Multi-Actor Multi-Criteria Decision Making for Life Cycle Sustainability Assessment under Uncertainties

Jingzheng Ren[2, **], Xusheng Ren[1], Lichun Dong[1, *], Alessandro Manzardo[3], Chang He[4], Ming Pan[4]

[1]School of Chemistry and Chemical Engineering, Chongqing University, Chongqing 400044, China

[2]Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

[3]CESQA University of Padua, Department of Industrial Engineering, Via Marzolo 9, 35131 Padua, Italy

[4]School of Chemical Engineering and Technology, Guangdong Engineering Center for Petrochemical Energy Conservation, Sun Yat-sen University, Zhuhai 519082, China

Corresponding address: School of Chemistry and Chemical Engineering, Chongqing University, Chongqing 400044, China

Tel./fax: 86-23-65111179

Email: lcdong72@cqu.edu.cn (L. Dong)

renjingzheng123321@163.com; jzhren@polyu.eud.hk (J. Ren)

Abstract. This paper aims at developing a generic multi-actor multi-criteria decision making (MAMCDM) method for life cycle sustainability assessment (LCSA) of industrial systems under uncertainties, which can help multiple stakeholders/decision-makers to prioritize the alternative industrial systems in a group decision-making approach. The interval best-worst method, which can address the ambiguity, vagueness and hesitations existing in human's judgments, was developed for determining the weight of the criteria in LCSA. The consensus convergence model was developed for aggregating the relative importance of each criterion determined by different stakeholders/decision-makers into an interval weight. Afterwards, a novel multi-criteria decision making method which can address the decision-making matrix with interval numbers was developed to prioritize industrial systems under data uncertainties. An illustrative case has been studied by the developed model, and it reveals that the developed model allows multiple stakeholders/decision-makers to participate in the decision-making processes and prioritize industrial systems accurately by using interval numbers.

Key Words: Sustainability assessment; multi-criteria decision making; best-worst method; life cycle sustainability assessment; uncertainties

Introduction

With the depletion of nonrenewable resource like fossil fuel as well as severe environmental degradation, the concepts of ‘sustainability’ and ‘sustainable development’ have been receiving more and more attention in chemical industry. In order to achieve the sustainable development, the sustainability assessment of different industrial processes in the early conceptual design stage is an essential prerequisite.[1] Accordingly, in the past several years, a variety of sustainability assessment and decision-making methodologies have been developed for helping the stakeholders/decision-makers to have a better understanding of different chemical process routes.[1-11] Lou *et al.*[9] developed a set of new sustainability indices to assess the environmental and economic performances as well as the sustainability of industrial systems. Serna *et al*[12] developed a multi-criteria decision analysis method for selecting sustainable chemical process routes in the early design stage, and the indicators for sustainability, the weights of the three dimensions of sustainability, and the influences among the three dimensions were incorporated in the developed sustainability cumulative index. Guillen-Gosalbez *et al*[13] developed a mathematical model by integrating life cycle thinking for structural optimization of process flowsheet, and the Pareto solutions can be determined for designing economically and environmentally sustainable chemical process by considering both the cost of chemical process and the life cycle environmental impacts. Aliabadi and Huang[14] develop a vector-based sustainability analytics method based on the concept of triple-bottom-line for sustainability assessment and improvement, and a novel concept-development imbalance angle was proposed for measuring the balance of triple-bottom-line based development. Othman[15] employed AHP as the decision support method for ranking chemical processes with the considerations of both hard criteria (economic and environmental criteria) and soft criteria (social criteria) for sustainability assessment. Hoffmann *et al*[16] developed a new approach for the selection of process alternatives based on approximating flowsheets with the considerations of various uncertainties. Besides the studies merely focusing on sustainability assessment or/and sustainability prioritization, there are also some studies focusing on both sustainability assessment and sustainability improvement. For instance, Liu and Huang[8] proposed a novel technology evaluation and decision-making method for enhancing the sustainability of industrial systems. Moradi-Aliabadi and Huang[17] developed a mathematical framework for multistage optimization to achieve chemical process sustainability enhancement by taking into account of economic, environmental and social concerns and technical feasibilities. These methodologies are very helpful for selecting the most sustainable chemical production or reaction routes by developing new indicators or quantifying the sustainability of industrial process routes.

Due to the specialty of the industrial systems, the sustainability assessment of industrial systems must incorporate the followed features. 1). Sustainability emphasizes to achieve economic prosperity, environment cleanness and social responsibility simultaneously.[2] Therefore, the sustainability assessment of industrial usually consist of three pillars, i.e. economic aspect, environmental issue and social performances.[18] Accordingly, there is an increasing trend to assess the sustainability of a process or product in life cycle perspective, namely life cycle sustainability assessment (LCSA), which is capable of quantifying all the three pillars of the sustainability assessment simultaneously.[19] LCSA is composed by life cycle assessment (LCA), life cycle cost (LCC), and social life cycle assessment (SLCA), which are used to assess the environmental issue, economic aspect and social performances of chemical process routes, respectively.[19] There are multiple criteria in each pillar of sustainability, thus the sustainability assessment of industrial systems should also be able to incorporate multiple criteria. 2). The decision-making on selecting the most sustainable industrial process usually involves multiple stakeholders and decision-makers[20,21], therefore, the participation of multiple stakeholders/decision-makers in the decision-making process should be allowed. Meanwhile it is usually difficult to determine the weights of the criteria for sustainability assessment based on the opinions and preferences of the stakeholders/decision-makers, because there are usually various types of ambiguities, vagueness and hesitations in human's judgments, therefore, a suitable method which can address ambiguities, vagueness and hesitations existing in human's judgments for weights determination is prerequisite in decision-making. 3). In many cases, it is difficult to describe the various chemical process quantitatively using definite numbers, where only uncertain and vague attributes are available[22], therefore, an applicable method for sustainability assessment should also be able to address uncertainties, especially various data uncertainties.

The objective of this paper is to propose a multi-actor multi-criteria decision-making framework which can simultaneously incorporate the above-mentioned three features of sustainability assessment of industrial systems for ranking industrial systems under uncertainties, in life cycle perspective and with the considerations of the preferences of multiple stakeholders/decision-makers. Firstly, LCSA by combining LCA, LCC and SLCA was employed to determine the life cycle sustainability decision-making matrix in which the data representing the environmental, economic and social performances of industrial systems can be obtained in life cycle perspective rather than in one or several stages of the industrial systems. Subsequently, the interval best-worst method was developed for determining the weights of the criteria for sustainability assessment of industrial systems, and the developed weighting method uses the interval numbers to compare the relative preference between each pair of criteria for addressing the ambiguities, vagueness and hesitations existing in human's judgments. Then, an improved Leher-Wagner model which is a consensus convergence method for aggregating individuals' criterion weights to form a consensual weight for the group was developed for determining the weight of each criterion for sustainability assessment by incorporating the opinions and preferences of different stakeholders/decision-makers. Finally, an interval multi-criteria decision making method which can handle the decision-making matrix with interval numbers for representing data uncertainties was developed for prioritizing the industrial systems. All in all, the developed framework for life cycle sustainability prioritization of industrial systems can consider the three pillars of sustainability in life cycle perspective, incorporate the preferences and opinions of multiple stakeholders/decision-makers and address uncertainties simultaneously.

Beside the introduction section, the remaining of this study has been organized as follows: mathematical models were firstly presented; an illustrative case was subsequently studied; then, sensitivity analysis was carried out and the results were also discussed; and finally, this study has been concluded.

Mathematical Models

In the proposed assessment method, LCSA method is used to determine the evaluation criteria for the industrial process routes and collect the corresponding data. An improved interval MCDM method that can address the uncertainties is used to rank the priority sequence of the different processes, in which, an interval best-worst method that is able to allow multiple actors to participate in the decision-making and address the interval comparison matrix was developed for calculating the interval weights of the criteria. The advantage of the developed weighting method is that it can reflect not only the preferences of multiple stakeholders/decision-makers, but also tackle the difficulty when facing the vagueness in the comparison matrices. The framework of the methodology is presented in Figure 1, which consists of four stages:

Stage 1: Determining the criteria for life cycle sustainability assessment, and collecting the data of the industrial processes with respect to the sustainability criteria;

Stage 2: Calculating weights of the criteria by the developed interval best-worst method;

Stage 3: Using the consensus convergence model to aggregate the individuals' criterion weights to form a consensual weight for the whole group;

Stage 4: Ranking the sustainability sequence of the alternative industrial processes by the developed interval TODIM (an acronym in Portuguese of Interactive and Multi-criteria Decision Making).

Criteria for life cycle sustainability assessment

In this study, LCA, LCC, and SLCA methods, the three components of LCSA methodology, are used to determine the assessment criteria of economic aspect, environmental issue and social performances of alternative industrial processes, respectively. The advantages of LCSA methodology is that it is able to collect the data of the assessment criteria in a life cycle perspective from “cradle” (e.g. grain production and coal mining) to “grave” (e.g. waste disposal) instead of mere production process. For instance, for bioethanol from grain, the life cycle consists of grain production (seeding, irrigation, weeding, harvesting, etc.), grain transport, bioethanol production and waste treatment, and bioethanol transport to the users. The determination of the criteria for sustainability assessment in life cycle perspective by using LCSA methodology consists of three steps. 1). Goal and scope definition, taking bioethanol production from grain as the example, the goal is to investigate the sustainability of its production in environmental, economic and social aspect, and the scope is from grain production to waste disposal and bioethanol transport; 2). Inventory analysis, namely using LCA, LCC and SLCA as tools to collect the data used in the inventory; 3). Impact assessment, the purpose of this step is to aggregate the data in the inventory into the corresponding criteria or calculate the values for the corresponding criteria used in LCA, LCC, and SLCA, respectively. The criteria concerning environmental, economic and social aspects can be determined by LCA, LCC, and SLCA, respectively, in this process. Thus, all the criteria for sustainability assessment of alternative chemical processes can be obtained.

By following previous studies,[1-11, 23-27] multiple criteria in each dimension were selected in this study to assess the sustainability of chemical process routes in life cycle perspective (see Figure 1). The criteria assessing the environmental aspect in LCA consist of several criteria for measuring environmental performances, i.e., the global warming potential (*GWP*), ozone layer depletion potential (*OLDP*), photochemical oxidation potential (*PCOP*), acidification potential (*AP*), human toxicity potential by ingestion (*HIPI*), human toxicity potential by either inhalation or dermal exposure (*HTPE*), aquatic toxicity potential (*ATP*), and terrestrial toxicity potential (*TTP*). It is worth pointing out that there are several life cycle impact assessment (LCIA) methods can be selected, i.e. Eco-indicator 99, CML 2001 (Life Cycle Assessment-An Operational Guide to the ISO Standards 2001), and ReCiPe 2008 method, etc. The evaluation criteria for measuring environmental performances are different when choosing different LCIA methods.

The criteria assessing the economic aspect in LCC include a set of criteria for measuring economic performances, i.e. life cycle cost (LCC), capital cost (CC), net present value (*NPV*) and internal rate of return (*IRR*), which are the most popular indices that are usually used to measure the economic performances of industrial processes. Similar to the criteria in environmental aspect, different users can select different criteria for measuring the economic performances of industrial processes according to their preferences and the actual conditions.

The criteria assessing the social aspect in SLCA comprise multiple criteria for measuring social performances[28-29], i.e. child labor (*CL*), fair salary (FS), forced labor (FL), health and safety (HS), social benefits (SB), discrimination (DI), community engagement (CE), and contribution to economic development (CED). These criteria mainly influence three groups of stakeholders including workers, society and local community, as presented in Table 1. All the criteria in social aspect are usually easy to be qualitatively described but difficult to be measured and formulated, consequently, scaling system method is often used to quantify these criteria. Decision-makers can organize a symposium by inviting multiple stakeholders to discuss these criteria, and let them to use 'linguistic terms' to describe the performance of these criteria and score them with the ten scales (see Table 1).

It is notable that it is difficult to use an exact number as the score or use an exact number with units to describe the performance of some criteria in social dimension accurately. Thus, this study developed a novel method for the stakeholders to determine the relative scores of these alternatives regarding some criteria in social dimension.

After determining the data in the life cycle inventory, the data regarding different criteria usually need to be aggregated into a generic index by using the so-called "weighting method", for comparing the priorities of different alternative industrial processes. The weights of the criteria reflect not only their importance but also the preferences of the decision-makers/stakeholders. Meanwhile, a generic index as a measure of sustainability could be obtained by aggregating various attributes or criteria into one index based on the weights of the criteria. Thus, the accurate determination of the weights of each criterion is a prerequisite for reliable sustainability assessment of industrial processes.

There are usually various methods for determining the weights of the criteria, and they can be classified into two categories: objective methods and subjective methods[17]. The subjective weighting methods, e.g. Delphi method and analytic hierarchy process (AHP) method, can reflect the preferences of the stakeholders/decision-makers, but neglect the objective importance and impact of every criterion on a system.[30] On the contrary, the objective weighting methods, e.g. entropy weighting method and vertical & horizontal method, [30-32] can reflect the importance and the impact of every criterion on a system, but neglect the preferences of the stakeholders/decision-makers.

Among them, AHP is the most popular method since it is organized in a tree structure and has the ability to decompose a complex problem into several sub-problems, meanwhile it has the advantages of simplicity in concept and easy-for-operation.[33, 34] Moreover, it is a semi-quantitative methodology which can incorporate both the preferences of the stakeholder/decision-makers and the consideration to actual conditions. To some extent, AHP is an object-oriented method.

In the conventional AHP method, the pairwise comparison method proposed by Saaty[35] in 1978 is used to determine the comparison matrix, in which, the scale from 1 to 9 is used for comparison with 1 indicating equal importance and 9 indicating very absolutely important of one criterion over another.

The comparison matrix for determining the weights has to be consistent with the consistency check. However, it is usually difficult for the users to determine a consistent comparison matrix due to the ambiguity and vagueness in human judgments, because they have to make $n(n-1)/2$ times of comparison when establishing a $n \times n$ comparison matrix for determining the weights/relative importance of n criteria. Rezaei[36,37] developed a great and powerful tool that can conduct the comparisons in a particularly structured way, such that not only is less information is required, but the comparisons are also more consistent.

The nine-scale system including the numbers from 1 to 9 and their reciprocals was used to to determine the weights of the criteria by establishing the BO and OW vectors when using the BW method, and the two vectors are also determined based on the preferences of a stakeholder/decision-maker or a bad consensus by trade-off among several stakeholder/decision-makers, so it cannot reflect the preferences of all the stakeholders/decision-makers accurately due to the difference of opinions. Moreover, the nice-scale method is usually difficult for the stakeholders/decision-makers to express their options when comparing two factors clearly and accurately. For instance, it is impossible for the stakeholders/decision-makers to use a crisp number among 1 to 9 and their reciprocals to express the relative importance of a criterion over another if they held the view that the relative importance of a criterion over another is between “equal importance” (corresponding to 1) and “moderate importance” (corresponding to 3), and the interval $[1 \quad 3]$ rather than the crisp numbers (i.e. 1, 2, 3) is more suitable to depict this comparison. Moreover, the awareness of different stakeholders/decision-makers is different. Accordingly, different stakeholders/decision-makers will establish different comparison matrices for determining the weights of the criteria.

All in all, there are two limitations in the BW method, one is that it cannot address the ambiguity, vagueness and subjectivity existed in human judgments, and another is that it does not allow group decision-making. In order to overcome these two limitations, an interval BW method was developed in this study by extending the traditional BW method to interval conditions. The interval numbers for addressing the ambiguity, vagueness and subjectivity existed in human judgments was used for expressing the relative preference of a criterion over another, and the interval BW method was then developed.

There are three widely used approaches for addressing uncertainties, stochastic theory, fuzzy theory, and interval theory.[38] However, the use of the stochastic theory and the fuzzy needs to know the probability distributions and membership functions which are usually difficult for the users to determine in practice; the interval approach is easier for the users to implement in practice, because the users only need to determine the possible lower and upper bounds. For more details of interval numbers, the readers can refer to the **Supplementary Materials** for the definition[39, 40], midpoint of interval number[39], the arithmetic operations between the interval numbers [39,41], the Euclidean distance between two interval numbers[42], the possibility degree of an interval number to be greater than another[37], and the greater than relationship[43]. Based on interval numbers, the interval BW method was presented in as follows.

Interval Best-Worst method

The interval BW method which consists of four sub-steps was developed to determine the weights of the criteria (see the **Supplementary Materials**). The BW method developed by Rezaei[36,37] was extended to interval environment by integrating the traditional BW method and the work of Sugihara *et al*. (2004)[44]. In the interval BW method, interval numbers are used to represent the relative importance of the criteria, which can be determined according to the nine-scale system in Saaty method[35]. For instance, the two intervals <1, 2> and <1/4, 1/3> can be used to measure the relative importance instead of the crisp numbers.

Comparing with the traditional BW method, the developed interval BW method has a significant advantage-the ambiguity, vagueness and hesitations existing in human's judgments can be addressed, because the users of the interval BW method are allowed to use interval numbers instead of crisp numbers to express their opinions and preferences of the decision-makers in the process of determining the relative priorities of the criteria.

Consensus Convergence Model for Group Decision-making

There are a total of s decision-makers/stakeholders, and s different interval comparison matrices $A^t(t=1,2,\cdots,s)$ will be developed due to the different preferences and willingness. Accordingly, there will be a total of s weight vectors $\left[\tilde{\omega}_1^t \quad \tilde{\omega}_2^t \quad \cdots \quad \tilde{\omega}_n^t\right](t=1,2,\cdots,s)$ which can be determined by the interval BW model presented above, as presented in Eq.1.

$$\begin{bmatrix} \tilde{\omega}_1^1 & \tilde{\omega}_2^1 & \cdots & \tilde{\omega}_n^1 \\ \tilde{\omega}_1^2 & \tilde{\omega}_2^2 & \cdots & \tilde{\omega}_n^2 \\ \vdots & \cdots & \ddots & \vdots \\ \tilde{\omega}_1^m & \tilde{\omega}_2^m & \cdots & \tilde{\omega}_n^m \end{bmatrix} \tag{1}$$

where $\tilde{\omega}_j^t\left(t=1,2,\cdots,s;\, j=1,2,\cdots,n\right)$ is the weight of the *j*-th criterion determined by the *t*-th decision-maker.

There are two main mathematical aggregating methods for incorporating the opinions of all the decision-makers: the aggregation of individual priorities (AIP) and the aggregation of individual judgments (AIJ). The AIP method is to aggregate the different weight vectors into a single weight vector. Accordingly, the *s* weight vectors should be aggregated into a single weight vector. The AIJ method is to aggregate the different interval comparison matrices into a single interval comparison matrix. Accordingly, the s different interval comparison matrices $A^t(t=1,2,\cdots,s)$ should also be aggregated into a single interval comparison matrix. There are various AIP and AIJ methods, i.e. weighted geometric mean (WGM) AIP method, weighted geometric mean (WGM) AIJ method, weighted arithmetic mean (WAM) AIP method, the and Leher-Wagner (LW) model, etc.[45] Grošelj et al. (2015)[45] compared the performances of various aggregation techniques using group AHP, and the group Euclidean distance (GED) index, group minimum violations (GMV), distance between weights (WD), the satisfactory (SAT) index, and fitting performance (FP) index were used as evaluation measures for comparing these aggregation techniques, and Leher-Wagner (LW) model was recognized as a more promising method for group decision-making for its advantages of performing well in most of the measures including SAT, GED, WD. However, the traditional LW model was applied in the traditional AHP dealing the crisp numbers, thus, an improved LW model (see the **Supplementary Materials**) was developed in this study to deal with the interval BW method with interval numbers based on the work of Regan *et al*.[46] and that of Yaniv[47].

Interval Multi-Criteria Decision Making

Sustainability assessment of industrial processes usually consists of multiple criteria, therefore, determining the priority sequence of the alternative industrial processes can only be addressed by a multi-criteria decision making (MCDM) method, which can assist decision-making by analyzing and comparing different alternatives with multiple interactive or even conflicting criteria. Among the various MCDM methods, e.g. ELimination Et Choix Traduisant la REalité (ELECTRE) II method, ELECTRE III method,[48-49] Data Envelopment Analysis (DEA),[50-51] and Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) method,[23,52] Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) [53-57], and TODIM,[58] etc., the TODIM (an acronym in Portuguese of interactive and multi-criteria decision making) method is the most suitable for sustainability assessment, because this is a discrete MCDM method based on prospect theory, and the global value function of this method can aggregate all measures of gains and losses by considering all criteria.[59] Meanwhile, the aversion and propensity to risk during the decision-making can be incorporated based on prospect theory.[60]

TODIM method[58] developed by Gomes and Lima in 1992 ranks the alternatives by determining the dominance degree of each alternative over the others by using the utility function originating from the prospect theory.[61] However, the traditional TODIM method cannot address the multi-criteria decision making problem with data uncertainties, thus an innovative interval TODIM (ITODIM) method (see the **Supplementary Materials**) was developed by extending the tradition TODIM method to the conditions of interval numbers in this study.

Case Study

For illustrating the proposed method, a hypothetical case with five alternative industrial process routes for electricity generation in UK was studied, and they are coal-pulverised (A_1), combined cycle gas turbines (A_2), nuclear-pressurised water reactor (A_3), offshore wind powder based electricity (A_4), and solar-photovoltaics (A_5). For more details, the readers can refer to the work of Stamford and Azapagic[62]. A total of fourteen criteria including four criteria (capital cost-Ec_1, operation and maintenance cost-Ec_2, fuel cost-Ec_3, and total cost-Ec_4) in economic dimension, six criteria (global warming potential-En_1, ozone depletion- En_2, acidification potential-En_3, eutrophication-En_4,photochemical smog-En_5, and land occupation-Ec_6) in environmental dimension, and four criteria (social acceptability-S_1, employment-S_2, Human toxicity potential-S_3, and total health impacts from radiation-S_4) in social dimension were employed for life cycle sustainability assessment of these five industrial process routes for electricity generation in UK.

As a multi-actor multi-criteria decision-making problem, four groups of decision-makers/stakeholders including producer group (DM#1), governor group (DM#2), consumer group (DM#3) and academic group (DM#4) are invited to participate in the decision-making process. The producer group consists of five engineers from the power industry, the governor group includes a senior manager and three administrators from the government, the consumer group has seven electricity users, and the academic group consists of two professors of power engineering, three PhDs in energy and environmental engineering, and a postdoctoral fellow in chemical engineering. A coordinator was nominated in each group, and he/she firstly invited all the members to participate in a survey for determining the interval comparison matrix which evaluate the relative importance of the three aspects including economic aspect, environmental aspect, and social aspect and that of the criteria in each aspect. Then, the final interval comparison matrices for determining the weights of the three dimensions of sustainability and that of the criteria in each dimension will be determined after a consensus is achieved in each group.

The weights of the three dimensions of sustainability and the local weights of the criteria in each dimension can be firstly determined by the developed interval BW method, and the results based on the opinions and preferences of the four groups of stakeholders are different. After that the aggregated weights of the three dimensions and that of the criteria in each dimension can subsequently be determined by the developed LW model. The procedures were specified in the **Supplementary**

Materials.

As for the data in the life cycle sustainability decision-making matrix, the data of the five electricity generation systems with respect to the hard criteria (all the fourteen criteria except social acceptability-S_1) were derived from the work of Stamford and Azapagic[62]. However, the aggregated relative priorities of the five alternative electricity scenarios (coal-A_1, gas-A_2, nuclear-A_3, wind-A_4 and solar-A_5) with respect to social acceptability which incorporates the opinions and preferences of all the four groups of stakeholders were determined by the developed interval BW method (the procedures were specified in the **Supplementary Materials**). The life cycle sustainability decision-making matrix was presented in Table 2. Then, the overall priorities of the alternatives based on the life cycle sustainability data can be determined by the developed ITODIM method, and the results were presented in Figure 2. Finally, the sustainability sequence of the five alternative electricity scenarios were ranked, which shows that A_4 is the most sustainable routes followed by A_2, A_3, A_5 and A_1, respectively. Therefore, the offshore wind powder based electricity (A_4) is the most sustainable, following by combined cycle gas turbines (A_2), nuclear-pressurised water reactor (A_3), solar-photovoltaics (A_5) and coal-pulverised (A_1) in the descending order.

The illustrated study is a generic case and consists of some of the criteria for sustainability assessment of industrial processes, thus in the real cases, the stakeholders/decision-makers could select partial criteria according to the actual situations and the preferences of the stakeholders.

Sensitivity Analysis and Validation

Sensitivity analysis

In order to understand how the weights of the criteria influence the final ranking, sensitivity analysis was implemented in this section by altering the weights of the criteria, and the following cases were investigated for comparing with the base case (the weights of the criteria determined by interval BW method in the base case):

Case 0: $\tilde{\omega}_j^* = \frac{1}{14} \quad (j = 1, 2, \cdots, 14)$**,** the relative importance of all the fourteen criteria was assumed to be equal;

Case 1-14: $\tilde{\omega}_j^* = 0.35(j = 1, 2, \cdots, 14), \tilde{\omega}_k^* = 0.05 \quad (k = 1, 2, \cdots, 14, k \neq j)$ in case j, a dominant weight was assigned to one criterion with a weight of 0.35, and the other criteria were recognized as equal with a weight of 0.05.

The integrated priorities of the five scenarios under the above-mentioned cases were presented in Figure 3. Wind powder based electricity (A_4) was recognized as the most sustainable in all the fifteen cases though combined cycle gas turbines (A_2) was also identified as the most sustainable in case 1, and coal-pulverised (A_1) was regarded as the worst in all the cases. However, the sustainability ranking of the three scenarios including combined cycle gas turbines (A_2), nuclear-pressurised water reactor (A_3), and solar-photovoltaics (A_5) varies when changing the weights of the criteria.

It could be summarized that the weights of the criteria for life cycle sustainability assessment have influences on the sustainability ranking; however, the results of the most sustainable and the least sustainable scenario for electricity generation are robust in this case. However, the accurate reflection of the preferences of the decision-makers and the relative importance of the criteria is critical for life cycle sustainability assessment, because the weights of the criteria can influence the final sustainability ranking.

Comparison with interval sum weighted method

An interval sum weighted method (ISWM) was used to determine the integrated superiorities of the five electricity scenarios. The interval SWM was presented as follows.

After determining the normalized decision-making matrix in the interval TODIM method, the weighted decision-making matrix can then be determined, as presented in Eq.2. .

$$V = \left|\tilde{v}_{ij}\right|_{m\times n} = \begin{vmatrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{\omega}_1^* \tilde{r}_{11} & \tilde{\omega}_2^* \tilde{r}_{12} & \cdots & \tilde{\omega}_n^* \tilde{r}_{1n} \\ A_2 & \tilde{\omega}_1^* \tilde{r}_{21} & \tilde{\omega}_2^* \tilde{r}_{22} & \vdots & \tilde{\omega}_n^* \tilde{r}_{2n} \\ \vdots & \vdots & \cdots & \ddots & \vdots \\ A_m & \tilde{\omega}_1^* \tilde{r}_{m1} & \tilde{\omega}_2^* \tilde{r}_{m2} & \cdots & \tilde{\omega}_n^* \tilde{r}_{mn} \end{vmatrix} \quad (2)$$

where $\tilde{\omega}_j^*$ represents the normalized interval weight of the j-th criterion, $\tilde{r}_{ij}$ represents the data of the i-th alternative with respect to the j-th criterion, and $\tilde{v}_{ij}$ represents the weighted value of the i-th alternative with respect to the j-th criterion.

Then, the integrated superiorities of the alternatives can be determined by Eq.3.

$$IS_i = \sum_{j=1}^{n} \tilde{v}_{ij} \quad (3)$$

where IS_i which is an interval number represents the integrated superiority of the *i*-th alternative.

The results were presented in Table 3, and the results reveal that the consistency between the results determined by the developed interval TODIM and that by the interval SWM.

However, the IWSM determines the integrated superiorities of the alternatives based on simple sum but cannot fully consider the difference of each pair of two alternatives with respect to each criterion compared with the interval TODIM method.

Discussion

This study developed a multi-actor multi-criteria decision making framework for life cycle sustainability assessment and prioritization of industrial processes, and the developed framework has the following advantages:

(1) Life cycle thinking has been incorporated in the process of selecting the most sustainable industrial systems, and the economic, environmental, and social performances of industrial processes can be investigated in a “from cradle to grave” approach rather than merely focusing on the production stage;

(2) Multiple stakeholders are allowed to participate in the decision-making. The opinions and preferences of different stakeholders rather than that of a special group of stakeholders have been incorporated in the decision-making process, and the sustainability order of industrial systems determined by the proposed method are based on democratic decision-making;

(3) Data uncertainties are considered when selecting the most sustainable

industrial system rather than assuming that all the data for sustainability assessment are fixed crisp numbers. In other words, the uncertainty factors can be incorporated in the prioritization of industrial systems according to their integrated sustainability performances.

Besides the advantages, there are also some limitations and challenges when using the developed framework for selecting the most sustainable industrial system among multiple alternatives:

(1) The difficulty in data collection: it is usually difficult or impossible to simultaneously obtain the data about the life cycle economic, environmental and social performances of the emerging technologies[63];

(2) The lack of considering the interdependences and interactions among the criteria for sustainability assessment: all the criteria for sustainability assessment of industrial systems are assumed to be independent, but this assumption does not match with the actual conditions, because there are usually various interdependences and interactions among the criteria for sustainability assessment[23, 64];

(3) The lack of the ability to address the decision-making matrix with hybrid types of numbers: as mentioned-above, it is usually difficult or impossible to obtain the data for decision-making, and some other types of numbers (i.e. fuzzy numbers and grey numbers) are also widely used for rating the industrial systems in terms of their performances on some criteria for sustainability assessment, but the proposed method in this study cannot deal with the

decision-making matrix with hybrid types of numbers;

(4) The loss of useful information when using the interval numbers for representing data uncertainties: the users employing the interval numbers to address data uncertainties do not need to know the mechanisms of data variations in industrial systems, but some useful information of the mechanism cannot be effectively used.

Conclusions

A multi-actor multi-criteria decision-making methodology was proposed for sustainability assessment and ranking of industrial processes under uncertainties in a life cycle approach, which can help the stakeholders/decision-makers to select the most sustainable routine among multiple alternatives. In the proposed methodology, the evaluation criteria and the corresponding data were collected to evaluate the economic, environmental and social aspects of the alternative industrial processes in life cycle perspective. Then an extended interval TODIM method was used to rank the different processes by aggregating the various criteria into a generic index as a measure of the sustainability, in which, an interval BW method was used to calculate the weights indicating the relative importance of the evaluation criteria. The developed method can not only allow multiple stakeholders/decision-makers to participate in the decision-making, but also address uncertainties by allowing the stakeholders/decision-makers to use interval number to represent the relative preference of a criterion over another.

An illustrative case including five electricity generation systems including coal-pulverised, combined cycle gas turbines, nuclear-pressurised water reactor, offshore wind powder based electricity, and solar-photovoltaics was studied by the proposed method, and the offshore wind powder based electricity was recognized as the most sustainable, following by combined cycle gas turbines, nuclear-pressurised water reactor, solar-photovoltaics and coal-pulverised in the descending order. As discussed above, there are also some limitations in the developed method, and the future work of the authors is to develop a multi-actor multi-criteria decision making method which can not only achieve group decision-making under uncertainties, but also incorporate the interdependences and interactions among the criteria for sustainability assessment and address the decision-making matrix with hybrid types of numbers, for life cycle sustainability assessment and prioritization of industrial systems.

Acknowledgment

This work is financially supported by the National Science Foundation of China (21776025).

Notation

Abbreviation

AHP=Analytic Hierarchy Process

AP=acidification potential

ATP=aquatic toxicity potential

CE=community engagement

CED=contribution to economic development

CL=child labor

DI=discrimination

FL=forced labor

FS=fair salary

GWP=global warming potential

HIPI=human toxicity potential by ingestion

HTPE=human toxicity potential by either inhalation or dermal exposure

HS=health and safety

IRR=internal rate of return

LCA=life cycle assessment

LCC=life cycle cost

LCSA=life cycle sustainability assessment

NPV=net present value

OPD=ozone layer depletion potential

PCOP=photochemical oxidation potential

SB=social benefits

SLCA=social life cycle assessment

TOPSIS=Order Preference by Similarity to the Ideal Solution

TTP=terrestrial toxicity potential

Literature Cited

1. Zheng K, Lou HH, Gangadharan P, Kanchi K. Incorporating Sustainability into Conceptual Design of Chemical Process-Reaction Routes Selection. *Ind Eng Chem Res.* 2012; 51: 9300-9309.
2. Fermeglia M, Longo G, Toma L. Computer aided design for sustainable industrial processes: Specific tools and applications. *AIChE J* 2009; 55(4): 1065-1078.
3. Piluso C, Huang J, Liu Z, Huang Y. Sustainability Assessment of Industrial Systems under Uncertainty: A Fuzzy Logic Based Approach to Short-Term to Midterm Predictions. *Ind Eng Chem Res.* 2010; 49: 8633-8643.
4. Conner JA, Phillis YA, Manousiouthakis VI. On a sustainability interval index and its computation through global optimization. *AIChE J* 2012; 58(9): 2743-2757.
5. Piluso C, Huang Y, Lou HH. Ecological Input-Output Analysis-Based Sustainability Analysis of Industrial Systems. *Ind Eng Chem Res.* 2008; 47: 1955-1966.
6. Lou HH, Kulkarni MA, Singh A, Huang Y. A game theory based approach for emergy analysis of industrial of industrial ecosystem under uncertainty. *Clean Techn Environ Policy.* 2004; 6: 156-161.
7. Li X, Zanwar A, Jayswal A, Lou HH, Huang Y. Incorporating Exergy Analysis and Inherent Safety Analysis for Sustainability Assessment of Biofuel. *Ind Eng Chem Res.* 2011; 50: 2981-2933.
8. Liu Z, Huang Y. Technology Evaluation and Decision Making for Sustainability Enhancement of Industrial Systems Under Uncertainty. *AIChE.J* 2012; 58(6):

1841-1852.

9. Lou HH, Kulkarni MA, Singh A, Hopper JR. Sustainability Assessment of Industrial System. *Ind Eng Chem Res* 2004; 43: 4233-4242.
10. Young DM, Cabezas H. Designing sustainable processes with simulation: the waste reduction (WAR) algorithm. *Comput Chemi Eng.* 1999; 23: 1477-1491.
11. Gangadharan P, Zanwar A, Zheng K, Gossage J, Lou HH. Sustainability assessment of polygeneraton process based on syngas derived from coal and natural gas. *Comput Chem Eng.* 2012; 39, 105-117.
12. Serna, J, Martinez, END, Rincón, PCN, Camargo M, Gálvez D, Orjuela Á. Multi-criteria decision analysis for the selection of sustainable chemical process routes during early design stages. *Chem. Eng. Res. Design* 2016; 113, 28-49.
13. Guillen-Gosalbez, G, Caballero, JA, Jimenez, L. Application of life cycle assessment to the structural optimization of process flowsheets. *Ind. Eng. Chem. Res*. 2008; 47(3), 777-789.
14. Aliabadi, MM, Huang, Y. Vector-Based Sustainability Analytics: A Methodological Study on System Transition toward Sustainability. *Ind. Eng. Chem. Res*. 2015, 55(12), 3239-3252.
15. Othman, MR, Repke JU, Wozny G, Huang, Y. A modular approach to sustainability assessment and decision support in chemical process design. *Ind. Eng. Chem. Res*. 2010, 49(17), 7870-7881.
16. Hoffmann, VH, McRae, GJ, Hungerbühler K. Methodology for early-stage technology assessment and decision making under uncertainty: Application to the

selection of chemical processes. *Ind. Eng. Chem. Res*. 2004, 43(15), 4337-4349.

17. Moradi-Aliabadi, M, Huang, Y. Multistage optimization for chemical process sustainability enhancement under uncertainty. ACS Sustain. Chem. Eng. 2016; 4(11), 6133-6143.
18. Sikdar，SK. Sustainable Development and Sustainability Metrics. *AIChE. J* 2003; 49(8): 1928-1932.
19. Heijungs, R., Huppes, G., Guinee, J.B. Life cycle assessment and sustainability analysis of products, materials and technologies. Towards a scientific framework for sustainability life cycle analysis. *Polym Degrad Stabi* .2010; 95, 422-428.
20. Turcksin L, Maharis C, Lebeau K, Boureima F, Mierlo JV, Bram S, Ruyck JD, Mertens L, Jossart JM, Gorissen L, Pelkmans L. A multi-actor multi-criteria framework to assess the stakeholder support for different biofuel options: The case of Belgium. *Energy Policy.* 2011; 39: 200-214.
21. Diaz-Chavez RA. Assessing biofuels: Aiming for sustainable development or complying with the market? *Energy Policy.* 2011; 39: 5763-5769.
22. Ren, J., Ren, X., Liang, H., Dong, L., Zhang, L., Luo, X.,Yang, Y., Gao, Z. Multi-actor multi-criteria sustainability assessment framework for energy and industrial systems in life cycle perspective under uncertainties. Part 2: Improved extension theory. *Int. J. LCA* 2017; 22(9), 1406-1417..
23. Ren J, Xu D, Gao H, Wei S, Dong L, Goodsite ME. Sustainability decision support framework for industrial system prioritization. *AICHE J*. 2016; 62(1): 108-130.

24. Sikdar SK. Sustainable development and sustainability metrics. *AIChE. J* 2003; 49(8): 1928-1932.

25. Allen DT, Shonnard DR. Sustainability in chemical engineering education: Identifying a core body of knowledge. *AIChE. J* 2012; 58(8): 2296-2302.

26. Bakshi BR, Fiksel J. The quest for sustainability: Challenges for process systems engineering. *AIChE. J* 2003; 49(6): 1350-1358.

27. Tugnoli A, Santarelli F, Cozzani V. Implementation of sustainability drivers in the design of industrial chemical processes. *AIChE. J* 2011; 57(11): 3063-3084.

28. Foolmaun RK, Ramjeawon T. Life cycle sustainability assessment (LCSA) of four disposal scenarios for used polyethylene terephthalate (PET) bottles in Mauritius. *Environ Dev Sustain*. 2013; 15: 783-806.

29. Foolmaun RK, Ramjeawon T. Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. *Int J Life Cycle Assess.* 2013; 18: 155-171.

30. Wang JJ. Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew Sustain Energy Rev.* 2009; 13: 2263-2278.

31. Wang JJ, Jing YY, Zhang CF. Weighting methodologies in multi-criteria evaluations of combined heat and power systems. *Int J Energy Res.* 2009; 33: 1023-1039.

32. Jing YY, Bai H, Wang JJ. A fuzzy multi-criteria decision-making model for CCHP systems driven by different energy sources. *Energy Policy.* 2012; 42: 286-296.

33. Fei NY, Sambasivan M. Evaluation of critical success factors of implementation of ISO 14001 using analytic hierarchy process (AHP): a case study from Malaysia. *J Clean Pro.* 2008; 16: 1424-1433.
34. Pilavachi PA, Chatzipanagi AI, Spyropoulou AI. Evaluation of hydrogen production methods sing the Analytic Hierarchy Process. *Int J Hydrogen Energy*. 2009; 34: 5294-5303.
35. Saaty TL. Exploring the interface between the hierarchies, multiple objectives and the fuzzy sets. *Fuzzy Sets Sys.* 1978; 1: 57–68.
36. Rezaei J. Best-worst multi-criteria decision-making method. *Omega.* 2015; 53: 49-57.
37. Rezaei J. Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega.*2016; 64: 126-130.
38. Ren J, An D, Liang H, Dong L, Gao Z, Geng Y, Zhu Q, Song S, Zhao W. Life cycle energy and CO 2 emission optimization for biofuel supply chain planning under uncertainties. *Energy.* 2016; 103: 151-166.
39. Alefeld G, Herzberger J. Introduction to interval computation. 2012; Academic press.
40. Xu ZS, Da QL. The uncertain OWA operator. *Int. J. Intell. Syst*. 2002; 17(6): 569-575.
41. Xu Z. Dependent uncertain ordered weighted aggregation operators. *Inform. Fusion* 2008; 9(2), 310-316.
42. Wang, Z, Xu, G, Ren, J, Li, Z, Zhang, B, Ren, X. Polygeneration system and

sustainability: Multi-attribute decision-support framework for comprehensive assessment under uncertainties. *J. Clean. Prod.* 2017, 167, 1122-1137.

43. Wang YM, Yang JB, Xu DL. A preference aggregation method through the estimation of utility intervals. *Comput. Oper. Res.* 2005; 32(8): 2027-2049.
44. Sugihara K, Ishii H, Tanaka H. Interval priorities in AHP by interval regression analysis. *Eur. J. Oper. Res.* 2004; 158(3): 745-754.
45. Grošelj P, Stirn LZ, Ayrilmis N, Kuzman MK. Comparison of some aggregation techniques using group analytic hierarchy process. *Expert Syst. Appl.* 2015; 42(4): 2198-2204.
46. Regan HM, Colyvan M, Markovchick-Nicholls L. A formal model for consensus and negotiation in environmental management. J. Environ. Manage. 2006; 80(2): 167-176.
47. Yaniv I. Receiving other people’s advice: influence and benefit. Organizational Behavior and Human Decision Processes 2004; 93 (1): 1–13.
48. Roy B. Classement et choix en présence de points de vue multiples (la méthode ELECTRE). *La Revue d'Informatique et de Recherche Opérationelle (RIRO)*. 1968; 8: 57–75.
49. Ines HH, Ammar FB. ELECTRE II Multi-criteria Decision Making for Optimum Design of Modular Multilevel Inverter Building Bloc. Int. Rev. Electrc. Eng. 2010; 5(3): 870-879.
50. Charnes A. Measuring the efficiency of decision-making units. *Eur. J. Oper. Res.* 1978; 2: 429-444.

51. Determining the life cycle energy efficiency of six biofuel systems in China: A Data Envelopment Analysis. Bioresour. Tech. 2014; 162: 1-7.

52. Behzadian M, Kazemzadeh R.B., Albadvi A, Aghdasi M. PROMETHEE: A comprehensive literature review on methodologies and applications. *Eur. J. Oper. Res.* 200(1): 198-215.

53. Yue Z. An extended TOPSIS for determining weights of decision makers with interval numbers. *Knowledge-based Syst.* 2011; 24: 146-153.

54. Yue Z. Extension of TOPSIS to determine weight of decision makers for group making problems with uncertain information. *Expert Syst & Appl.* 2012; 39: 6343-6350.

55. Torfi F, Farahani RZ, Rezapour S. Fuzzy AHP to determine the relative weights of evaluation criteria and Fuzzy TOPSIS to rank the alternatives. *Appl Soft Comput.* 2010; 10: 520-528.

56. Torlak G, Sevkli M, Sanal M, Zaim S. Analyzing business competition by using fuzzy TOPSIS method: An example of Turish domestic airline industry. *Expert Syst. Appl.* 2011; 38: 3396-3406.

57. Wang JW, Cheng CH, Cheng HK. Fuzzy hierarchical TOPSIS for supplier selection. *Appl Soft Comput.* 2009; 9: 377-386.

58. Gomes LFAM., Lima MMPP. TODIM: Basics and application to multicriteria ranking of projects with environmental impacts. *Found. Comput. and Decis. Sci.* 1992; 16(4): 113-127.

59. Arshadi Khamseh A, Mahmoodi M. A new fuzzy TOPSIS-TODIM hybrid method

for green supplier selection using fuzzy time function. *Adv. Fuzzy Syst.* 2014; 2014 (3),1-11.

60. Rangel LAD, Gomes LFAM, Cardoso FP. An application of the TODIM method to the evaluation of broadband Internet plans. *Pesquisa Operacional* 2011; 31(2): 235-249.
61. Qin J, Liu X, Pedrycz W. An extended TODIM multi-criteria group decision making method for green supplier selection in interval type-2 fuzzy environment. *Eur. J. Oper. Res.* 2016; 258: 626-638.
62. Stamford L, Azapagic A. Life cycle sustainability assessment of electricity options for the UK. *Int. J. Energy Res.* 2012; 36(14): 1263-1290.
63. Ren, J, Liang, H. Multi-criteria group decision-making based sustainability measurement of wastewater treatment processes. *Environ. Impact Assess. Rev.* 2017, 65, 91-99.
64. Ren, J, Liang, H, Dong, L, Gao, Z, He, C, Pan, M, Sun, L. Sustainable development of sewage sludge-to-energy in China: Barriers identification and technologies prioritization. *Renew. Sustain. Energy Rev.* 2017, 67, 384-396.

Figures

Figure captions

Figure 1: The framework of the proposed sustainability assessment methodology of industrial processes

Figure 2: The overall priorities of the four alternative electricity generation systems

Figure 3: The results of sensitivity analysis

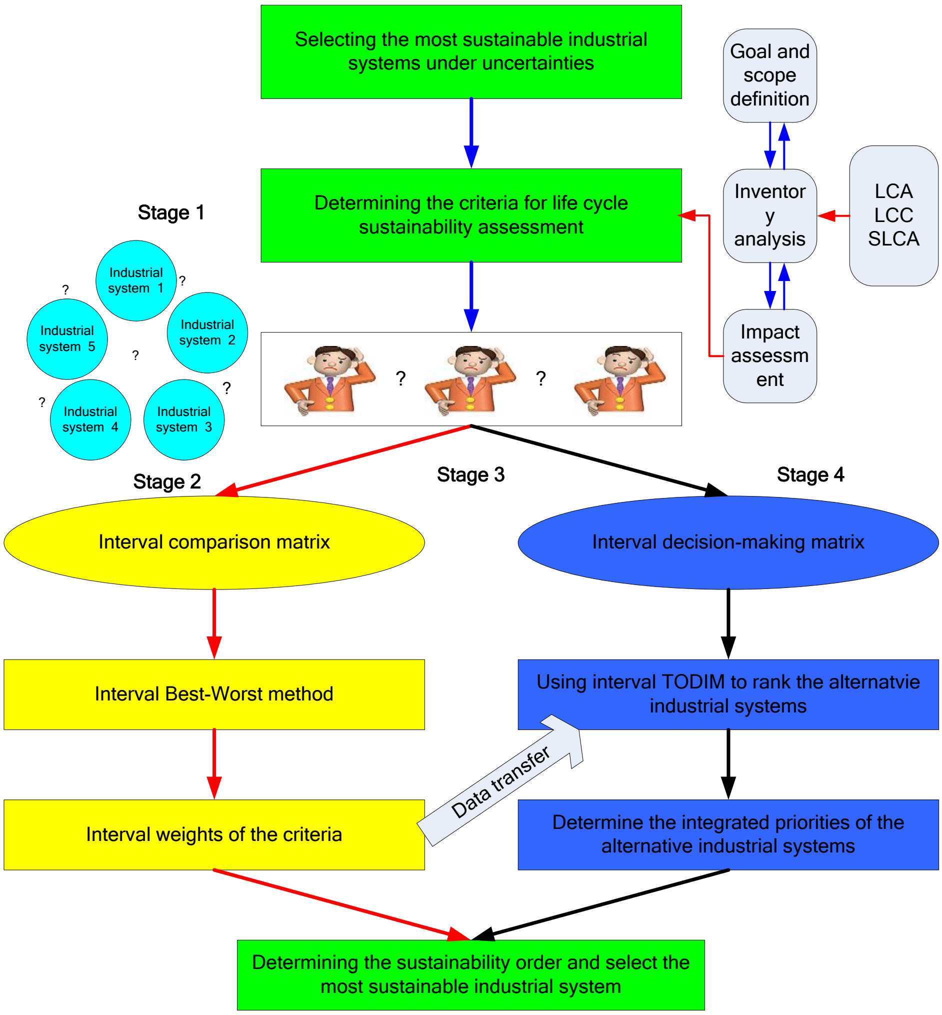

Figure 1: The framework of the proposed sustainability assessment methodology of industrial processes

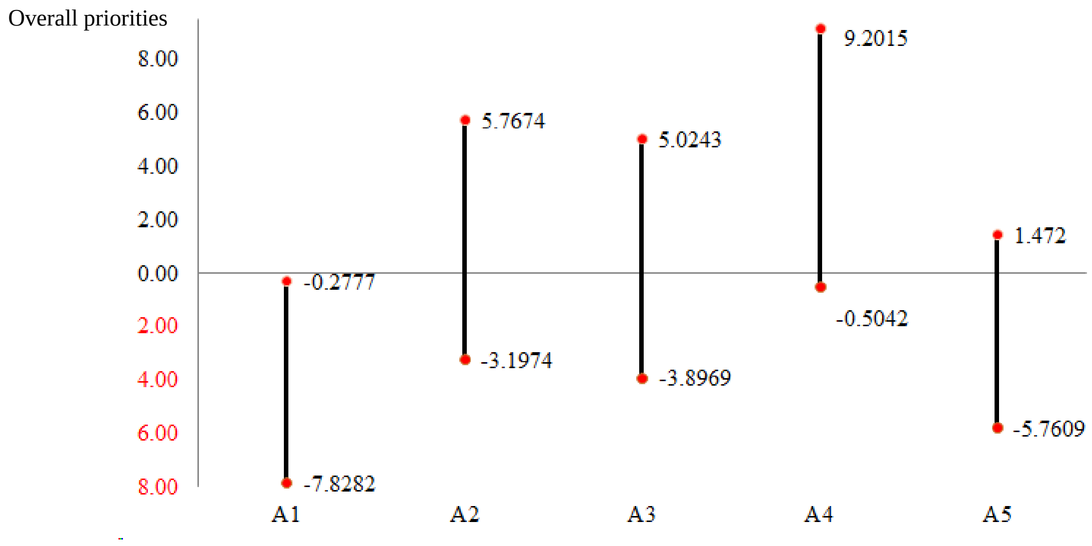

Figure 2: The overall priorities of the four alternative electricity generation systems

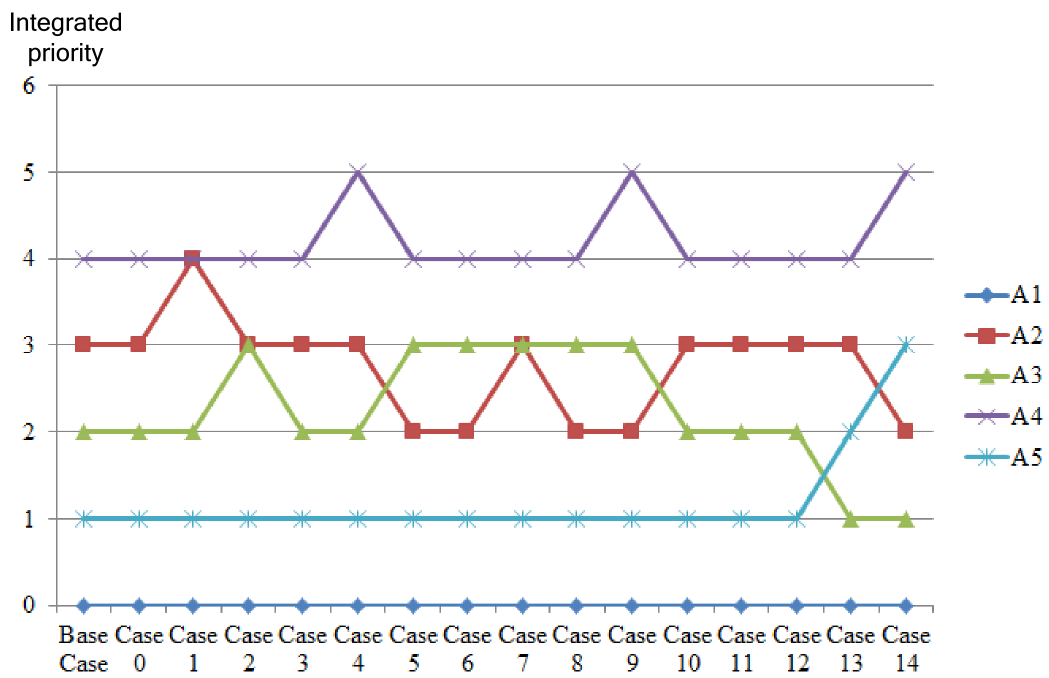

Figure 3: The results of sensitivity analysis

Tables

Table 1: Scaling system for the criteria in social aspect

Stakeholders	Subcategory indicators	Definitions	Scaling system
Workers	Child labor	Percentage of child labors in the organization	Lowly serious — Medium — Highly serious 1 — 5 — 10
	Fair salary	Satisfaction about the salary paid by organization	Lowly satisfied — Medium — Highly satisfied 1 — 5 — 10
	Forced labor	Degree of the workers to be forced to work	Lowly serious — Medium — Highly serious 1 — 5 — 10
	Health and safety	Health and safety status of the workers	Worst — Medium — Best 1 — 5 — 10
	Social benefits	Social benefits provided to the workers	Worst — Medium — Best 1 — 5 — 10
	Discrimination	Existence of sex and racial discrimination during recruitment	Lowly serious — Medium — Highly serious 1 — 5 — 10
Local community	Community engagement	Percentage of corporate social responsibility fund spent on community projects	Lowest — Medium — Most 1 — 5 — 10
Society	Contribution to economic development	Number of jobs created	Lowest — Medium — Most 1 — 5 — 10

Reference: adapted from references[29]

Table 2: The life cycle sustainability decision-making matrix

	A_1	A_2	A_3	A_4	A_5
Ec_1(£.MWh^{-1})	[28.40 61.70]	[11.10 12.40]	[51.30 79.40]	[88.50 144.60]	[156.10 479.12]
Ec_2(£.MWh^{-1})	[10.70 13.10]	[6.00 6.00]	[10.90 14.30]	[23.00 45.80]	[3.12 44.21]
Ec_3(£.MWh^{-1})	[13.00 24.40]	[25.40 66.40]	[4.20 6.30]	[0 0]	[0 0]
Ec_4(£.MWh^{-1})	[52.60 95.00]	[42.50 83.60]	[66.80 99.00]	[111.50 190.50]	[181.70 510.31]
En_1(kg CO_2 eq.kWh^{-1})	[9.65E-01 1.48E+00]	[3.66E-01 4.96E-01]	[5.13E-03 1.31E-02]	[4.73E-03 1.42E-02]	[6.48E-02 1.26E-01]
En_2(kg CFC-11 eq.kWh^{-1})	[3.20E-09 1.05E-08]	[2.80E-09 1.38E-08]	[5.26E-10 7.28E-08]	[2.55E-10 8.52E-10]	[3.34E-09 2.52E-08]
En_3(kg SO_2 eq.kWh^{-1})	[1.66E-03 9.80E-03]	[1.22E-04 3.70E-04]	[3.76E-05 9.34E-05]	[3.35E-05 8.41E-05]	[3.16E-04 6.18E-04]
En_4(kg PO_4^{3-} eq.kWh^{-1})	[1.41E-04 2.24E-03]	[6.00E-05 7.11E-05]	[6.42E-06 2.23E-05]	[2.05E-05 6.01E-05]	[3.81E-05 1.04E-04]
En_5(kg C_2H_4 eq.kWh^{-1})	[1.33E-04 4.57E-04]	[2.31E-05 6.30E-05]	[4.50E-06 8.08E-06]	[3.47E-06 9.81E-06]	[3.39E-05 9.27E-05]
En_6(m^2yr)	[2.07E-02 4.04E-02]	[2.76E-04 3.79E-03]	[5.28E-04 7.71E-04]	[1.56E-04 4.61E-04]	[3.14E-03 6.82E-03]
S_1(/)	[0.0589 0.0758]	[0.0993 0.1450]	[0.0953 0.1283]	[0.3077 0.3304]	[0.3619 0.3818]
S_2(person-years.TWh^{-1})	[5.56E+01 1.91E+02]	[2.66E+01 6.24E+01]	[5.59E+01 8.08E+01]	[3.11E+01 3.68E+01]	[5.37E+02 6.53E+02]
S_3(kg DCB eq.kWh^{-1})	[7.28E-02 4.58E-01]	[3.68E-03 1.41E-02]	[1.35E-02 1.35E-01]	[3.03E-02 7.52E-02]	[3.57E-02 1.51E-01]
S_4(DALY.kWh^{-1})	[2.15E-10 2.21E-09]	[1.16E-11 2.53E-09]	[2.03E-08 3.19E-08]	[1.86E-11 6.66E-11]	[1.13E-09 2.88E-09]

References: the data of the five electricity generation systems were derived from the work of Stamford and Azapagic[62]

Table 3: The integrated superiorities of the five electricity scenarios

	A_1	A_2	A_3	A_4	A_5
IS_i by ISWM	[0.4296 1.2585]	[0.8289 2.4988]	[0.7658 2.3296]	[1.0094 3.1253]	[0.6336 1.1234]
Ranking by ISWM	5	2	3	1	4
Ranking by ITODIM	5	2	3	1	4