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Life Cycle Assessment of Municipal Solid Waste Systems to Prioritize and Compare Their Methods with Multi-Criteria Decision Making

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ABSTRACT: How to choose an energy-efficient, environmentally friendly and economically affordable municipal solid waste (MSW) management system has been a major challenge to be taken up by decision makers. Although life cycle assessment (LCA) has been widely used for the evaluation of energy consumption and environmental burden, the economic factor is not considered yet in LCA procedures. Thus, in the present study life cycle 2E (energy and environment) assessment is extended to a 3E (energy, environment, and economy) model. To evaluate economic performance, life cycle cost (LCC) is adjusted in accordance with LCA. Afterwards, multi-criteria decision making (MCDM) method is improved to integrate 3E factors. Besides, a two-step weight factor analysis is added, not only to test the robustness of the model, but also to adopt different preferences proposed by different stakeholder groups. This novel 3E model is then applied for the comparison of different MSW treatment technologies. (1) Landfill; (2) landfill with biogas conversion to electricity; (3) incineration with energy recovery. A result shows that incineration and performs best among all scenarios; landfill with biogas to electricity, with final score ranks second; and landfill without energy recovery is the worst choice. Furthermore, the weight factor analysis also shows a highly credibility of the results: when changing each factor's weight from 0 to 1, less than 30% of the cases exhibit the variation in ranking order; almost no change in ranking order occurs when considering the different perspectives from government, enterprise and residents.

KEYWORDS: Municipal Solid Waste, Life Cycle Assessment (LCA), Multi-Criteria Decision-Making (MCDM).

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1. INTRODUCTION

How to manage municipal solid waste (MSW) in an appropriate way is a worldwide issue and draws particular attention in China, where rapid economic growth has resulted in an unprecedented rise in MSW generation. More than 200 million tons of MSW are produced every year, with an annual increasing rate of 8–10%. Facing this pressure, strategies and policies relating to waste management become a major challenge to be developed by decision makers.

Different governments have implemented various laws and regulations to enhance waste management. A waste hierarchy involving recycling and reuse has been proposed, but improvements on treatment technologies are still indispensable. At present, only a limited number of technologies are widely applied. Landfill is most commonly used and accounts for approximately 95% of the total collected MSW worldwide. But it incurs the large possibility to cause leachate contaminations to underground water as well as methane release to the atmosphere. Incineration is another mainstream technology and has seen rapid development in recent However, toxic substances such as heavy metals and dioxin released during combustion may cause negative effects to the environment. Meanwhile, increasing attentions have been paid to advanced thermal treatment technologies like pyrolysis and gasification. Both advantages and shortcomings exist for their further large-scale applications. As a consequence, the establishment of a model, which can help to determine the most suitable treatment technology from a multidimensional perspective, becomes significant. Currently, the onset of global issues has led to the close attention to the environment: MSW system should move from end-of pipe treatment towards an integrated approach. Life cycle assessment (LCA) is an effective and useful tool that considers the overall environmental impacts of waste management systems. All energy consumption and emission factors, including the related up-stream and down-stream activities, are all calculated. It has been widely used to compare different scenarios for a specific treatment technology; and to compare waste management systems using different technologies.

However, although LCA can be utilized successfully to evaluate energy and environmental (2E) performance, economic factor can't be measured. In order to provide an energy-efficient, environmentally friendly and economically affordable solution, this cost component is essential. In the last decades, several types of economic models have been proposed, such as total cost assessment and cost-benefit analysis, but few of them are expressed in a life cycle perspective. Life cycle cost (LCC) has a similar structure as LCA and becomes more suitable to build the model. The term LCC views the system as a single economic actor and estimates all costs in the whole life span. However, only few LCC applications have been conducted in MSW field, and a side-by-side comparison of different MSW technologies has never been investigated. Besides, as pointed out by Norris, many differences still exist between LCC and LCA, but they are often neglected. Therefore, the first aim of the present study is to solve the most important inconsistencies between LCC and LCA, in order to give a comprehensive economic assessment of different MSW treatment technologies in parallel with LCA.

Consequently, the overall aim of the present paper is to establish a 3E model that can evaluate different waste management systems from the life cycle perspective. LCA is used to calculate energy consumption and environmental burden; LCC is adjusted for the measurement of economic performance in parallel with LCA. Afterwards, a method to combine these factors is analyzed; thus the model can be designed considering environmental, energy and economic performance simultaneously.

2. THEORETICAL AND EXPERIMENTAL RESEARCH

Energy from waste is also recycled. This huge incinerator that is designed for this purpose will be possible. Today, in addition to the incinerator, waste pyrolysis and RDF production needed to produce energy from municipal solid waste has been used. Recently this technology with rising energy price in industrial countries is taken to consideration. However the kilns burning waste are well-designed and built and if properly exploited, combustible waste problem will be solved. Bacteria and insects are destroyed in the gas stream and dispose the rest of ashes, metals has less health care importance.

According to municipal solid waste management and the nee of urban society, especially in big cities, it is necessary to conduct a full investigation and comprehensive alatrafy. In this study, an extensive research of the resources and field work was done. Then in consideration with the principles of multi-criteria decision making based on expert opinion, modeling and decision-making process was completed.

3. CONCEPTUAL MODEL FORMULATION

It is essential to provide an assessment model that is simple, reliable and practical. In the present study, the concept of LCC is defined as financial LCC, i.e. financial burden related to a system/project. According to the proposed approaches Barney, J. B., & Hansen, M. H in (1995) Environmental cost, for example the cost of rehabilitation the environment or eco-taxes are not included. This needs to emphasize because in different researches, the definition of LCC sometimes differs. The following reasons are given for omitting the environmental cost: (1) No models are well accepted for the measurement of environmental cost around the world, and no model is completely suitable for all countries; (2) Currently, there are no penalty standards or laws for pollutions discharged, so that a calculation basis is unavailable.

Some issues need to be solved when linking 3E factors together:

(1) Different factors always have different units and orders of magnitude. Thus, a ‘‘normalization’’ step is essential to make the factors comparable to each other.

(2) The model should be able to reflect the preferences made by different stakeholder groups. For MSW management, society is often divided into three groups, Barratt M. per year (2004) has expressed: government, enterprise and residents.

It is a commonly used decision support tool that can provide solutions to problems involving conflicts and multiple objectives. Meanwhile, results in order to determine the weights, convincingly, TOPSIS are improved by combing a weight calculation method named analytical hierarchy process (AHP).

TOPSIS is a widely accepted MCDM technique based on the concept that the ideal alternative has the best level for all considered attributes; According to theoretical discussions, Bauer F.L. & Fike, C., This year (1960) while the negative ideal is the one with all worst attribute values. Solutions are defined as points that are farthest from the negative ideal point and closest to the ideal point simultaneously. There are many weight calculation methods for TOPSIS, but AHP is the most reasonable one. The main reason to use AHP is its advantage based on pair-wise comparison, which makes it convenient to judge the relative importance of each criterion. Moreover, a rating scale can be used to represent the priority of criteria, so that the weights can be determined rationally. Meanwhile, in order to overcome the possible subjectivity brought by MCDM, as well as to reflect different priorities by different stakeholder groups, a weight factor analysis is added. Changes in the final ranking of alternatives are observed when giving different weights to each factor. Therefore, a more general and regular conclusion can be obtained to adapt complex situations. However, although LCA can be utilized successfully to evaluate energy and environmental (2E) performance, economic factor can’t be measured. In order to provide an energy-efficient, environmentally friendly and economically affordable solution, this cost component is essential. In the last decades, several types of economic models have been proposed, such as total cost assessment and cost-benefit analysis, but few of them are expressed in a life cycle perspective.

4. Mathematical model formulation

4.1. LCA Calculation

Four steps: (1) Goal and scope definition; (2) Life cycle inventory (LCI); (3) Life cycle impact assessment (LCIA); and (4) Interpretation. LCI and LCIA are key steps in LCA. In LCI phase, data on material flows and environmental emissions are compiled, considering both upstream and downstream activities. LCIA is aiming at evaluating the magnitude and significance of LCI result into different impact categories, through some consecutive steps including classification, characterization, normalization and weighting. Currently, many LCIA methods have been developed and widely used, such as Eco-indicator, EDIP, EPS et al. They can be applied for the calculation of energy and environmental performance of the 3E model.

4.2. LCC Calculation

In general, costs can be divided into investment cost, operation cost, and decommissioning cost. In order to share the same time boundary as LCA, time value of money is considered. Future cost is discounted to present value by using discounting rate, as estimated in Eq.

$$PV=FV\frac{1}{(1+a)^t} \tag{1}$$

(Present value) PV / (Project life time) t / (Future value) FV / (Discounting rate) α

$$PV=OM\,\frac{(1+a)^t-1}{a\times(1+a)^t} \tag{2}$$

(Operation cost annually) OM

4.3. MCDM Calculation

The calculation procedure of combined TOPSIS and AHP are presented as follows:

Step 1: Calculate the normalized decision matrix:

$$r_{ij}=\frac{f_{ij}}{\sqrt{\sum_{j=1}^{m} {f_{ij}}^2}} \quad (i = 1,2, \dots , m; = 1,2, \dots , n) \tag{3}$$

Where, rij = normalized value for each criterion; fij = original calculation value for each criterion; m = the number of alternatives; n = the number of criteria. In the present study, 3E factors are defined as the three evaluation criteria

Step 2: Determine the weight for each criterion by AHP.

According to Bénabou, R. & Tirole, J. in (2010) Pair-wise comparisons are carried out to decide which criterion is more preferred and how much greater than the other one, where larger number means larger differences between criteria levels. Afterwards, the comparison matrix is generated to compute the entire weight for each criterion. The reliability of the weights can be accepted if CR (consistency ratio) is less than 0.1.

Step 3: Calculate the weighted normalized decision matrix:

$$v_{ij} = r_{ij} \times w_j \quad (i = 1,2,\dots,m; = 1,2,\dots,n) \tag{4}$$

1. $\mathbf{v_{ij}}$ (weighted normalized value for each criterion)

2. $\mathbf{w_j}$ (criterion weight from the matrix in AHP)

Step 4: Calculate the ideal and negative ideal solution:

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\} = \{(\max v_{ij} | j \in I'), (\min v_{ij} \,|\, j \in I'')\} \tag{5}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \{(\min v_{ij} | j \in I'), (\max v_{ij} \,|\, j \in I'')\} \tag{6}$$

$\mathbf{A^+}$ (ideal solution)

$\mathbf{A^-}$ (negative ideal solution)

Step 5: Calculate the separation measures of each alternative:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \quad (i = 1,2,\dots,m) \tag{7}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad (i = 1,2,\dots,m) \tag{8}$$

$\mathbf{d_i^+}$ (the separation from ideal solution)

$\mathbf{d_i^-}$ (the separation from negative ideal solution)

Step 6: Calculate the relative closeness coefficient for each alternative to the ideal solution:

$$r_i^* = \frac{d_i^-}{d_i^+ + d_i^-} \quad (i = 1,2,\dots,m) \tag{9}$$

$\mathbf{r^*_i}$ (the relative closeness coefficient to the ideal solution)

Step 7: Rank for alternatives, where a higher closeness coefficient is expected to be obtained.

4.4. Weight Factor Analysis

A two-step weight factor analysis is considered. Firstly, weight variations from 0 to 1 are assigned to each criterion until changes in final ranking appear. Thus, stability intervals for different ranking situations can be obtained, to test the robustness of the model result.

Meanwhile, the importance of each criterion given by different stakeholder groups may also be different. Whether a stakeholder group assigns a higher or lower weight than other groups, the final ranking may change. Thus, the second step of the weight factor analysis is to adopt the different priority of the criteria made by each stakeholder group, to observe if there is any change in final ranking.

4.5. Decision Procedure

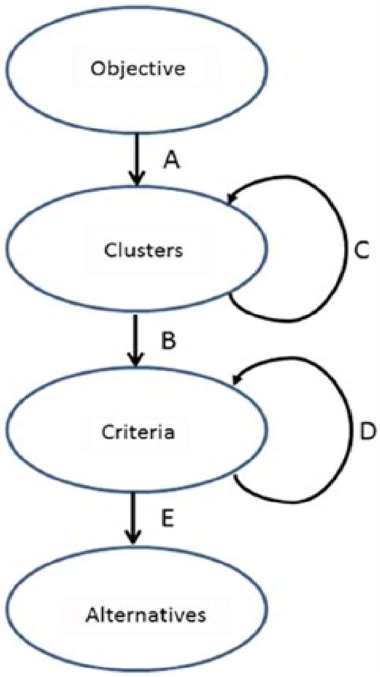

Fig. 1 Illustration of the ANP model for CO_2-based supplier evaluation, capital letters refer to the submatrices.

$$
\begin{array}{l}
\\
\text{Objective} \\
\text{Clusters} \\
\text{Criteria} \\
\text{Alternatives}
\end{array}
\begin{array}{c}
\begin{array}{cccc} \text{Objective} & \text{Clusters} & \text{Criteria} & \text{Alternatives} \end{array} \\
\left[\begin{array}{cccc}
0 & 0 & 0 & 0 \\
A & C & 0 & 0 \\
0 & B & D & 0 \\
0 & 0 & E & I
\end{array}\right]
\end{array}
$$

Fig. 2 Location of the sub-matrices in the *S-Matrix*.

5. MATRIX CALCULATION

$$AW = W\ \lambda_{max} \tag{10}$$

Here λ_{max} is the largest eigenvalue of. Provides several algorithms for approximating the eigenvector W. A two-stage algorithm to solve for ANP-procedure was programmed. This involves forming a new n* n matrix by dividing each element in a column by the sum of the column elements and then summing the elements in each row of the resultant matrix and dividing by the n elements in the row. The procedure may be algebraically represented as:

Table 1
Pairwise comparison matrix of the ANP clusters.

Obj.	*SP*	*CC*	*IM*	*OF*	*RF*	e-Vector
SP	1.0000	2.6207	0.3816	0.3684	0.7937	0.1444
CC	0.3816	1.0000	0.3816	0.3467	0.6300	0.0925
IM	2.6207	2.6207	1.0000	2.0000	2.6207	0.3621
OF	2.7144	2.8845	0.5000	1.0000	1.2599	0.2440
RF	1.2599	1.5874	0.3816	0.7937	1.0000	0.1570

Notes: λ_{max} = 5.1685; n = 5; RI = 1.11; CR = 0.0379 ⩽ 0.10.

$$W_i = \frac{\sum_{i=1}^{I}\left(a_{ij}/\sum_{j=1}^{J} a_{ij}\right)}{J} \tag{11}$$

W_i (weighted priority for component i)

To verify the consistency of the comparison matrices, a ‘consistency index’ as well as a ‘consistency ratio’ was adopted. The consistency index (CI) was deployed:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{12}$$

The consistency ratio (CR) is useful for identifying errors in the decision makers’ judgments as well as actual inconsistencies in the judgments themselves.

Where the ‘average consistency index’ (RI) varies depending on the size (n) of the matrix. Accordingly, the acceptable range for the consistency ratio also varies as a function of the matrix size. For example, for matrices with n≥5, i.e., the matrix dimension is 5* 5 or larger.

CR ≤ 0.1 .That implies:

If CR ≤ 0.1 the estimated value of w is accepted; otherwise, the corresponding decision maker was asked to adapt the priorities again Until CR ≤ 0.1. CR was calculated for each matrix (more than 100) of the three decision makers as well as after combining the matrices on the basis of the geometric mean.

The results of the inconsistency check for the cluster, including the required values as well as the e-Vector, which is important to determine the most suitable supplier, are presented by

Bottani ،E. ،& Rizzi ،A. (2005) in Table 1. The priority weights show that the cluster ‘implementation management’ (IM) has the most influence on the objective (Obj.) with a priority of 0.3621. This is followed by the cluster ‘Organizational factors’ (OF) with 0.2440; ‘risk factors’ (RF) with 0.1570; ‘supplier profile’ (SP) with 0.1444; and finally ‘CO2 management competencies’ (CC) with 0.0925. Within this matrix, CR was calculated as follows:

$$\mathrm{CR_{obj}} = \frac{\frac{5.1685-5}{5-1}}{1.11} = 0.0379 \leq 0.10$$

6. Conclusion

- This paper presents a multidimensional life cycle 3E model for MSW systems that accounts for energy, environment and cost. LCA is used to calculate the energy consumption and environmental Burden; while LCC examines the system’s financial cost in parallel with LCA. Afterwards, MCDM is conducted to integrate all the 3E factors, where TOPSIS and AHP are combined and implemented.

- To illustrate the model. Three commonly Used MSW treatment technologies are compared: (1) scenario 1: landfill without energy recovery; (2) scenario 2: landfill; (3) scenario 3: incineration with WTE.

- Results show that scenario 3 is the best choice from the perspective of energy an environment, while scenario 2 performs better from the economic perspective. Scenario 1 is always ranking last. Aggregating the individual factors, the 3E model show that scenario 3 is the best technology to be recommended, with scenario 1 the worst choice.

7. Practical suggestions

If land is not available for landfilling as well as much of the energy is proposed, the incinerator can be used. Incineration systems has been made in several sizes in which can be used for different types of waste according to humidity, amount of solid waste, and amount of heat generated. This method is mainly recommended for industrial and hospital facilities which produced hazardous waste. The reason of its recommendation, is to eliminate waste quickly and needing relatively small space. The residual ash provides less risk in the environment. Incineration is controlled in this combustion technology for a variety of material including solid, liquid, sludge and gas which is applicable.

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None.

ETHICAL CONSIDERATION

Authenticity of the texts, honesty and fidelity has been observed.

AUTHOR CONTRIBUTIONS

Planning and writing of the manuscript was done by the authors.

CONFLICT OF INTEREST

Author/s confirmed no conflict of interest.

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