6	A7	A8
ω_e	0.1	0.2	0.34	0.4	0.5	0.6	0.7	0.8
ω_c	0.45	0.4	0.33	0.3	0.25	0.2	0.15	0.1
ω_w	0.45	0.4	0.33	0.3	0.25	0.2	0.15	0.1

Table A2.6 Weights assignment of Group B

	B1	B2	B3	B4	B5	B6	B7	B8
ω_e	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1
ω_c	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
ω_w	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1

Table A2.7 Weights assignment of Group C

	C1	C2	C3	C4	C5	C6	C7	C8
ω_e	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1
ω_c	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1
ω_w	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8

III. Uncertainty analysis

Table A2.8 Energy recovery efficiency of each situation for different amount of energy recovery from AD (data in parentheses is the difference between the original data in the case study)

Coefficient	T	TC	TD	TI	TIM	TM
0.75	1.17% (-0.39%)	1.15% (-0.38%)	0.85% (-0.28)	18.08% (-0.33%)	17.77% (-0.33%)	26.85% (-0.36%)
1	1.56%	1.53%	1.14%	18.42%	18.10%	27.21%
1.25	1.95% (0.39%)	1.92% (0.38%)	1.42% (0.28%)	18.75% (0.33%)	18.43% (0.33%)	27.57 (0.36%)
1.5	2.33% (0.78%)	2.30% (0.77%)	1.71% (0.57%)	19.09% (0.67%)	18.76% (0.66%)	27.93% (0.72%)
1.75	2.72% (1.17%)	2.68% (1.15%)	1.99% (0.85%)	19.42% (1.00%)	19.09% (0.99%)	28.29% (1.08%)
2	3.11%	3.07%	2.28%	19.76%	19.42%	28.65%

	(1.56%)	(1.53%)	(1.14%)	(1.34%)	(1.31%)	(1.44%)
2.25	3.50%	3.45%	2.56%	20.09%	19.75%	29.01%
	(1.95%)	(1.92%)	(1.42%)	(1.67%)	(1.64%)	(1.80%)
2.5	3.89%	3.83%	2.84%	20.43%	20.07%	29.37%
	(2.33%)	(2.30%)	(1.71%)	(2.01%)	(1.97%)	(2.16%)
2.75	4.28%	4.22%	3.13%	20.76%	20.40%	29.73%
	(2.72%)	(2.68%)	(1.99%)	(2.34%)	(2.30%)	(2.525)
3	4.67%	4.60%	3.41%	21.09%	20.73%	30.09%
	(3.11%)	(3.07%)	(2.28%)	(2.67%)	(2.63%)	(2.88%)
3.25	5.06%	4.98%	3.70%	21.43%	21.06%	30.45%
	(3.50%)	(3.45%)	(2.56%)	(3.01%)	(2.96%)	(3.24%)
3.5	5.45%	5.37%	3.98%	21.76%	21.39%	30.81%
	(3.89%)	(3.83%)	(2.84%)	(3.34%)	(3.29%)	(3.60%)
3.75	5.84%	5.75%	4.27%	22.10%	21.72%	31.17%
	(4.28%)	(4.22%)	(3.13%)	(3.68%)	(3.61%)	(3.96%)
4	6.22%	6.13%	4.55%	22.43%	22.05%	31.53%
	(4.67%)	(4.60%)	(3.41%)	(4.01%)	(3.94%)	(4.32%)
4.25	6.61%	6.52%	4.84%	22.77%	22.37%	31.89%
	(5.06%)	(4.98%)	(3.70%)	(4.35%)	(4.27%)	(4.68%)
4.5	7.00%	6.90%	5.12%	23.10%	22.70%	32.26%
	(5.45%)	(5.37%)	(3.98%)	(4.68%)	(4.60%)	(5.04)

Table A2.9 The score of energy recovery of each situation for different amount of energy recovery from AD (data in parentheses is the difference between the original data in the case study)

Coefficient	T	TC	TD	TI	TIM	TM
0.75	0.0121	0.0114	0	0.6628	0.6508	1
	(-0.0040)	(-0.0038)	(0)	(1.318E-05)	(0.0002)	(0)
1	0.0160	0.0152	0	0.6628	0.6506	1
1.25	0.0200	0.0189	0	0.6628	0.6504	1
	(0.0040)	(0.0037)	(0)	(-1.31E-05)	(-0.0002)	(0)
1.5	0.0239	0.0226	0	0.6628	0.6502	1
	(0.0079)	(0.0075)	(0)	(-2.61E-05)	(-0.0004)	(0)
1.75	0.0278	0.0263	0	0.6628	0.6500	1
	(0.0118)	(0.0111)	(0)	(-3.91E-05)	(-0.0006)	(0)
2	0.0317	0.0300	0	0.6627	0.6499	1
	(0.0157)	(0.0148)	(0)	(-5.19E-05)	(-0.0008)	(0)
2.25	0.0356	0.0336	0	0.6627	0.6497	1
	(0.0195)	(0.0185)	(0)	(-6.47E-05)	(-0.0010)	(0)
2.5	0.0394	0.0373	0	0.6627	0.6495	1
	(0.0234)	(0.0221)	(0)	(-7.75E-05)	(-0.0012)	(0)
2.75	0.0432	0.0409	0	0.6627	0.6493	1
	(0.0272)	(0.0257)	(0)	(-9.01E-05)	(-0.0014)	(0)
3	0.0470	0.0445	0	0.6627	0.6491	1
	(0.0310)	(0.0293)	(0)	(-0.0001)	(-0.0016)	(0)
3.25	0.0508	0.0480	0	0.6627	0.6489	1
	(0.0348)	(0.0329)	(0)	(-0.0001)	(-0.0017)	(0)
3.5	0.0546	0.0516	0	0.6627	0.6487	1
	(0.0385)	(0.0364)	(0)	(-0.0001)	(-0.0019)	(0)
3.75	0.0583	0.0551	0	0.6627	0.6485	1
	(0.0423)	(0.0399)	(0)	(-0.0001)	(-0.0021)	(0)
4	0.0620	0.0586	0	0.6626	0.6483	1
	(0.0460)	(0.0435)	(0)	(-0.0002)	(-0.0023)	(0)
4.25	0.0657	0.0621	0	0.6626	0.6482	1
	(0.0497)	(0.0469)	(0)	(-0.0002)	(-0.0025)	(0)
4.5	0.0694	0.0656	0	0.6626	0.6480	1
	(0.0533)	(0.0504)	(0)	(-0.0002)	(-0.0027)	(0)

Table A2.10 Energy recovery efficiency of each situation for different LHV of sewage sludge (data in parentheses is the difference between the original data in the case study)

Coefficient	T	TC	TD	TI	TIM	TM
0.8	1.90% (0.34%)	1.86% (0.33%)	1.31% (0.17%)	21.79% (3.37%)	21.34% (3.24%)	32.65% (5.44%)
0.85	1.80% (0.24%)	1.77% (0.23%)	1.26% (0.12%)	20.83% (2.41%)	20.43% (2.33%)	31.09% (3.88%)
0.9	1.71% (0.15%)	1.68% (0.15%)	1.22% (0.08%)	19.96% (1.54%)	19.59% (1.49%)	29.68% (2.47%)
0.95	1.63% (0.07%)	1.60% (0.07%)	1.18% (0.04%)	19.16% (0.74%)	18.82% (0.71%)	28.39% (1.18%)
1	1.56%	1.53%	1.14%	18.42%	18.10%	27.21%
1.05	1.49% (-0.07%)	1.47% (-0.07%)	1.10% (-0.04%)	17.73% (-0.69%)	17.44% (-0.66%)	26.12% (-1.09%)
1.1	1.43% (-0.13%)	1.41% (-0.12%)	1.07% (-0.07%)	17.10% (-1.32%)	16.82% (-1.28%)	25.12% (-2.09%)
1.15	1.37% (-0.18%)	1.35% (-0.18%)	1.04% (-0.10%)	16.51% (-1.91%)	16.25% (-1.85%)	24.19% (-3.02%)
1.2	1.32% (-0.24%)	1.30% (-0.23%)	1.01% (-0.13%)	15.95% (-2.47%)	15.72% (-2.39%)	23.33% (-3.88%)

Table A2.11 The score of energy recovery of each situation for different LHV of sewage sludge (data in parentheses is the difference between the original data in the case study)

Coefficient	T	TC	TD	TI	TIM	TM
0.8	0.0187 (0.0027)	0.0177 (0.0025)	0 (0)	0.6534 (-0.0094)	0.6393 (-0.0113)	1 (0)
0.85	0.0180 (0.0019)	0.0170 (0.0018)	0 (0)	0.6561 (-0.0067)	0.6425 (-0.0081)	1 (0)
0.9	0.0173 (0.0012)	0.0163 (0.0011)	0 (0)	0.6585 (-0.0043)	0.6454 (-0.0052)	1 (0)
0.95	0.0166 (0.0006)	0.0157 (0.0006)	0 (0)	0.6607 (-0.0021)	0.6481 (-0.0025)	1 (0)
1	0.0160	0.0152	0	0.6628	0.6506	1
1.05	0.0155 (-0.0006)	0.0147 (-0.0005)	0 (0)	0.6647 (0.0019)	0.6530 (0.0023)	1 (0)
1.1	0.0150 (-0.0011)	0.0142 (-0.0010)	0 (0)	0.6665 (0.0037)	0.6551 (0.0045)	1 (0)
1.15	0.0145 (-0.0016)	0.0137 (-0.0014)	0 (0)	0.6681 (0.0053)	0.6571 (0.0065)	1 (0)
1.2	0.0140 (-0.0020)	0.0133 (-0.0019)	0 (0)	0.6697 (0.0069)	0.6590 (0.0084)	1 (0)

Table A2.12 Total carbon emissions of each situation for different C content of sewage sludge (data in parentheses is the difference between the original data in the case study in percentage)

C content (wt%)	T	TC	TD	TI	TIM	TM	Variation in value
20.00%	1164.2733 (-52.50%)	1228.1833 (-51.17%)	1878.5233 (-40.66%)	1622.4433 (-44.24%)	1709.3633 (-42.95%)	1531.7333 (-45.66%)	-1287
22.50%	1255.9400 (-48.76%)	1319.8500 (-47.52%)	1970.1900 (-37.76%)	1714.1100 (-41.08%)	1801.0300 (-39.89%)	1623.4000 (-42.41%)	-1195.3333
25.00%	1347.6067	1411.5167	2061.8567	1805.7767	1892.6967	1715.0667	-1103.6667

	(-45.02%)	(-43.88%)	(-34.87%)	(-37.93%)	(-36.83%)	(-39.15%)	
27.50%	1439.2733	1503.1833	2153.5233	1897.4433	1984.3633	1806.7333	-1012
	(-41.28%)	(-40.24%)	(-31.97%)	(-34.78%)	(-33.77%)	(-35.90%)	
30.00%	1530.9400	1594.8500	2245.1900	1989.1100	2076.0300	1898.4000	-920.3333
	(-37.55%)	(-36.59%)	(-29.07%)	(-31.63%)	(-30.72%)	(-32.65%)	
32.50%	1622.6067	1686.5167	2336.8567	2080.7767	2167.6967	1990.0667	-828.6667
	(-33.81%)	(-32.95%)	(-26.18%)	(-28.48%)	(-27.66%)	(-29.40%)	
35.00%	1714.2733	1778.1833	2428.5233	2172.4433	2259.3633	2081.7333	-737
	(-30.07%)	(-29.30%)	(-23.28%)	(-25.33%)	(-24.60%)	(-26.15%)	
37.50%	1805.9400	1869.8500	2520.1900	2264.1100	2351.0300	2173.4000	-645.3333
	(-26.33%)	(-25.66%)	(-20.39%)	(-22.18%)	(-21.54%)	(-22.89%)	
40.00%	1897.6067	1961.5167	2611.8567	2355.7767	2442.6967	2265.0667	-553.6667
	(-22.59%)	(-22.01%)	(-17.49%)	(-19.03%)	(-18.48%)	(-19.64%)	
42.50%	1989.2733	2053.1833	2703.5233	2447.4433	2534.3633	2356.7333	-462
	(-18.85%)	(-18.37%)	(-14.59%)	(-15.88%)	(-15.42%)	(-16.39%)	
45.00%	2080.9400	2144.8500	2795.1900	2539.1100	2626.0300	2448.4000	-370.3333
	(-15.11%)	(-14.72%)	(-11.70%)	(-12.73%)	(-12.36%)	(-13.14%)	
47.50%	2172.6067	2236.5167	2886.8567	2630.7767	2717.6967	2540.0667	-278.6667
	(-11.37%)	(-11.08%)	(-8.80%)	(-9.58%)	(-9.30%)	(-9.89%)	
50.00%	2264.2733	2328.1833	2978.5233	2722.4433	2809.3633	2631.7333	-187
	(-7.63%)	(-7.43%)	(-5.91%)	(-6.43%)	(-6.24%)	(-6.63%)	
52.50%	2355.9400	2419.8500	3070.1900	2814.1100	2901.0300	2723.4000	-95.3333
	(-3.89%)	(-3.79%)	(-3.01%)	(-3.28%)	(-3.18%)	(-3.38%)	
55.00%	2447.6067	2511.5167	3161.8567	2905.7767	2992.6967	2815.0667	-3.6667
	(-0.15%)	(-0.15%)	(-0.12%)	(-0.13%)	(-0.12%)	(-0.13%)	
55.10%	2451.2733	2515.1833	3165.5233	2909.4433	2996.3633	2818.7333	-

Table A2.13 Direct carbon emissions of each situation for different C content of sewage sludge (data in parentheses is the difference between the original data in the case study)

C content (wt%)	T	TC	TD	TI	TIM	TM
20.00%	38.65%	36.64%	23.95%	50.54%	47.97%	29.38%
	(20.29%)	(18.75%)	(9.74%)	(22.36%)	(20.60%)	(13.41%)
22.50%	35.83%	34.09%	22.84%	47.84%	45.53%	27.72%
	(17.47%)	(16.20%)	(8.62%)	(19.65%)	(18.16%)	(11.75%)
25.00%	33.39%	31.88%	21.82%	45.41%	43.32%	26.24%
	(15.03%)	(13.99%)	(7.61%)	(17.23%)	(15.96%)	(10.27%)
27.50%	31.27%	29.94%	20.90%	43.22%	41.32%	24.91%
	(12.91%)	(12.05%)	(6.68%)	(15.03%)	(13.96%)	(8.94%)
30.00%	29.39%	28.22%	20.04%	41.22%	39.50%	23.70%
	(11.04%)	(10.32%)	(5.83%)	(13.04%)	(12.13%)	(7.74%)
32.50%	27.73%	26.68%	19.26%	39.41%	37.83%	22.61%
	(9.38%)	(8.79%)	(5.04%)	(11.22%)	(10.46%)	(6.65%)
35.00%	26.25%	25.31%	18.53%	37.75%	36.29%	21.62%
	(7.89%)	(7.42%)	(4.31%)	(9.56%)	(8.93%)	(5.65%)
37.50%	24.92%	24.07%	17.86%	36.22%	34.88%	20.70%
	(6.56%)	(6.17%)	(3.64%)	(8.03%)	(7.51%)	(4.74%)
40.00%	23.71%	22.94%	17.23%	34.81%	33.57%	19.87%
	(5.36%)	(5.05%)	(3.01%)	(6.62%)	(6.20%)	(3.90%)
42.50%	22.62%	21.92%	16.64%	33.50%	32.36%	19.09%
	(4.26%)	(4.03%)	(2.43%)	(5.32%)	(4.99%)	(3.13%)
45.00%	21.62%	20.98%	16.10%	32.29%	31.23%	18.38%
	(3.27%)	(3.09%)	(1.88%)	(4.11%)	(3.86%)	(2.41%)
47.50%	20.71%	20.12%	15.59%	31.17%	30.17%	17.72%
	(2.35%)	(2.23%)	(1.37%)	(2.99%)	(2.81%)	(1.75%)

50.00%	19.87% (1.52%)	19.33% (1.44%)	15.11% (0.89%)	30.12% (1.94%)	29.19% (1.82%)	17.10% (1.13%)
52.50%	19.10% (0.74%)	18.60% (0.70%)	14.66% (0.44%)	29.14% (0.95%)	28.27% (0.90%)	16.52% (0.56%)
55.00%	18.39% (0.03%)	17.92% (0.03%)	14.23% (0.02%)	28.22% (0.04%)	27.40% (0.03%)	15.99% (0.02%)
55.10%	18.36%	17.89%	14.22%	28.18%	27.37%	15.96%

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Appendix Part III: Sustainability Assessment and Alternative Selection for Sludge Valorization Technologies Based on Process Simulation and Fuzzy Multi-Criteria Decision Analysis

I. Process simulation

Description for the process simulation

Scenario 1: AD-based treatment for steam and power generation.

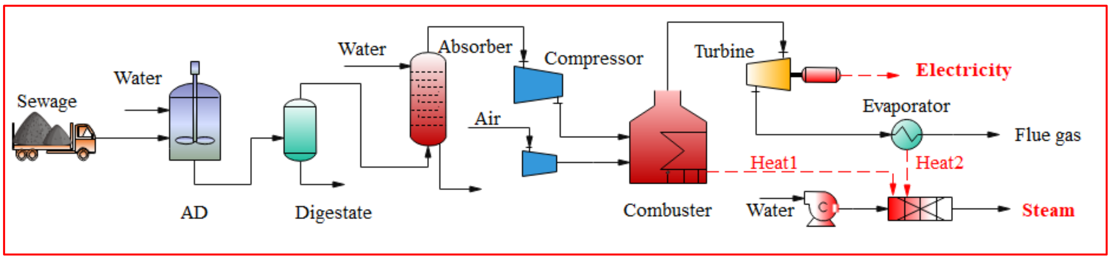


Figure A3.1 Process flowchart of sludge anaerobic digestion with power generation and heat recovery

Sludge anaerobic digestion for power generation and heat recovery is simulated according to the flowchart shown by Figure A3.1. Since the anaerobic digestion process involves lots of components in the hydrolysis, acidogenesis and methanogenesis, the following reactions (i.e., Eqs. (A3.1)-(A3.5)) are assumed to occur and finally methane can be obtained under the mild conditions. As shown in Figure A3.1, the sewage sludge is further sent into the mesophilic AD tank. During the anaerobic digestion module, several reactions were assumed and shown by Eqs. (A3.1)-(A3.5), and the obtained gas was cleaned to remove the acid gas such as NH_3 and H_2S. Cleaning gas which mainly consists of CH_4 and H_2, and CO_2 was further compressed and then enter the combustor to generate power. The operating conditions of anaerobic digestion were set to be 35 °C and 1 atm, which is called a mesophilic AD process (Medina-Martos et al., 2020). After

AD, the digestate is collected for further treatment and the generated biogas is applied for electricity generation with heat recovery. The conversion rate of carbon contained in sludge is around 40%.

$$C+O_2 \rightarrow CO_2 \tag{A3.1}$$

$$N_2+3H_2 \rightarrow 2NH_3 \tag{A3.2}$$

$$C+2H_2 \rightarrow CH_4 \tag{A3.3}$$

$$H_2+S \rightarrow H_2S \tag{A3.4}$$

$$C+2H_2O \rightarrow CH_4+CO_2 \tag{A3.5}$$

Scenario 2: Incineration-based treatment for power generation

The major process of sludge incineration by process simulation software is shown by Figure A3.2. Incineration temperature was assumed to be 850 °C (de Andrés et al., 2019; Environmental Protection Department, 2021e). The whole process starts from the drying unit to reduce the moisture content of the sewage sludge which was achieved by using low-pressure steam as heat source. The final moisture content fed into the decomposition block is set as 10 wt%. The nonconventional dried stream is decomposed into the conventional components like carbon, sulfur, hydrogen, oxygen and nitrogen according to the ultimate analysis of the sewage sludge. Those components mixed with the air and make oxidation reaction happens in the combustor. The post-combustion ash was further removed by a cyclone while the other flue gas with high temperature were condensed by a heat exchanger which is coupled into the power generation system.

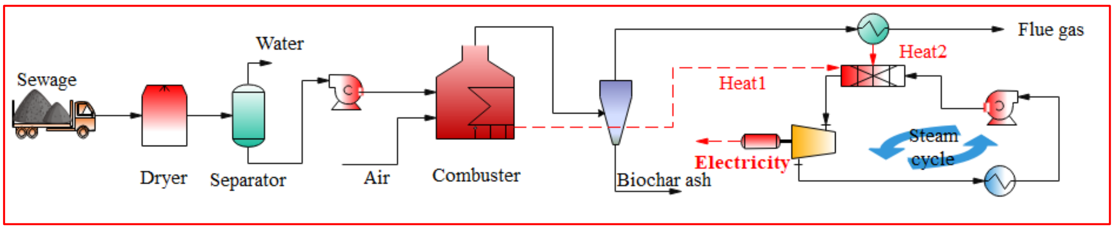


Figure A3.2 Process flowchart of sludge incineration with electricity generation

Scenario 3: Gasification-based treatment for syngas generation

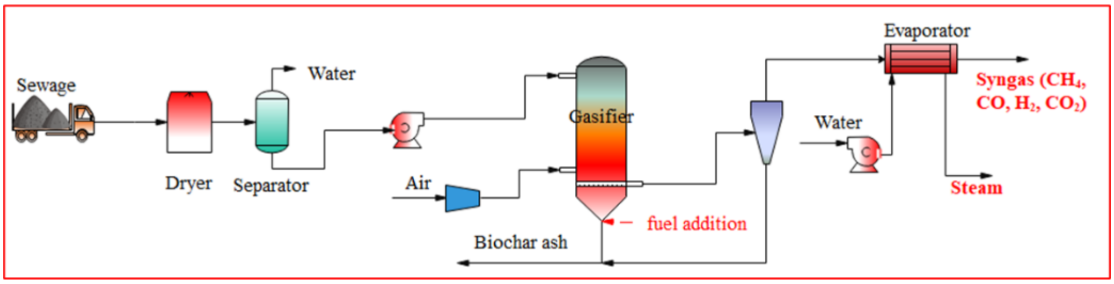


Figure A3.3 Process flowchart of sludge gasification for syngas production

In this section, a conceptual commercial sludge gasification process is simulated according to the flowchart diagram which is illustrated in Figure A3.3. The sewage sludge stream specified by the unconventional component is fed into the dry unit to achieve the reduction of moisture to 10 wt% for air gasification. Through the "Flash" model in Aspen Plus, dried sludge can be obtained and was introduced into the "RYiled" block to achieve the effective and conceptual decomposition of nonconventional sludge. Similar to the simulation of the sludge incineration, the decomposed components are converted into the syngas and ash by using a thermodynamic equilibrium "Gibbs" block. Additionally, some basic assumptions were made to simplify the downdraft gasifier before conducting the simulation (Cao et al., 2019). The gasification system is at steady state isothermal condition, the nitrogen and sulphur were fully converted into NH_3 and H_2S, ash is inert and tar formation are neglected because of the low content in the outlet gas stream from downdraft gasifier, and char is assumed to be totally carbon which will be burned completely (La Villetta et al., 2017). Syngas comprised of CH_4, CO, CO_2, H_2, N_2 and H_2O will be obtained from the gasifier. The major reactions involved in sludge gasification are summarized in Eqs. (A3.6) - (A3.15) (Motta et al., 2019).

Char particle combustion: $C+0.5O_2 \rightarrow CO$ (A3.6)

Char complete combustion: $C+O_2 \rightarrow CO_2$ (A3.7)

Hydrogen combustion: $H_2+0.5O_2 \rightarrow H_2O$ (A3.8)

CO partial combustion: $CO+0.5O_2 \rightarrow CO_2$ (A3.9)

Methane combustion: $CH_4+3O_2 \rightarrow CO_2+H_2O$ (A3.10)

Boudouard reaction: $C+CO_2 \rightarrow 2CO$ (A3.11)

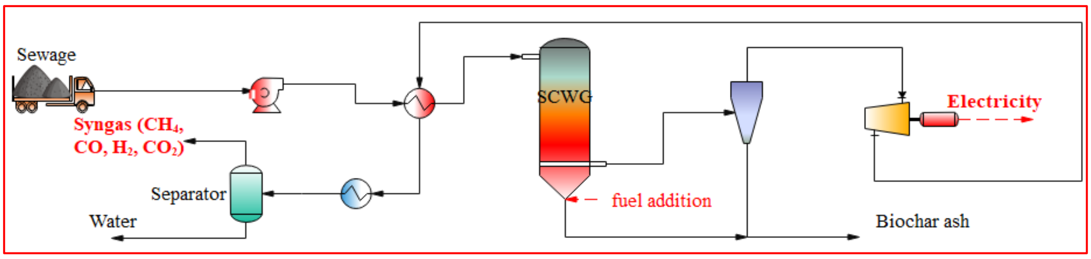
Water-gas reaction: $C+H_2O \rightarrow CO+H_2$ (A3.12)

Water-gas shift reaction: $CO+H_2O \leftrightarrow CO_2+H_2$ (A3.13)

Methanation reaction: $C+2H_2 \rightarrow CH_4$ (A3.14)

Methane steam reforming: $CH_4+H_2O \leftrightarrow CO+H_2$ (A3.15)

Scenario 4: SCWG-based treatment for hydrogen-rich gases and power generation



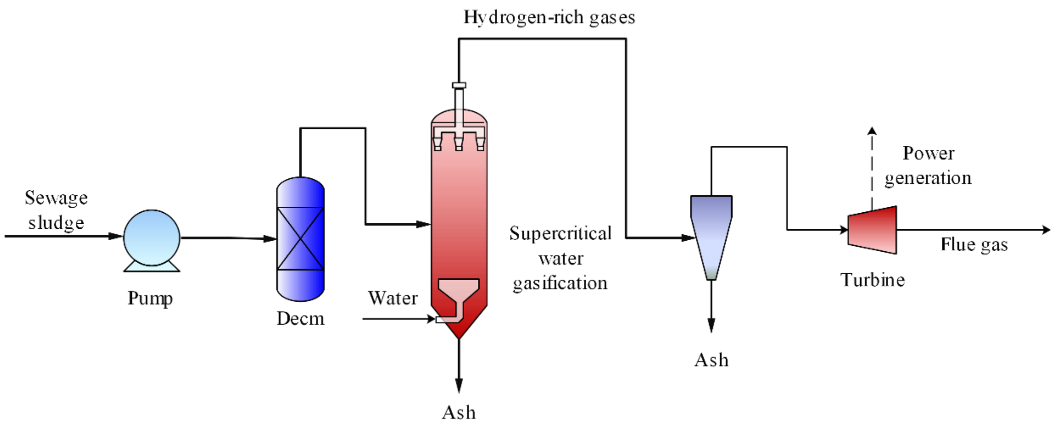


Figure A3.4 Process flowchart of supercritical water gasification for sludge treatment and hydrogen-rich gases production

Currently, SCWG is still an emerging technology without wide application or commercial promotion. A conceptual SCWG process is simulated according to the flowchart shown in Figure A3.4. The overall SCWG process is based on the previous research (Ruya et al., 2020). During the process simulation, the raw sewage sludge is fed into the decomposition reactor which converts the unconventional component into the conventional substances according to the ultimate analysis results of sewage sludge. The yield of different elements is set and achieved by using a calculator subroutine (Abdelrahim et al., 2020). Before the decomposition simulation, the sewage sludge is preheated by the product syngas stream to achieve the heat exchange and avoid the tar formation (Ruya et al., 2020). Under the supercritical condition 254 MPa and 700 °C the sludge went through the gasification reaction as shown in Eqs. (A3.6)) - (A3.15) above. The syngas was further separated from the solid-gas mixture and was expanded to generate power. The discharge pressure of the turbine was set as 1.5 bar based on the research. The outlet stream with reduced pressure will be used to preheat the feed stream and decrease the utility energy consumption.

II. Sustainability evaluation

The initial performance data on the considered indicators are shown in Table A3.1 and the detailed data for the economic estimations are shown in Table A3.2.

Table A3.1 Initial performance data on each criterion

Aspect	Criteria	Unit	S1	S2	S3	S4
AS1	C_1	%	100	9.7828	5.0225	5.8712
	C_2	%	100	8.5994	5.7479	4.3811
	C_3	%	100	5.5765	16.5313	11.6126
	C_4	%	100	13.1652	18.7099	11.1265
AS2	C_5	USD/year	25087754	24458590	18977128	30482065
	C_6	USD/year	15483997	12737910	10745089	11439674
	C_7	USD/year	26161567	9817200	33229642	19071794
AS3	C_8	-	0.45414	0.0367	0.3889	0.3675
	C_9	-	(M,H)	(VH,H)	(M,L)	(M,L)
	C_{10}	-	(H,VH)	(H,M)	(M,H)	(L,M)
AS4	C_{11}	-	(H,M)	(L,M)	(L,M)	(M,H)

Note:
Performance data of environmental, economic aspects and energy efficiency were estimated based on the process simulation results.

Table A3.2 Detailed data for the cost estimations (Unit: USD/year)

	Fixed capital cost (FCC)	Working capital cost (WCC)	Land cost (LC1)	Operating costs (OC)	Transportation costs (TC)	Landfill costs (LC2)
S1	21804145	2834539	449070	12952546	7321	2524131
S2	21257330	2763453	437808	11965053	2214	770643
S3	16493308	2144130	339690	9343608	4040	1397442
S4	26492422	3444015	545628	9969114	4240	1466320

Note:
Total capital costs=FCC+WCC+LC1; Total Operating costs=OC+TC+LC2.
FCC, WCC, LC1 and OC are estimated by the process simulation results and assumptions. Landfill costs refer to the expense for the final landfill disposal, which are roughly estimated based on the treatment for the residues and the fee for landfill from the reference (Soltani et al., 2016).
Service year of the sludge treatment facility is assumed to be 20 years. Electricity price is assumed to be 0.052 USD/kWh.
The volume of the truck for transportation is assumed to be 20 m^3. Cost for diesel is 12.87 HKD/L (Lam et al., 2016). 1 USD=7.75 HKD.

III. Calculation process for the fuzzy weights

Fuzzy best-worst method

A new fuzzy best-worst method (fuzzy BWM) proposed by Dong et al. (2021) was applied in this study. The detailed calculation steps are described as follows.

Step 1: The decision criteria system has been constructed in the manuscript, which is shown by Table 5.3.

Step 2: The best and the worst aspect and the best and the worst criterion for each aspect are determined according to the preferences of decision-makers, as is shown by Table A3.3. Since there is only one indicator in social dimension, the fuzzy weight of social aspect is exactly the weight of social acceptance.

Table A3.3 The best/worst aspect and the best/worst criterion of each aspect

	Aspect	Environmental (AS1)	Economic (AS2)	Technical (AS3)
Best aspect/criterion	AS1	Climate change (C1)	Product sales (C7)	Energy efficiency (C8)
Worst aspect/criterion	AS3	Eutrophication potential (C4)	Total operating costs (C6)	Technology maturity (C9)

Step 3: Conduct the fuzzy comparisons for the best aspect to the other aspects. Similar comparisons are also carried out for the best criterion to the other criteria. The transformation rules of the linguistic descriptions to the triangular fuzzy numbers (TFNs) are shown in Table A3.4. The fuzzy comparison results of each aspect and criterion are listed in Table A3.5 - Table A3.8.

Table A3.4 Transformation principles between the triangular fuzzy numbers and corresponding linguistic description (Guo and Zhao, 2017)

Linguistic terms	Membership
Equally important (EI)	(1, 1, 1)
Weakly important (WI)	(2/3, 1, 3/2)
Fairly important (FI)	(3/2, 2, 5/2)
Very important (VI)	(5/2, 3, 7/2)
Absolutely important (AI)	(7/2, 4, 9/2)

Table A3.5 Fuzzy comparisons of Environmental (AS_1) aspect to other aspects

Aspect	AS_1	AS_2	AS_3	AS_4
Best aspect AS_1	EI	FI	AI	VI
TFNs	(1,1,1)	(3/2,2,5/2)	(7/2,4,9/2)	(5/2,3,7/2)

Table A3.6 Fuzzy comparisons of Climate change (C_1) to other criteria in Environmental aspect

Criterion	C_1	C_2	C_3	C_4
Best criterion C_1	EI	WI	FI	VI
TFNs	(1,1,1)	(2/3,1,3/2)	(3/2,2,5/2)	(5/2,3,7/2)

Table A3.7 Fuzzy comparisons of Product sales (C_7) to other criteria in Economic aspect

Criterion	C5	C6	C7
Best criterion C_7	FI	VI	EI
TFNs	(3/2,2,5/2)	(7/2,4,9/2)	(1,1,1)

Table A3.8 Fuzzy comparisons of Energy efficiency (C_8) to other criteria in Technical aspect

Criterion	C8	C9	C10
Best criterion C_8	EI	VI	FI
TFNs	(1,1,1)	(5/2,3,7/2)	(3/2,2,5/2)

Step 4: Similar with **Step 3**, the fuzzy comparisons between the other aspects or criteria and the worst aspect or criterion are conducted and the corresponding results are shown in Table A3.9 - Table A3.12.

Table A3.9 Fuzzy comparisons of the other aspects to Technical (AS_3) aspect

Aspect	Worst aspect AS3	TFNs
AS1	AI	(7/2,4,9/2)
AS2	VI	(5/2,3,7/2)
AS3	EI	(1,1,1)
AS4	FI	(3/2,2,5/2)

Table A3.10 Fuzzy comparisons of the other criteria to Eutrophication potential (C_4) in Environmental aspect

Criterion	Worst criterion C4	TFNs
C1	VI	(5/2,3,7/2)
C2	FI	(3/2,2,5/2)
C3	WI	(2/3,1,3/2)
C4	EI	(1,1,1)

Table A3.11 Fuzzy comparisons of the other criteria to Total operating cost (C_6) in Economic aspect

Criterion	Worst criterion C6	TFNs
C5	FI	(3/2,2,5/2)
C6	EI	(1,1,1)
C7	VI	(7/2,4,9/2)

Table A3.12 Fuzzy comparisons of the other criteria to Technology maturity (C_9) in Technical aspect

Criterion	Worst criterion C9	TFNs
C8	VI	(5/2,3,7/2)
C9	EI	(1,1,1)
C10	WI	(2/3,1,3/2)

Step 5: Suitable values of the tolerance parameters p_j^t and q_j^t ($j=1,2,\ldots,n$; $t=l,m,u$) should be determined by the decision-makers based on their preference and the features of the decision-making problem. According to the principles in the reference (Dong et al., 2021), p_j^t and q_j^t can take any values within the interval [1,9]. In the case study, all the tolerance parameters p_j^t and q_j^t are set to be 1.

Step 6: There are three different types of optimization model for solving the fuzzy weights in this fuzzy BWM, which can be classified to optimistic type, pessimistic type and neutral type according to the risk attitude of the decision-makers. Optimistic type of optimization model is selected in this case study to determine the fuzzy weights of the criteria system. The optimal fuzzy weights of each aspect and criterion can be obtained by solving the constrained optimization problems. The fuzzy consistency ratio (FCR) for each problem has also been checked according to the computation principles provided in the study of Dong et al. (2021). Since all the fuzzy consistency ratios are less than 0.1, the consistency of the weighting results is acceptable. The weighting result of each aspect and the fuzzy weight of each criterion has been presented in Table 5.8 and Table 5.9 in the Chapter 5, respectively. The local weight of each criterion is shown in Table A3.13 - Table A3.15

Table A3.13 Local weight for environmental indicators

	C1	C2	C3	C4
Fuzzy weight	0.3856	0.3074	0.1845	0.1225

FCR=0.0222

Table A3.14 Local weight for economic indicators

	C5	C6	C7
Fuzzy weight	0.2464	0.1043	0.6493

FCR=0.0664

Table A3.15 Local weight for technical indicators

	C8	C9	C10
Fuzzy weight	0.6070	0.1491	0.2439

FCR=0.0953

IV. Sensitivity analysis

Table A3.16 Weighting assignments for the sensitivity analysis to investigate the influence of weights variations

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
G1	0.25	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
G2	0.075	0.25	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
G3	0.075	0.075	0.25	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
G4	0.075	0.075	0.075	0.25	0.075	0.075	0.075	0.075	0.075	0.075	0.075
G5	0.075	0.075	0.075	0.075	0.25	0.075	0.075	0.075	0.075	0.075	0.075
G6	0.075	0.075	0.075	0.075	0.075	0.25	0.075	0.075	0.075	0.075	0.075
G7	0.075	0.075	0.075	0.075	0.075	0.075	0.25	0.075	0.075	0.075	0.075
G8	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.25	0.075	0.075	0.075
G9	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.25	0.075	0.075
G10	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.25	0.075
G11	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.25

V. Uncertainty analysis

Table A3.17 Detailed results of the value of $\phi(S3)$ and final ranking under different parameter variation

Variation of indicator	Value of the phi+	Variation of the phi+	Value of the phi-	Variation of the phi-	Value of the phi	Variation of the phi	Final ranking
0	0.9551	0.00%	0.1682	0	0.7869	0.00%	S3>S4>S2>S1
-5%	0.9498	-0.56%	0.1682	0	0.7816	-0.68%	S3>S4>S2>S1
-4%	0.9510	-0.42%	0.1682	0	0.7829	-0.52%	S3>S4>S2>S1
-3%	0.9522	-0.30%	0.1682	0	0.7840	-0.37%	S3>S4>S2>S1
-2%	0.9533	-0.19%	0.1682	0	0.7851	-0.23%	S3>S4>S2>S1
-1%	0.9542	-0.09%	0.1682	0	0.7861	-0.11%	S3>S4>S2>S1
1%	0.9558	0.08%	0.1682	0	0.7877	0.10%	S3>S4>S2>S1
2%	0.9565	0.15%	0.1682	0	0.7883	0.18%	S3>S4>S2>S1
3%	0.9570	0.20%	0.1682	0	0.7889	0.25%	S3>S4>S2>S1
4%	0.9575	0.25%	0.1682	0	0.7893	0.31%	S3>S4>S2>S1
5%	0.9579	0.29%	0.1682	0	0.7897	0.36%	S3>S4>S2>S1

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Appendix Part IV: Sustainability Prioritization of Sludge-to-Energy Technologies Under Multi-Data Conditions

I. Calculation process of fuzzy BWM

Table A4.1 Triangular fuzzy number (TFN) of corresponding linguistic description (Guo and Zhao, 2017)

Linguistic terms	Membership
Equally important (EI)	(1, 1, 1)
Weakly important (WI)	(2/3, 1, 3/2)
Fairly important (FI)	(3/2, 2, 5/2)
Very important (VI)	(5/2, 3, 7/2)
Absolutely important (AI)	(7/2, 4, 9/2)

Step1: The decision criteria system has been established in the manuscript, which is listed in Table 6.1.

Step 2: The best aspect and the worst aspect, the best criterion and the worst criterion for each aspect were decided according to the preferences of decision-makers, which was listed in Table A4.2.

Table A4.2 The best/worst aspect and the best/worst criterion of the specific aspect

	Aspect	Environmental	Economic	Social	Technical
Best criterion/aspect	Economic (AS_2)	Climate change (C_1)	Operation and maintenance cost (C_7)	Policy support (C_8)	Maturity (C_{10})
Worst criterion/aspect	Social (AS_3)	Ozone layer depletion (C_5)	Capital cost (C_6)	Social acceptance (C_9)	Volume reduction rate (C_{11})

Step 3: The fuzzy comparisons for the best criterion to the other criteria were conducted according to the principles. The linguistic description of the comparison between each aspect and criterion were listed in Table A4.3 - Table A4.7.

Table A4.3 Fuzzy comparisons of Economic (AS_2) aspect to other aspect

Aspect	AS_1	AS_2	AS_3	AS_4
Best aspect AS_2	WI	EI	VI	FI

Table A4.4 Fuzzy comparisons of Climate change (C_1) to other criteria in Environmental aspect

Criterion	C_1	C_2	C_3	C_4	C_5
Best Criterion C_1	EI	FI	WI	WI	VI

Table A4.5 Fuzzy comparisons of Operation and maintenance cost (C_7) to other criteria

Criterion	C_6	C_7
Best criterion C_7	WI	EI

Table A4.6 Fuzzy comparisons of Policy support (C_8) to other criteria

Criterion	C_8	C_9
Best criterion C_8	EI	FI

Table A4.7 Fuzzy comparisons of Maturity (C_{10}) to other criteria

Criterion	C_{10}	C_{11}	C_{12}	C_{13}
Best criterion C_{10}	EI	VI	FI	WI

Step 4: Similar in **Step 3**, the fuzzy comparisons between the other aspects or criteria and the worst aspect or criterion were carried out, which were shown in Table A4.8 - Table A4.12.

Table A4.8 Importance comparisons of other aspects to the worst aspect Social (AS_3)

Aspect	Worst aspect AS_3
AS_1	VI
AS_2	VI
AS_3	EI
AS_4	FI

Table A4.9 Importance comparisons of other criteria to Ozone layer depletion (C_5) in Environmental aspect

Criterion	Worst criterion C_5
C_1	VI
C_2	WI
C_3	FI
C_4	FI
C_5	EI

Table A4.10 Importance comparisons of other criteria to Capital cost (C_6) in Economic aspect

Criterion	Worst criterion C_6
C_6	EI
C_7	WI

Table A4.11 Importance comparisons of other criteria to Social acceptance (C_9) in Social aspect

Criterion	Worst criterion C_9
C_8	FI
C_9	EI

Table A4.12 Importance comparisons of other criteria to Volume reduction rate (C_{11}) in Technical aspect

Criterion	Worst criterion C_{11}
C_{10}	VI
C_{11}	EI
C_{12}	FI
C_{13}	FI

Step 5: Calculate the optimal fuzzy weights for each aspect and criterion by solving the nonlinearly constrained optimization problems. The optimization problem for each aspect can be obtained based on the fuzzy comparisons and their corresponding TFN. The results of fuzzy weights for each aspect and criterion were listed in Table 6.3 of the manuscript and Table A4.13 - Table A4.16, respectively. The global fuzzy weights of al the criteria were shown in Table 6.4 in the Chapter 6. The total consistency ratio was obtained by the same principle with AHP method.

Table A4.13 Local fuzzy weight of each criterion in Environmental aspect

	C_1	C_2	C_3	C_4	C_5	CR
Weight	0.2876	0.1357	0.2323	0.2391	0.1053	0.0429

Table A4.14 Local fuzzy weight of each criterion in Economic aspect

	C_6	C_7	CR
Weight	0.5065	0.4935	0

Table A4.15 Local fuzzy weight of each criterion in Social aspect

	C_8	C_9	CR
Weight	0.6647	0.3353	0

Table A4.16 Local fuzzy weight of each criterion in Technical aspect

	C_{10}	C_{11}	C_{12}	C_{13}	CR
Weight	0.4069	0.1276	0.2327	0.2327	0.0312

II. DS-FBWM for incomplete information decision-making

Table A4.17 The focal elements for each criterion

Criterion	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**
Focal elements	{S1}, {S2}, {S3}, {S4}, Θ	{S1}, {S2}, {S3}, {S4}, Θ	{S1}, {S2}, {S3}, Θ	{S1}, {S2}, {S3}, Θ	{S1}, {S2}, {S3}, Θ
Criterion	**C_6**	**C_7**	**C_8**	**C_9**	**C_{10}**
Focal elements	{S1}, {S2}, {S3}, {S4}, Θ	{S1}, {S2}, {S3}, {S4}, Θ	{S1,S2}, {S3}, {S4}, Θ	{S1}, {S3}, {S2,S4}, Θ	{S1}, {S3}, {S2,S4}, Θ
Criterion	**C_{11}**	**C_{12}**	**C_{13}**		
Focal elements	{S1}, {S4}, {S2,S3}, Θ	{S1}, {S4}, {S2,S3}, Θ	{S1}, {S3}, {S2,S4}, Θ		

Note:

For C_8 and C_{10} of S1 – S3, there were three experts providing different judgments. The final performances of these two indices for the three scenarios were determined by the average performance. The performances of C_8 for S1 – S3 were evaluated as: Medium, Medium, Good. The performances of C_{10} were Medium, Very poor, Very good (Ren et al., 2017b).

Table A4.18 The preference of each focal element transformed according to knowledgeable scale

C_1	**Priority**	**C_2**	**Priority**	**C_3**	**Priority**	**C_4**	**Priority**	**C5**	**Priority**
{S1}	$3w_1$	{S1}	$6w_2$	{S1}	$5w_3$	{S1}	$5w_4$	{S1}	w_5
{S2}	$5w_1$	{S2}	$3w_2$	{S2}	$3w_3$	{S2}	$2w_4$	{S2}	$3w_5$
{S3}	w_1	{S3}	$5w_2$	{S3}	$2w_3$	{S3}	$3w_4$	{S3}	$5w_5$
{S4}	$6w_1$	{S4}	w_2	Θ	1	Θ	1	Θ	1
Θ	1	Θ	1						
C_6	**Priority**	**C_7**	**Priority**	**C_8**	**Priority**	**C_9**	**Priority**	**C_{10}**	**Priority**

{S1}	$4w_6$	{S1}	$5w_7$	{S1, S2}	$3w_8$	{S1}	$3w_9$	{S1}	$3w_{10}$
{S2}	$3w_6$	{S2}	$2w_7$	{S3}	$5w_8$	{S3}	$5w_9$	{S3}	$6w_{10}$
{S3}	$2w_6$	{S3}	$4w_7$	{S4}	w_8	{S2,S4}	$2w_9$	{S2, S4}	w_{10}
{S4}	$5w_6$	{S4}	w_7	Θ	1	Θ	1	Θ	1
Θ	1	Θ	1						
C11	**Priority**	**C12**	**Priority**	**C13**	**Priority**				
{S1}	$5w_{11}$	{S1}	$6w_{12}$	{S1}	$5w_{13}$				
{S2,S3}	$3w_{11}$	{S2,S3}	$2w_{12}$	{S3}	$3w_{13}$				
{S4}	$2w_{11}$	{S4}	$5w_{12}$	{S2, S4}	$2w_{13}$				
Θ	1	Θ	1	Θ	1				

Table A4.19 The priority of the focal elements

C1	**Priority**	**C2**	**Priority**	**C3**	**Priority**	**C4**	**Priority**	**C5**	**Priority**
{S1}	0.1161	{S1}	0.1580	{S1}	0.2134	{S1}	0.2170	{S1}	0.0259
{S2}	0.1935	{S2}	0.0790	{S2}	0.1280	{S2}	0.0868	{S2}	0.0777
{S3}	0.0387	{S3}	0.1316	{S3}	0.0854	{S3}	0.1302	{S3}	0.1294
{S4}	0.2322	{S4}	0.0263	Θ	0.5732	Θ	0.5660	Θ	0.7670
Θ	0.4196	Θ	0.6051						
C6	**Priority**	**C7**	**Priority**	**C8**	**Priority**	**C9**	**Priority**	**C10**	**Priority**
{S1}	0.2053	{S1}	0.2836	{S1, S2}	0.1350	{S1}	0.0836	{S1}	0.1361
{S2}	0.1540	{S2}	0.1135	{S3}	0.2266	{S3}	0.1393	{S3}	0.2723
{S3}	0.1027	{S3}	0.2269	{S4}	0.0453	{S2,S4}	0.0557	{S2, S4}	0.0454
{S4}	0.2566	{S4}	0.0567	Θ	0.5921	Θ	0.7215	Θ	0.5462
Θ	0.2814	Θ	0.3193						
C11	**Priority**	**C12**	**Priority**	**C13**	**Priority**				
{S1}	0.1033	{S1}	0.1664	{S1}	0.1611				
{S2,S3}	0.0620	{S2,S3}	0.0666	{S3}	0.0966				
{S4}	0.0413	{S4}	0.0666	{S2, S4}	0.0644				
Θ	0.7933	Θ	0.7005	Θ	0.6779				

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Appendix Part V: Sustainability-Oriented Multi-Stakeholder Decision-Making Analysis for Sludge-to-Energy Strategies based on Game Theory

I. Sustainability assessment results

Table A5.1 Environmental life cycle impacts on the investigated indicators (data is presented by per function unit)

Impact category	Unit	S1	S2	S3	S4
Climate change	kg CO_2 eq.	9.7632	9.4881	0.2000	9.9600
Acidification	kg SO_2 eq.	0.0551	0.0536	0.0005	0.0040
Eutrophication	kg PO_4^{3-} eq.	0.0083	0.0080	0.0001	-0.0006

Table A5.2 Normalized environmental life cycle impacts on the investigated indicators

Impact category	S1	S2	S3	S4
Climate change	0.0202	0.0483	1	0
Acidification	0	0.0269	1	0.9360
Eutrophication	0	0.0245	0.9192	1

Table A5.3 Estimation of the economic net costs for the case study in Hong Kong (Unit: USD /per functional unit)

Player 1's choice-Player 2's choice	Player 1 – Sludge treatment facility	Player 2 - Government
S1-S1	0.0821	-4.4356
S1-S2	0.0821	-0.1440
S1-S3	0.0821	-0.1440
S1-S4	0.0821	-4.4356
S2-S1	-0.0180	-4.4356
S2-S2	-0.0180	-0.1440
S2-S3	-0.0180	-0.1440
S2-S4	-0.0180	-4.4356
S3-S1	0.2112	-4.4356
S3-S2	0.2112	-0.1440
S3-S3	0.2112	-0.1440
S3-S4	0.2112	-4.4356
S4-S1	0.2181	-4.4356
S4-S2	0.2181	-0.1440
S4-S3	0.2181	-0.1440
S4-S4	0.2181	-4.4356

Note:

Price of electricity: 1 .108 HKD/kWh=0.144 USD/kWh (1 HKD=0.13 USD) (Lam et al., 2016).

Table A5.4 Normalization of the economic net costs for the two players in the case study

Player 1's choice-Player 2's choice	Player 1 – Sludge treatment facility	Player 2 - Government
S1-S1	0.5761	1
S1-S2	0.5761	0
S1-S3	0.5761	0
S1-S4	0.5761	1
S2-S1	1	1
S2-S2	1	0
S2-S3	1	0
S2-S4	1	1
S3-S1	0.0292	1
S3-S2	0.0292	0
S3-S3	0.0292	0
S3-S4	0.0292	1
S4-S1	0	1
S4-S2	0	0
S4-S3	0	0
S4-S4	0	1

Table A5.5 Performance evaluation for the assessed scenarios on social and technical indicators reflected from four decision-makers (DM) by linguistic terms

DM#1	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	M	H	M	M
	C6	H	VH	M	M
	C7	M	H	VH	VH
Technical	C8	M	M	VG	VG
	C9	M	M	VH	H
	C10	VH	VH	H	H
	C11	VH	VH	H	H
DM#2	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	M	H	M	VH
	C6	M	M	M	H
	C7	M	M	H	M
Technical	C8	G	G	P	P
	C9	M	M	M	M
	C10	M	M	H	H
	C11	M	H	H	M
DM#3	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	H	H	VH	H
	C6	M	H	VH	H
	C7	M	VH	VH	H
Technical	C8	M	M	P	P
	C9	H	H	VH	H
	C10	VH	M	L	H
	C11	VH	M	L	VH
DM#4	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	VH	H	M	M
	C6	M	H	H	H
	C7	M	H	VH	VH
Technical	C8	P	M	G	M
	C9	M	H	VH	H
	C10	H	H	M	M
	C11	H	M	H	H

Table A5.6 Performance evaluation for the assessed scenarios on social and technical indicators reflected from four decision-makers (DM) by triangular fuzzy numbers (TFNs)

DM#1	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	(3, 5, 7)	(5, 7, 9)	(3, 5, 7)	(3, 5, 7)
	C6	(5, 7, 9)	(7, 9, 9)	(3, 5, 7)	(3, 5, 7)
	C7	(3, 5, 7)	(5, 7, 9)	(7, 9, 9)	(7, 9, 9)
Technical	C8	(3, 5, 7)	(3, 5, 7)	(7, 9, 9)	(7, 9, 9)
	C9	(3, 5, 7)	(3, 5, 7)	(7, 9, 9)	(5, 7, 9)
	C10	(7, 9, 9)	(7, 9, 9)	(5, 7, 9)	(5, 7, 9)
	C11	(7, 9, 9)	(7, 9, 9)	(5, 7, 9)	(5, 7, 9)
DM#2	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	(3, 5, 7)	(5, 7, 9)	(3, 5, 7)	(7, 9, 9)
	C6	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(5, 7, 9)
	C7	(3, 5, 7)	(3, 5, 7)	(5, 7, 9)	(3, 5, 7)
Technical	C8	(5, 7, 9)	(5, 7, 9)	(1, 3, 5)	(1, 3, 5)
	C9	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)
	C10	(3, 5, 7)	(3, 5, 7)	(5, 7, 9)	(5, 7, 9)
	C11	(3, 5, 7)	(5, 7, 9)	(5, 7, 9)	(3, 5, 7)
DM#3	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	(5, 7, 9)	(5, 7, 9)	(7, 9, 9)	(5, 7, 9)
	C6	(3, 5, 7)	(5, 7, 9)	(7, 9, 9)	(5, 7, 9)
	C7	(3, 5, 7)	(7, 9, 9)	(7, 9, 9)	(5, 7, 9)
Technical	C8	(3, 5, 7)	(3, 5, 7)	(1, 3, 5)	(1, 3, 5)
	C9	(5, 7, 9)	(5, 7, 9)	(7, 9, 9)	(5, 7, 9)
	C10	(7, 9, 9)	(3, 5, 7)	(1, 3, 5)	(5, 7, 9)
	C11	(7, 9, 9)	(3, 5, 7)	(1, 3, 5)	(7, 9, 9)
DM#4	**Denotation**	**S1**	**S2**	**S3**	**S4**
Social	C5	(7, 9, 9)	(5, 7, 9)	(3, 5, 7)	(3, 5, 7)
	C6	(3, 5, 7)	(5, 7, 9)	(5, 7, 9)	(5, 7, 9)
	C7	(3, 5, 7)	(5, 7, 9)	(7, 9, 9)	(7, 9, 9)
Technical	C8	(1, 3, 5)	(3, 5, 7)	(5, 7, 9)	(3, 5, 7)
	C9	(3, 5, 7)	(5, 7, 9)	(7, 9, 9)	(5, 7, 9)
	C10	(5, 7, 9)	(5, 7, 9)	(3, 5, 7)	(3, 5, 7)
	C11	(5, 7, 9)	(3, 5, 7)	(5, 7, 9)	(5, 7, 9)

Table A5.7 Integrated performance evaluation for the assessed scenarios on social and technical indicators by TFNs

Aspect	Indicator	S1	S2	S3	S4
Social	C_5	(4.5,6.5,8)	(5.5,7.5,9)	(4,6,7.5)	(4.5,6.5,8)
	C_6	(3.5,5.75,7.5)	(5,7,8.5)	(5,7,8.5)	(4.5,6.5,8.5)
	C_7	(3,5,7)	(5,7,8.5)	(6.5,8.5,9)	(5.5,7.5,8.5)
Technical	C_8	(3,5,7)	(3.5,5.5,7.5)	(4.5,5.5,7)	(3,5,6.5)
	C_9	(3.5,5.5,7.5)	(4,6,8)	(6,8,8.5)	(4.5,6.5,8.5)
	C_{10}	(5.5,7.5,8.5)	(4.5,6.5,8)	(3.5,5.5,7.5)	(4.5,6.5,8.5)
	C_{11}	(5.5,7.5,8.5)	(4.5,6.5,8)	(4,6,8)	(5,7,8.5)

Table A5.8 Defuzzied performance data on social and technical indicators

Aspect	Indicator	S1	S2	S3	S4
Social	C_5	6.42	7.42	5.92	6.42
	C_6	5.67	6.92	6.92	6.50
	C_7	5.00	6.92	8.25	7.33
Technical	C_8	5.00	5.50	5.42	4.92
	C_9	5.50	6.00	7.75	6.50
	C_{10}	7.33	6.42	5.50	6.50
	C_{11}	7.33	6.42	6.00	6.92

Table A5.9 Normalized performance evaluation on social and technical indicators for the three scenarios

Aspect	Indicator	S1	S2	S3	S4
Social	C_5	0.33	1.00	0.00	0.33
	C_6	0.00	1.00	1.00	0.67
	C_7	0.00	0.59	1.00	0.72
Technical	C_8	0.14	1.00	0.86	0.00
	C_9	1.00	0.78	0.00	0.56
	C_{10}	0.33	0.17	0.00	0.18
	C_{11}	1.00	0.31	0.00	0.69

II. Criteria weighting by GI-FBWM

The adapted fuzzy best-worst method was proposed and developed in the previous research (Hafezalkotob and Hafezalkotob, 2017).

Table A5.10 Linguistic description of the importance preference and corresponding triangular fuzzy numbers (Hafezalkotob and Hafezalkotob, 2017)

Linguistic description	Fuzzy preferences
Extremely more importance (ExI)	(7,9,9)
Very strong importance (VI)	(5,7,9)
Strong importance (SI)	(3,5,7)
Moderate importance (MI)	(1,3,5)
Equal importance (EI)	(1,1,3)
Completely equal importance (CeI)	(1,1,1)

Perspective of STF manager

Step 1: The set of decision criteria has been established in the manuscript, which is shown in Table 7.3.

Step 2: According to the feedback from STF manager, the best aspect and the worst aspect, the best criterion and the worst criterion for each aspect were decided, which are listed in Table A5.11.

Table A5.11 The best/worst aspect and the best/worst criterion of the corresponding aspect from the perspective of STF manager

	Aspect	Environmental	Social	Technical
Best criterion/aspect	Environmental (AS1)	Climate change (C_1)	Government supporting (C_6)	Technical accessibility (C_{11})
Worst criterion/aspect	Economic (AS2)	Acidification (C_2)	Education significance (C_7)	Odors control (C_8)

Step 3: The fuzzy preference degree of the best criterion over the other criteria were carried out based on the principles. The linguistic preference of the comparison between each aspect and criterion were shown in Table A5.12 - Table A5.15.

Table A5.12 Fuzzy comparisons of Environmental aspect (AS1) to the other aspects

Aspect	AS1	AS2	AS3	AS4
Best aspect AS1	(1,1,1)	(5,7,9)	(3,5,7)	(1,3,5)

Table A5.13 Fuzzy comparisons of Climate change (C_1) to other criteria in Environmental aspect

Criterion	C_1	C_2	C_3
Best criterion C_1	(1,1,1)	(5,7,9)	(3,5,7)

Table A5.14 Fuzzy comparisons of Government supporting (C_6) to other criteria in Social aspect

Criterion	C_5	C_6	C_7
Best criterion C_6	(1,3,5)	(1,1,1)	(5,7,9)

Table A5.15 Fuzzy comparisons of Technical accessibility (C_{11}) to other criteria in Technical aspect

Criterion	C_8	C_9	C_{10}	C_{11}
Best criterion C_{11}	(7,9,9)	(3,5,7)	(1,3,5)	(1,1,1)

Step 4: Similar to **Step 3**, the fuzzy preference degree of the other aspects or criteria

and the worst aspect or criterion can be obtained and the results and shown in Table A5.16 - Table A5.19.

Table A5.16 Fuzzy preference degree of the other aspects over Economic aspect (AS2)

Aspect	Worst aspect AS2
AS1	(5,7,9)
AS2	(1,1,1)
AS3	(1,3,5)
AS4	(3,5,7)

Table A5.17 Fuzzy preference degree of the other criteria over Acidification (C_2) in Environmental aspect

Criterion	Worst criterion C_2
C_1	(5,7,9)
C_2	(1,1,1)
C_3	(1,3,5)

Table A5.18 Fuzzy preference degree of the other criteria over Education significance (C_7) in Social aspect

Criterion	Worst criterion C_7
C_5	(3,5,7)
C_6	(5,7,9)
C_7	(1,1,1)

Table A5.19 Fuzzy preference degree of the other criteria over Odors control (C_8) in Technical aspect

Criterion	Worst criterion C_8
C_8	(1,1,1)
C_9	(1,3,5)
C_{10}	(5,7,9)
C_{11}	(7,9,9)

Step 5: Calculate the optimal weights from the perspective of STF manager by solving the corresponding optimization problem considering the fuzzy constraints. The results of fuzzy weights for each aspect were listed in Table A5.20. The local fuzzy weights for each criterion are shown in Table A5.21. The global fuzzy weight was

obtained by the product of the local weight for the criterion and the fuzzy weight of the corresponding aspect, and the results are shown in Table A5.22. It should be noted that since the senior decision-maker is the dominate role in this case study, the weights of the criteria system are just determined by the senior DM as it has been shown in Table A5.22.

Table A5.20 Local weight of each aspect from the perspective of STF manager

Aspect	Environmental AS1	Economic AS2	Social AS3	Technical AS4
Local weight	0.6216	0.0541	0.1351	0.1892

Table A5.21 Local weight of each indicator in each aspect from the perspective of STF manager

AS1	**C1**	**C2**	**C3**	
Local weight	0.7667	0.0667	0.1667	
AS3	**C5**	**C6**	**C7**	
Local weight	0.2188	0.7188	0.0625	
AS4	**C8**	**C9**	**C10**	**C11**
Local weight	0.0465	0.1163	0.2093	0.6279

Table A5.22 Global weight of each indicator in each aspect from the perspective of STF manager

AS1	**C1**	**C2**	**C3**	
Global weight	0.4766	0.0414	0.1036	
AS2	**C4**			
Global weight	0.0541			
AS3	**C5**	**C6**	**C7**	
Global weight	0.0296	0.0971	0.0084	
AS4	**C8**	**C9**	**C10**	**C11**
Global weight	0.0088	0.0220	0.0396	0.1188

Perspective of government

Step 1: The set of decision criteria is the same as that of STF manager, which is shown in Table 7.3.

Step 2: The best aspect and the worst aspect, the best criterion and the worst criterion for each aspect were decided based on the feedback from the government manager, which are listed in Table A5.23. It should be noted that the significance of three environmental indicators are regarded to be the same. Hence, fuzzy BWM is not applied to the environmental aspect.

Table A5.23 The best/worst aspect and the best/worst criterion of the corresponding aspect from the perspective of government manager

	Aspect	Social	Technical
Best criterion/aspect	Environmental (AS1)	Social acceptance (C_5)	Technical accessibility (C_{11})
Worst criterion/aspect	Technical (AS4)	Government supporting (C_6)	Technical complexity (C_9)

Step 3: The fuzzy preference degree of the best criterion over the other criteria were carried out based on the principles. The linguistic preference of the comparison between each aspect and criterion were shown in Table A5.24 - Table A5.26.

Table A5.24 Fuzzy comparisons of Environmental aspect (AS1) to the other aspects from the viewpoint of government

Aspect	AS1	AS2	AS3	AS4
Best aspect AS1	(1,1,1)	(3,5,7)	(1,3,5)	(5,7,9)

Table A5.25 Fuzzy comparisons of Social acceptance (C_5) to other criteria in Social aspect from the viewpoint of government

Criterion	C_5	C_6	C_7
Best criterion C_5	(1,1,1)	(3,5,7)	(1,3,5)

Table A5.26 Fuzzy comparisons of Technical accessibility (C_{11}) to other criteria in Technical aspect from the viewpoint of government

Criterion	C_8	C_9	C_{10}	C_{11}
Best criterion C_{11}	(3,5,7)	(5,7,9)	(1,3,5)	(1,1,1)

Step 4: Similar to **Step 3**, the fuzzy preference degree of the other aspects or criteria and the worst aspect or criterion can be obtained and the results and shown in Table

A5.27 - Table A5.29.

Table A5.27 Fuzzy preference degree of the other aspects over Technical aspect (AS4) from the perspective of government

Aspect	Worst aspect AS4
AS1	(5,7,9)
AS2	(3,5,7)
AS3	(3,5,7)
AS4	(1,1,1)

Table A5.28 Fuzzy preference degree of the other criteria over Government supporting (C_6) in Social aspect from the viewpoint of government

Criterion	Worst criterion C_6
C_5	(3,5,7)
C_6	(1,1,1)
C_7	(1,3,5)

Table A5.29 Fuzzy preference degree of the other criteria over Technical complexity (C_9) in Technical aspect from the perspective of government

Criterion	Worst criterion C_9
C_8	(1,3,5)
C_9	(1,1,1)
C_{10}	(3,5,7)
C_{11}	(5,7,9)

Step 5: The optimal weights from the perspective of government manager can be obtained by solving the corresponding optimization problem considering the fuzzy constraints. The results of fuzzy weights for each aspect were listed in Table A5.30. The local fuzzy weights for each criterion are shown in Table A5.31. The global fuzzy weights are shown in Table A5.32. Similar to the situation of STF, the weights of the criteria system are just determined by the senior DM.

Table A5.30 Local weight of each aspect from the perspective of the Government

Aspect	Environmental AS1	Economic AS2	Social AS3	Technical AS4
Local weight	0.5619	0.1624	0.2274	0.0483

Table A5.31 Local weight of each indicator in each aspect from the perspective of the Government

AS1	**C1**	**C2**	**C3**	
Local weight	0.3333	0.3333	0.3333	
AS3	**C5**	**C6**	**C7**	
Local weight	0.7083	0.0833	0.2083	
AS4	**C8**	**C9**	**C10**	**C11**
Local weight	0.1351	0.0541	0.1892	0.6216

Table A5.32 Global weight of each indicator in each aspect from the perspective of the Government

AS1	**C1**	**C2**	**C3**	
Global weight	0.1873	0.1873	0.1873	
AS2	**C4**			
Global weight	0.1624			
AS3	**C5**	**C6**	**C7**	
Global weight	0.1611	0.0189	0.0474	
AS4	**C8**	**C9**	**C10**	**C11**
Global weight	0.0065	0.0026	0.0091	0.0300

III. Sensitivity analysis

Perspective of STF

Table A5.33 Weight variations of environmental aspect

Group	Environmental AS1	Economic AS2	Social AS3	Technical AS4
1	0.2000	0.2667	0.2667	0.2667
2	0.4000	0.2000	0.2000	0.2000
3	0.6000	0.1333	0.1333	0.1333
4	0.8000	0.0667	0.0667	0.0667

Table A5.34 Global weights of the weighting assignment for each group under the variations for AS1 from the perspective of STF

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.153	0.013	0.033	0.267	0.058	0.192	0.017	0.012	0.031	0.056	0.167
2	0.307	0.027	0.067	0.200	0.044	0.144	0.013	0.009	0.023	0.042	0.126
3	0.460	0.040	0.100	0.133	0.029	0.096	0.008	0.006	0.016	0.028	0.084
4	0.613	0.053	0.133	0.067	0.015	0.048	0.004	0.003	0.008	0.014	0.042

Table A5.35 Weight variations of economic aspect

Group	Environmental AS1	Economic AS2	Social AS3	Technical AS4
1	0.2667	0.2000	0.2667	0.2667
2	0.2000	0.4000	0.2000	0.2000
3	0.1333	0.6000	0.1333	0.1333
4	0.0667	0.8000	0.0667	0.0667

Table A5.36 Global weights of the weighting assignment for each group under the variations for AS2 from the perspective of STF

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.204	0.018	0.044	0.200	0.058	0.192	0.017	0.012	0.031	0.056	0.167
2	0.153	0.013	0.033	0.400	0.044	0.144	0.013	0.009	0.023	0.042	0.126
3	0.102	0.009	0.022	0.600	0.029	0.096	0.008	0.006	0.016	0.028	0.084
4	0.051	0.004	0.011	0.800	0.015	0.048	0.004	0.003	0.008	0.014	0.042

Table A5.37 Weight variations of social aspect

Group	Environmental AS1	Economic AS2	Social AS3	Technical AS4
1	0.2667	0.2667	0.2000	0.2667
2	0.2000	0.2000	0.4000	0.2000
3	0.1333	0.1333	0.6000	0.1333
4	0.0667	0.0667	0.8000	0.0667

Table A5.38 Global weights of the weighting assignment for each group under the variations for AS3 from the perspective of STF

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.204	0.018	0.044	0.267	0.044	0.144	0.013	0.012	0.031	0.056	0.167
2	0.153	0.013	0.033	0.200	0.088	0.288	0.025	0.009	0.023	0.042	0.126
3	0.102	0.009	0.022	0.133	0.131	0.431	0.038	0.006	0.016	0.028	0.084
4	0.051	0.004	0.011	0.067	0.175	0.575	0.050	0.003	0.008	0.014	0.042

Table A5.39 Weight variations of technical aspect

Group	Environmental AS1	Economic AS2	Social AS3	Technical AS4
1	0.2667	0.2667	0.2667	0.2000
2	0.2000	0.2000	0.2000	0.4000
3	0.1333	0.1333	0.1333	0.6000
4	0.0667	0.0667	0.0667	0.8000

Table A5.40 Global weights of the weighting assignment for each group under the variations for AS4 from the perspective of STF

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.204	0.018	0.044	0.267	0.058	0.192	0.017	0.009	0.023	0.042	0.126
2	0.153	0.013	0.033	0.200	0.044	0.144	0.013	0.019	0.047	0.084	0.251
3	0.102	0.009	0.022	0.133	0.029	0.096	0.008	0.028	0.070	0.126	0.377
4	0.051	0.004	0.011	0.067	0.015	0.048	0.004	0.037	0.093	0.167	0.502

Perspective of the Government

Table A5.41 Global weights of the weighting assignment for each group under the variations for AS1 from the perspective of Government

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.067	0.067	0.067	0.267	0.189	0.022	0.056	0.036	0.014	0.050	0.166
2	0.133	0.133	0.133	0.200	0.142	0.017	0.042	0.027	0.011	0.038	0.124
3	0.200	0.200	0.200	0.133	0.094	0.011	0.028	0.018	0.007	0.025	0.083
4	0.267	0.267	0.267	0.067	0.047	0.006	0.014	0.009	0.004	0.013	0.041

Table A5.42 Global weights of the weighting assignment for each group under the variations for AS2 from the perspective of Government

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.089	0.089	0.089	0.200	0.189	0.022	0.056	0.036	0.014	0.050	0.166
2	0.067	0.067	0.067	0.400	0.142	0.017	0.042	0.027	0.011	0.038	0.124
3	0.044	0.044	0.044	0.600	0.094	0.011	0.028	0.018	0.007	0.025	0.083
4	0.022	0.022	0.022	0.800	0.047	0.006	0.014	0.009	0.004	0.013	0.041

Table A5.43 Global weights of the weighting assignment for each group under the variations for AS3 from the perspective of Government

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.089	0.089	0.089	0.267	0.142	0.017	0.042	0.036	0.014	0.050	0.166
2	0.067	0.067	0.067	0.200	0.283	0.033	0.083	0.027	0.011	0.038	0.124
3	0.044	0.044	0.044	0.133	0.425	0.050	0.125	0.018	0.007	0.025	0.083
4	0.022	0.022	0.022	0.067	0.567	0.067	0.167	0.009	0.004	0.013	0.041

Table A5.44 Global weights of the weighting assignment for each group under the variations for AS4 from the perspective of Government

No.	AS1			AS2	AS3			AS4			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	0.089	0.089	0.089	0.267	0.189	0.022	0.056	0.027	0.011	0.038	0.124
2	0.067	0.067	0.067	0.200	0.142	0.017	0.042	0.054	0.022	0.076	0.249
3	0.044	0.044	0.044	0.133	0.094	0.011	0.028	0.081	0.032	0.114	0.373
4	0.022	0.022	0.022	0.067	0.047	0.006	0.014	0.108	0.043	0.151	0.497

Table A5.45 Decision making result under each group of weighting assignment from the perspective of STF

	Environment aspect		Economic aspect	
Weighting assignment[1]	Nash equilibrium[2]	Final selection	Nash equilibrium[2]	Final selection
0.2	S2-S4	S4	S2-S4	S4
0.4	S3-S4	S4	S2-S4	S2
0.6	S3-S4	S3	S2-S4	S2
0.8	S3-S4	S3	S2-S4	S2
	Social aspect		Technical aspect	

Weighting assignment[1]	Nash equilibrium[2]	Final selection	Nash equilibrium[2]	Final selection
0.2	S2-S4	S4	S2-S4	S4
0.4	S2-S4	S2	S2-S4	S4
0.6	S2-S4	S2	S1-S4	S4
0.8	S2-S4	S2	S1-S4	S1

Note:

1 Weighting assignment refers to the assigned weight for the investigated aspect.

2 The pair of strategy is in an order as STF-Gov.

Table A5.46 Decision making result under each group of weighting assignment from the perspective of the Government

	Environment aspect		Economic aspect	
Weighting assignment[1]	Nash equilibrium[2]	Final selection	Nash equilibrium[2]	Final selection
0.2	S3-S4	S3	S3-S4	S3
0.4	S3-S4	S3	S3-S4	S3
0.6	S3-S3	S3	S3-S4	S4
0.8	S3-S3	S3	S3-S4	S4
	Social aspect		Technical aspect	
Weighting assignment[1]	Nash equilibrium[2]	Final selection	Nash equilibrium[2]	Final selection
0.2	S3-S4	S3	S3-S4	S3
0.4	S3-S4	S3	S3-S4	S3
0.6	S3-S2	S3	S3-S1	S3
0.8	S3-S2	S2	S3-S1	S3

Note:

1 Weighting assignment refers to the assigned weight for the investigated aspect.

2 The pair of strategy is in an order as STF-Gov.

Investigation for the influence of weight variation of each criterion

Table A5.47 Weighting assignment when C1 is selected as the major criterion

Criterion	C_1	C_2	C_3	C_4	C_5	C_6
Global weight	0.25	0.075	0.075	0.075	0.075	0.075
Criterion	C_7	C_8	C_9	C_{10}	C_{11}	
Global weight	0.075	0.075	0.075	0.075	0.075	

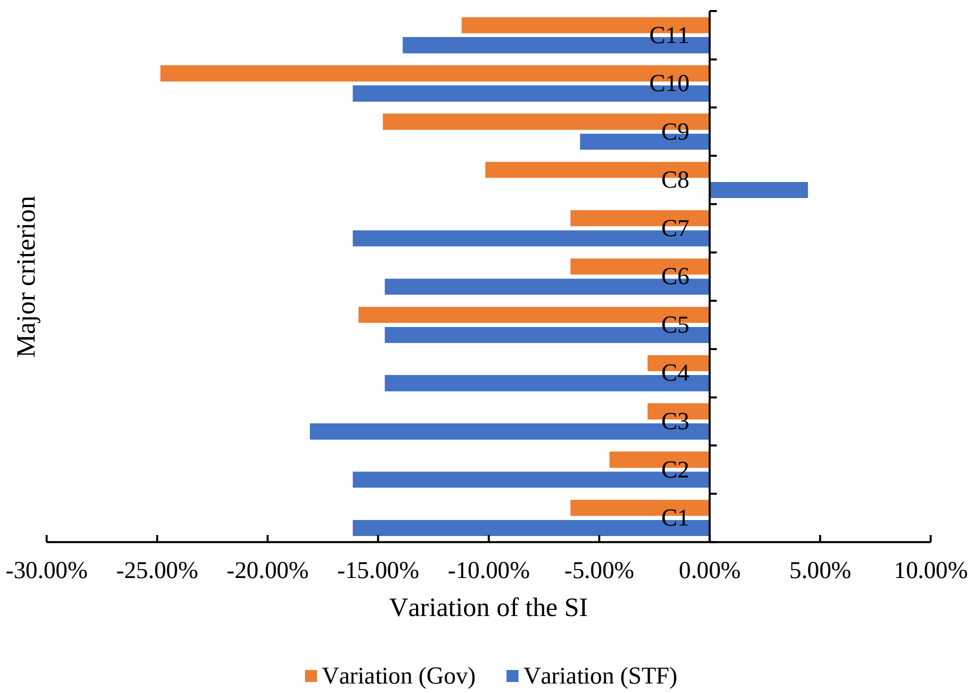

Figure A5.1 Variation of sustainability index when different criterion was selected as the major focus

Table A5.48 Detailed results of the SI variation and corresponding strategy selection under different groups of weighting assignments for STF

Major criterion	Strategy (STF-Gov)	SI - STF	SI Variation - STF	Final selection
C_1	S3-S4	0.6104	-16.15%	S4
C_2	S3-S4	0.6104	-16.15%	S4
C_3	S3-S4	0.5963	-18.09%	S4
C_4	S2-S4	0.621	-14.70%	S4
C_5	S2-S4	0.621	-14.70%	S4
C_6	S2-S4	0.621	-14.70%	S4
C_7	S3-S4	0.6104	-16.15%	S4
C_8	S3-S4	0.7604	4.45%	S3
C_9	S2-S4	0.6853	-5.87%	S2
C_{10}	S3-S4	0.6104	-16.15%	S4
C_{11}	S4-S4	0.6269	-13.89%	S4

Table A5.49 Detailed results of the SI variation and corresponding strategy selection under different groups of weighting assignments for the Gov

Major criterion	Strategy (STF-Gov)	SI - Gov	SI Variation - Gov	Final selection
C_1	S3-S3	0.6082	-6.30%	S3
C_2	S3-S4	0.6197	-4.53%	S3
C_3	S3-S4	0.6309	-2.80%	S3
C_4	S3-S4	0.6309	-2.80%	S3
C_5	S3-S2	0.5460	-15.89%	S3
C_6	S3-S3	0.6082	-6.30%	S3
C_7	S3-S3	0.6082	-6.30%	S3
C_8	S3-S3	0.5832	-10.15%	S3
C_9	S3-S4	0.5531	-14.78%	S3
C_{10}	S3-S4	0.4877	-24.86%	S3

C_{11}	S3-S4	0.5762	-11.23%	S3

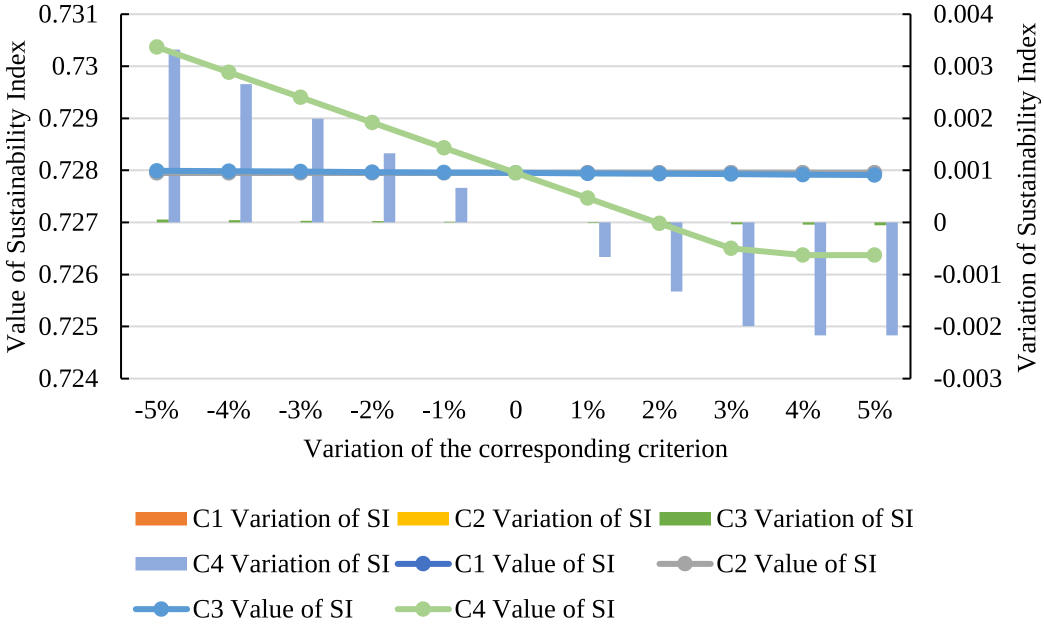

Figure A5.2 Variation of sustainability index of S3 in STF under different parameter uncertainty

Table A5.50 Detailed results of the SI variation of S3 under different parameter uncertainty

Variation of the criterion value	C_1		C_2		C_3		C_4	
	Value of SI	Variation of SI	Value of SI	Variation of SI	Value of SI	Variation of SI	Value of SI	Variation of SI
-5%	0.727952	0	0.727952	0	0.727992	5.56E-05	0.730368968	0.003321
-4%	0.727952	0	0.727952	0	0.727984	4.45E-05	0.729885484	0.002657
-3%	0.727952	0	0.727952	0	0.727976	3.34E-05	0.729402001	0.001993
-2%	0.727952	0	0.727952	0	0.727968	2.23E-05	0.728918517	0.001328
-1%	0.727952	0	0.727952	0	0.72796	1.11E-05	0.728435034	0.000664
0	0.727952	0	0.727952	0	0.727952	0	0.72795155	0
1%	0.727952	0	0.727952	0	0.727943	-1.11E-05	0.727468067	-0.000664
2%	0.727952	0	0.727952	0	0.727935	-2.23E-05	0.726984583	-0.001328
3%	0.727952	0	0.727952	0	0.727927	-3.34E-05	0.7265011	-0.001993
4%	0.727952	0	0.727952	0	0.727919	-4.45E-05	0.726371795	-0.00217
5%	0.727952	0	0.727952	0	0.727911	-5.56E-05	0.726371795	-0.00217

Weighting results obtained by fuzzy BWM (Guo and Zhao, 2017)

Table A5.51 Local weight of each aspect from the perspective of STF

Aspect	Environmental AS1	Economic AS2	Social AS3	Technical AS4
Local weight	0.4507	0.1029	0.1689	0.2775

Table A5.52 Global weight of each criterion from the perspective of STF by using fuzzy BWM

AS1	**C1**	**C2**	**C3**	
Global weight	0.2785	0.0657	0.1064	
AS2	**C4**			
Global weight	0.1029			
AS3	**C5**	**C6**	**C7**	
Global weight	0.0505	0.0900	0.0284	
AS4	**C8**	**C9**	**C10**	**C11**
Global weight	0.0286	0.0469	0.0770	0.1251

Table A5.53 Local weight of each aspect from the perspective of the Gov

Aspect	Environmental AS1	Economic AS2	Social AS3	Technical AS4
Local weight	0.4698	0.1507	0.2559	0.1236

Table A5.54 Global weight of each criterion from the perspective of the Gov by using fuzzy BWM

AS1	**C1**	**C2**	**C3**	
Global weight	0.1566	0.1566	0.1566	
AS2	**C4**			
Global weight	0.1507			
AS3	**C5**	**C6**	**C7**	
Global weight	0.1362	0.0429	0.0768	
AS4	**C8**	**C9**	**C10**	**C11**
Global weight	0.0215	0.0146	0.0357	0.0518

Weighting results obtained by fuzzy AHP (Wang et al., 2006)

Table A5.55 Local weight of each aspect from the perspective of STF

Aspect	Environmental AS1	Economic AS2	Social AS3	Technical AS4
Local weight	0.4709544	0.0970048	0.193871	0.2381699

Table A5.56 Global weight of each criterion from the perspective of STF by using fuzzy AHP

AS1	**C1**	**C2**	**C3**	
Global weight	0.2938	0.0647	0.1125	
AS2	**C4**			
Global weight	0.0970			
AS3	**C5**	**C6**	**C7**	
Global weight	0.0578	0.1042	0.0319	
AS4	**C8**	**C9**	**C10**	**C11**
Global weight	0.0228	0.0383	0.0662	0.1108

Table A5.57 Local weight of each aspect from the perspective of the Gov

Aspect	Environmental AS1	Economic AS2	Social AS3	Technical AS4
Local weight	0.4652	0.2506	0.1978	0.0864

Table A5.58 Global weight of each criterion from the perspective of the Gov by using fuzzy AHP

AS1	**C1**	**C2**	**C3**	
Global weight	0.1551	0.1551	0.1551	
AS2	**C4**			
Global weight	0.2506			
AS3	**C5**	**C6**	**C7**	
Global weight	0.1081	0.0417	0.0480	
AS4	**C8**	**C9**	**C10**	**C11**
Global weight	0.0170	0.0119	0.0239	0.0335

Table A5.59 Strategy recommendation obtained by different weighting methods

Weighting method	Strategy (STF-Gov)	Nash equilibrium (STF-Gov)	Final selection
GI-FBWM	S3-S4	(0.73,0.65)	S3
FBWM	S3-S4	(0.59,0.63)	S4
FAHP	S3-S4	(0.62,0.68)	S4

FAHP: fuzzy AHP

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Appendix Part VI: Urban Sludge-to-Energy Supply Chain Management for Circular Economy

Sensitivity analysis

Table A6.1 Amount of sludge transported from the i th sewage treatment work to the j th alternative position of sludge treatment facility for case 1 (Unit: t)

Sewage treatment works	STF1	STF2	STF3	STF4
1	0.00	116.50	0.00	0.00
2	0.00	0.00	116.50	0.00
3	0.00	0.00	33.15	0.00
4	0.00	85.24	0.00	0.00
5	0.00	8.05	0.00	0.00
6	0.00	0.00	44.04	0.00
7	0.00	0.00	56.83	0.00
8	500.00	290.21	78.05	268.32
9	0.00	0.00	161.01	0.00
10	0.00	0.00	10.42	0.00
11	0.00	0.00	0.00	5.49
Total	500.00	500.00	500.00	273.81

Note: The results were calculated based on the data provided by Drainage Service Department (2019, 2016, 2009i, 2009g, 2009c, 2009d, 2009e, 2009f, 2009b, 2009a, 2009h, 2009a) , assumptions, and the optimization model.

Table A6.2 Transportation cost between sewage treatment works and sludge treatment facilities for case 1 (USD/day)

Sewage treatment works	STF1	STF2	STF3	STF4
1	0.00	2310.31	0.00	0.00
2	0.00	0.00	2605.14	0.00
3	0.00	0.00	683.46	0.00
4	0.00	1258.25	0.00	0.00
5	0.00	92.30	0.00	0.00
6	0.00	0.00	834.23	0.00
7	0.00	0.00	734.64	0.00
8	2964.15	1450.37	533.77	2179.94
9	0.00	0.00	1361.85	0.00
10	0.00	0.00	72.39	0.00
11	0.00	0.00	0.00	33.75
Total	2964.15	5111.23	6825.48	2213.69

Case 2: Larger capacity of sludge treatment facilities

Table A6.3 Amount of sludge transported from the i th sewage treatment work to the j th alternative position of sludge treatment facility for case 2 (Unit: t)

Sewage treatment works	STF1	STF2	STF3	STF4
1	0.00	80.51	0.00	0.00
2	0.00	116.50	0.00	0.00
3	0.00	7.58	0.00	0.00
4	0.00	85.24	0.00	0.00
5	0.00	2.65	0.00	0.00
6	0.00	38.36	0.00	0.00
7	0.00	2.00	42.99	0.00
8	0.00	663.00	0.00	0.00
9	0.00	0.00	118.39	0.00
10	0.00	0.00	3.79	0.00
11	0.00	4.17	0.00	0.00
Total	0.00	1000.00	165.18	0.00

Note: The results were calculated based on the data provided by Drainage Service Department (2019, 2016, 2009i, 2009g, 2009c, 2009d, 2009e, 2009f, 2009b, 2009a, 2009h, 2009a) , assumptions, and the optimization model.

Table A6.4 Transportation cost between sewage treatment works and sludge treatment facilities for case 2 (USD/day)

Sewage treatment works	STF1	STF2	STF3	STF4
1	0.00	1596.56	0.00	0.00
2	0.00	2437.07	0.00	0.00
3	0.00	150.27	0.00	0.00
4	0.00	1258.25	0.00	0.00
5	0.00	30.41	0.00	0.00
6	0.00	760.46	0.00	0.00
7	0.00	29.63	555.79	0.00
8	0.00	3313.48	0.00	0.00
9	0.00	0.00	1001.36	0.00
10	0.00	0.00	26.32	0.00
11	0.00	27.49	0.00	0.00
Total	0.00	9603.61	1583.48	0.00

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