Multi-Actor Multi-Criteria Sustainability Assessment Framework for Energy and Industrial Systems in Life Cycle Perspective under Uncertainties. Part 1: Weighting Method

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Abstract

Purpose Life cycle sustainability assessment is meaningful for the decision-makers/stakeholders to select the most sustainable option among multiple alternatives; however there are usually various severe uncertainty problems in sustainability-oriented decision-making, i.e. the vagueness and ambiguity existed in human judgments and the lack of information. This study aims at developing a novel life cycle multi-criteria sustainability assessment method for helping the decision-makers/stakeholders to determine the sustainability level of the industrial and energy systems. In Part 1, an improved interval Analytic Hierarchy Process (AHP) which allows multiple decision-makers/stakeholders to participate in the decision-making was developed to determine the weights of the criteria which were used in life cycle sustainability assessment.

Methods It is usually difficult for the decision-makers/stakeholders to use the numbers from 1 to 9 and their reciprocals for determining the comparison matrix when using the traditional AHP method for weights calculation, because human judgments usually involves various uncertainties. In order to the overcome this weak point of the traditional AHP, an improved AHP, so-called "interval AHP", in which, multiple decision-makers/stakeholders are allowed to participate in the decision-making and allowed to use interval numbers instead of crisp numbers to establish the comparison matrix for determining the weights of the criteria for life cycle sustainability assessment, has been developed.

Results and discussion The proposed method was used to determine the weights of the four aspects for life cycle sustainability assessment including economic, safety, social and environmental aspects. Five representative stakeholders were invited to participate in the decision-making. After Monte Carlo simulation, the final weights of the four aspects have been determined with the proposed interval AHP.

Conclusions and perspective An interval AHP method was developed for determining the weights of the criteria for life cycle sustainability assessment, the decision-makers are allowed to use interval numbers to establish the comparison matrix for weights calculation. The weighting coefficients determined by Monte Carlo method can accurately reflect the preferences and willingness of multi-actor comparing with the traditional AHP method. This paper merely presents a novel method to calculate the weights of the criteria for life cycle sustainability assessment, but the method for determining the sustainability performance has been presented in part 2.

Key words: *Life cycle assessment; weights; multi-actor multi-criteria decision-making; analytical hierarchy process; interval number*

Nomenclature

Parameters	
a_{ij}	The relative importance of the criterion *i* comparing with the criterion *j*, namely the scale of the criterion *i* comparing with the criterion *j*, $a_{ij}=\frac{1}{a_{ji}}, a_{ij}>0, i, j=1,2,...,n$
a_{ij}^{*}	The element of cell (i, j) in the ideal comparison matrix
$A^{'}$	The ideal comparison matrix
ΔA	The interval-deviation matrix
ΔA^{+}	The positive deviation matrix
ΔA^{-}	The negative deviation matrix
CI	The consistency index
CR	The consistency ratio
m	The total times of Monte Carlo simulation
n	The dimension of the matrix
RI	The average random index of the matrix with the same dimension of A
t	The (*t*) th time running of Monte Carlo simulation
ω_i	The weight of the indicator *i*
W	The weighting vector
W^{*}	The ideal weighting vector
$W_{A^{'}}^{*}$	The normalized weighting vector of the ideal comparison matrix $A^{'}$
$W_{\max}$	The principal eigenvector
ΔW^{t}	The deviation vector of the weight in the (t) th Monte Carlo simulation
$\Delta \overline{w}_i$	The average deviation of the weights of the criterion *i*
$\Delta \omega_i^{t}$	The deviation of the weight of the criterion i in the (t) th Monte Carlo simulation
$\partial y / \partial x_i$	The sensitivity coefficients
$\lambda_{\max}$	The principal eigenvalue of matrix A
ω_i	The weighting coefficients
$\Delta \omega_i$	The derivation of the weight of the *i*-th criterion
$\Delta \omega_{i1}$	The deviation caused by the elements in the *i*-th row

$\Delta\omega_{i2}$	The deviation caused by the elements in the other rows (excepting the *i*-th row) of the deviation matrix

1 Introduction

With the contaminations of the environment, the depletion of resource and the risk of energy supply, the selection of the best energy and industrial option is meaningful and useful for promoting sustainable development, but the decision-makers/stakeholders usually face a difficult question: What is the sustainability degree of each industrial and energy option? In order to answer this question, it is prerequisite to provide a generic method which can quantify and evaluate the sustainability of different alternatives. Life cycle assessment (LCA) which usually consists of two steps for prioritizing the alternative energy and industrial systems: the first step is to determine the life cycle inventory (LCI) and the second step is life cycle inventory analysis. It is a useful tool to quantify the environmental sustainability of the alternative options. In order to rank the alternatives according to their relative priorities, the decision-makers usually need to aggregate the multiple indicators to a single score or index by the weighting method; then the sustainability of the alternatives can be compared with each other according to the single sustainability index (Soares et al. 2006). Therefore, the combination of the weighting method and life cycle thinking has been a hot spot for sustainability assessment of energy and industrial systems.

There are also two academic gaps in the previous studies. The first is the lack of convenient method for determining the weights of the criteria for sustainability assessment. The second gap is that the combination of weighting method and LCA can only measure the environmental sustainability of the alternative energy and industrial systems; however, sustainability usually consists of three pillars including economic, environmental and social aspects. Accordingly, developing life cycle sustainability assessment to substitute the traditional life cycle assessment is prerequisite for sustainability assessment. A multi-actor multi-criteria sustainability decision making method was developed in part 2 for determining the sustainability level of the energy and industrial systems.

As for the first gap, the decision-makers usually assign the weights subjectively or treat the criteria equally when aggregating the multiple criteria into a single index (Moradi Aliabadi and Huang, 2016; Othman et al., 2010). There are also some studies which used Analytic Hierarchy Process (AHP) to determine the weights of the criteria for aggregating the multiple criteria into a single index. For instance, NG (2016) developed an evidential reasoning-based AHP approach for selecting the environmental-friendly designs by combining AHP and LCA. Petrillo et al. (2016) developed a systematic sustainability assessment tool based on LCA and AHP to support decision-makers to select the most sustainable technology by applying it in a novel compressed air energy storage system. Pineda-Henson and Culaba (2004) developed a methodology for green productivity (GP) by integrating the essential components of life cycle assessment and multi-criteria decision analysis (namely AHP). Reza *et al*. (2011) developed an AHP-based life cycle analysis for sustainability assessment of flooring systems in the city of Tehran. However, it is usually difficult for the users to use the numbers from 1 to 9 and their reciprocals to establish the compassion matrix for determining the weights of the criteria for sustainability assessment, because human judgments usually involve various vagueness, ambiguity and subjectivity (Ren et al., 2015a). Therefore, various improved AHP method have been used in life cycle assessment for environmental sustainability assessment, and the most famous is the fuzzy AHP method. For instance, Zheng et al. (2011) combined LCA and fuzzy AHP to evaluate building energy conservation. Zare et al. (2016) proposed a MCDM method for industrial waste management by combining fuzzy AHP, goal programming model and LCA results. Chan et al. (2013) developed an extended fuzzy-AHP approach for the evaluation of green product designs. However, the users also need to use a single linguistic term (i.e. the linguistic terms like "important", "very important", and "significantly important") to compare the relative priority between each pair of alternatives firstly when using fuzzy AHP. Actually, the ambiguity and vagueness existed in human judgments have not been successfully resolved. For instance, sometime the decision-makers held the view that the relative importance of one alternative over another is between "important" and "significantly important"; however, the previous studies cannot successfully solve this problem. An improved AHP which allows multiple decision-makers/stakeholders to participate in the decision-making for weights calculation and can address the ambiguity, vagueness and subjectivity existed in human judgments is prerequisite.

Meanwhile, weighting method is a commonly used method in life cycle inventory analysis by assigning different weighting coefficients to the indicators in LCI, and the traditional AHP and various improved ANP methods are the most important methodologies to calculate the weighting coefficients based on the established comparison matrix. However, the comparison matrix in these methods is usually determined by a decision-maker which cannot reflect the willingness of all the decision-makers, Therefore, an improved AHP which allows multiple decision-makers to participate in the decision-making and can incorporate the preferences and willingness of all the decision-makers. Accordingly, the elements in the comparison matrix determined by the proposed methodology are interval numbers rather than crisp numbers. Therefore, the used of the interval numbers instead of crisp for establishing the comparison matrix is can reflect the preferences and willingness of all the decision-makers accurately.

All in all, the objective of this study is to propose an interval AHP method which allows multiple decision-makers/stakeholders to participate in the decision-making and allow them to use interval numbers to establish the comparison matrix for determining the weights of the criteria for sustainability assessment.

2 Methods

The Analytical Hierarchy Process (AHP) developed by Saaty (1978, 1987) is a widely used decision analysis method which considers both qualitative and quantitative information (Su and Zhang 2010). AHP arises from natural human ability for using information and experience for evaluating the pairwise comparisons, which helps us to calculate relative importance (weight) of individual criteria (Lipuscek et al. 2010). It has been widely used in various fields for the multi-criteria decision making problem. For instance, Ren et al. (2014) used AHP method to prioritize the hydrogen pathways for energy security enhancement. Hossaini et al. (2015) employed AHP to investigate the sustainability of six storey wood frame and concrete frame building in Vcancouver. Ren and Sovacool (2014) employed AHP method to rank the strategic measures for enhance China's energy security. Ren et al. (2013) combined AHP and the extension theory for selecting the most sustainable hydrogen supply chain. AHP performed well in these multi-criteria decision making problems, especially in weights calculation.

Suppose that there are n criteria for sustainability assessment, the pairwise comparison method proposed by Saaty (Saaty 1978) can be used to establish a $n \times n$ comparison matrix for determining the weights of the criteria. A scale system from 1 to 9 and their reciprocals is used for the comparison, the number 1 means that two criteria are of equal importance and 9 means a very strong importance of one criterion over another, the elements for comparing the relative importance of one criterion over another were presented in Table 1. As mentioned above, the traditional AHP methods replied on using the numbers from 1-9 and their reciprocals to establish the comparison matrix for determining the weights of the criteria; however, it cannot satisfy the requirements of the decision-makers due to the severe uncertainty problems existed in human judgments (Ren and Sovacool, 2014). Therefore, an improved AHP, so-called “interval AHP” was developed in this section.

There are four steps in the developed interval AHP: Step 1 is to determine the average interval comparison matrix; Step 2 is to determine the ideal comparison matrix; Step 3 is to determine the deviation of the weights through Monte Carlo simulation.

There are three assumptions in the interval AHP method:

(1) All the criteria studied by this method are independent, and there is no overlap in concept between each pair of criteria;

(2) All the representative stakeholders are independent, and there is no conflict of interest among them;

(3) The relative importance/priority between each pair of criteria can be described by the intervals formed by the numbers from 1-9 and their reciprocals.

Step 1:Average interval comparison matrix

Each representative stakeholder will be invited in to use the interval numbers formed by the numbers presented in Table 1 to establish the comparison matrix. For instance, the intervals (3, 5) will be used to depict the relative importance of one criterion over another if the stakeholder held the view that the relative importance is between “moderate importance” (corresponding to the number 3) and “essential importance” (corresponding to the number 5). Assume that there are a total of m representative stakeholders participate in the decision-making, the interval comparison matrix determined by the i-th stakeholder is:

$$A^i = \begin{bmatrix} 1 & <a_{12}^i, b_{12}^i> & \cdots & <a_{1n}^i, b_{1n}^i> \\ <a_{21}^i, b_{21}^i> & 1 & \cdots & <a_{2n}^i, b_{2n}^i> \\ \vdots & \cdots & \ddots & \vdots \\ <a_{n1}^i, b_{n1}^i> & <a_{n2}^i, b_{n2}^i> & \cdots & 1 \end{bmatrix} \quad (1)$$

Accordingly, there are a total of m interval comparison matrices. In order to incorporate the preferences and willingness of all the stakeholders, the arithmetic mean and geometric mean methods are usually used to arithmetic mean or geometric mean comparison matrix by aggregating the m matrices determined by the m decision-makers into a single comparison matrix (Ren et al., 2015b;

Ramanathan and Ganesh, 1994). In this study, the arithmetic mean method was used to determine the mean interval comparison matrix, as presented inEq.2, and it can also be transformed into Eq.5 by substituting the lower limit and upper limit with Eq.3 and Eq.4

$$A=\begin{bmatrix} 1 & <\frac{\sum_{i=i}^{m}a_{12}^{i}}{m},\frac{\sum_{i=i}^{m}b_{12}^{i}}{m}> & \cdots & <\frac{\sum_{i=i}^{m}a_{1n}^{i}}{m},\frac{\sum_{i=i}^{m}b_{1n}^{i}}{m}> \\ <\frac{\sum_{i=i}^{m}a_{21}^{i}}{m},\frac{\sum_{i=i}^{m}b_{21}^{i}}{m}> & 1 & \cdots & <\frac{\sum_{i=i}^{m}a_{2n}^{i}}{m},\frac{\sum_{i=i}^{m}b_{2n}^{i}}{m}> \\ \vdots & \cdots & \ddots & \vdots \\ <\frac{\sum_{i=i}^{m}a_{n1}^{i}}{m},\frac{\sum_{i=i}^{m}b_{n1}^{i}}{m}> & <\frac{\sum_{i=i}^{m}a_{n2}^{i}}{m},\frac{\sum_{i=i}^{m}b_{n2}^{i}}{m}> & \cdots & 1 \end{bmatrix} \quad (2)$$

$$a_{pl}^{L}=\frac{\sum_{i=i}^{m}a_{pl}^{i}}{m} \qquad p=1,2,\cdots,n;l=1,2,\cdots,n \quad (3)$$

$$a_{pl}^{U}=\frac{\sum_{i=1}^{m}b_{pl}^{i}}{m} \qquad p=1,2,\cdots,n;l=1,2,\cdots,n \quad (4)$$

$$A=\begin{bmatrix} 1 & [a_{12}^{L},a_{12}^{U}] & \cdots & [a_{1n}^{L},a_{1n}^{U}] \\ [a_{21}^{L},a_{21}^{U}] & 1 & \cdots & [a_{1n}^{L},a_{1n}^{U}] \\ \vdots & \cdots & \ddots & \vdots \\ [a_{n1}^{L},a_{n1}^{U}] & [a_{n2}^{L},a_{n2}^{U}] & \cdots & 1 \end{bmatrix} \quad (5)$$

Step 2: Ideal comparison matrix

In this step, the ideal comparison matrix was obtained from the mean interval comparison matrix obtained in step 1. Denotes the element in the ideal comparison matrix by a_{ij}^{*}, and it should satisfy the consistency check. Accordingly, an optimal programming model as presented in Eq.6 can be used to solve the ideal comparison matrix

$$\begin{aligned} & Min\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}(a_{ij}^{*}a_{jk}^{*}-a_{ik}^{*})^{2} \\ & subject\ to \quad a_{ij}^{*}\in[a_{ij}^{L},a_{ij}^{U}],a_{jk}^{*}\in[a_{jk}^{L},a_{jk}^{U}],a_{ik}^{*}\in[a_{ik}^{L},a_{ik}^{U}],a_{ii}=1,a_{ij}^{*}=\frac{a_{ik}^{*}}{a_{jk}^{*}} \end{aligned} \quad (6)$$

The programming model is a non-linear programming with a total of n(n-1) variables and (n＋

2)n(n-1) constraints. Lingo 11.0 which is a comprehensive tool designed to make building and solving linear and nonlinear (convex & nonconvex/global) optimization models and has been widely used optimization commercial software (Manzardo *et al.*, 2014; Ren *et al.*, 2015c) was applied to solve this kind of programming models in this study, the authors can find more information about this software at the Lingo Systems Inc. (http://www.lindo.com/index.php?id=2).

Then, the optimal solution a_{ij}^* can be calculated according to the programming model (6). Denotes the ideal comparison matrix by Eq.14, Subsequently, the ideal weights of the criteria can be obtained according to the traditional AHP method, as presented in Eqs.7-8.

$$A^{'} = \{a_{ij}^*\}_{n\times n} \qquad i, j = 1, 2, \cdots, n \tag{7}$$

$$W^* = (\omega_1, \omega_2, \cdots, \omega_n) \tag{8}$$

The positive deviation matrix and the negative deviation matrix can be calculated by Eq.9 and Eq.10, respectively. Then, the interval-deviation matrix can be determined, as shown in Eq.11

$$\Delta A^+ = \{a_{ij}^U - a_{ij}^*\}_{n\times n} = \{\Delta a_{ij}^+\}_{n\times n} \tag{9}$$

$$\Delta A^- = \{a_{ij}^L - a_{ij}^*\}_{n\times n} = \{\Delta a_{ij}^-\}_{n\times n} \tag{10}$$

$$\Delta A = \begin{bmatrix} 0 & [\Delta a_{12}^-, \Delta a_{12}^+] & \cdots & [\Delta a_{1n}^-, \Delta a_{1n}^+] \\ [\Delta a_{21}^-, \Delta a_{21}^+] & 0 & \cdots & [\Delta a_{2n}^-, \Delta a_{2n}^+] \\ \vdots & \cdots & \ddots & \vdots \\ [\Delta a_{n1}^-, \Delta a_{n1}^+] & [\Delta a_{n2}^-, \Delta a_{n2}^+] & \cdots & 0 \end{bmatrix} \tag{11}$$

Step 3: Deviation of the weights through Monte Carlo simulation

In this step, the sensitivity analysis method was firstly presented; then, the method for calculating the deviations of the weights determined by the ideal comparison matrix with the consideration of the interval-deviation matrix was deduced; finally, Monte Carlo simulation method was proposed for determining the final weights of the criteria.

There are various studies focusing on the combination of AHP and Monte Carlo simulation for determine the weights. For instance, Carmone et al. (1997) employed the Monte Carlo method based on the incomplete pairwise comparisons algorithm to investigate the effect of reduced sets of pairwise comparisons in the AHP. Jing et al. (2013) developed a hybrid stochastic-interval analytic hierarchy process (SIAHP) approach to address uncertainty in group decision making by integrating interval judgment, probabilistic distribution, lexicographic goal programming, and Monte Carlo simulation. Hsu and Pan (2009) employed the Monte Carlo AHP to rank the dental quality attributes. Banuelas and Antony (2004) developed a modified analytic hierarchy process, which incorporates probabilistic distributions to include uncertainty in the judgements, and the vector of priorities was calculated using Monte Carlo simulation in their proposed method. Most of these methods employed Monte Carlo as a tool to generate different comparison matrices and further to obtain different weight vector. However, Monte Carlo simulation method was used to determine the average derivation of the weight respect to each criterion. To the best of our knowledge, there are few studies combining the concept of interval-deviation matrix, derivation of the weight, and Monte Carlo method to determine the weights of the criteria.

Suppose the output variable y depends on n input variables (x_1, x_2,……, x_n), and the dependence is expressed by a function f, as shown in Eq.12; consequently, Eq.13 can be obtained after taking logarithm of both sides of Eq.12; then, Eq.13 is differentiated to yield Eq.14, the factors in determining the sensitivity is the change of the result (Δy) caused by the marginal changes in x_1, x_2,……, and x_n (Δx_1, Δx_2,……, Δx_n). This can be expressed by using the partial derivatives as shown in Eq.15

$$y = f(x_1, x_2, \cdots, x_n) \tag{12}$$

$$\ln y = \ln f(x_1, x_2, \cdots, x_n) \tag{13}$$

$$\frac{dy}{y} = \frac{1}{f(x_1, x_2, \cdots, x_n)} \left(\sum_{i=1}^{n} \frac{\partial y}{\partial x_i} dx_i\right) \tag{14}$$

$$\Delta y = \left(\sum_{i=1}^{n} \frac{\partial y}{\partial x_i} \Delta x_i\right) \tag{15}$$

Coefficients such as $\partial y / \partial x_i$ represent the sensitivity coefficients in this study. The calculation requires a specification of the function f. Thus, with f specified, the sensitivity coefficient of f with respect to input parameter x_i is defined as shown in Eq.16

$$\frac{\partial y}{\partial x_i} = \frac{\partial f(x_1, x_2, \cdots, x_n)}{\partial x_i} \tag{16}$$

If the comparison matrix presented in Eq.7 satisfies the consistency check, the weighting coefficients can be estimated by the geometric mean method (Adamcsek, 2008), as presented in Eq.17. According to the sensitivity analysis method presented in Eqs.12-16, the derivation of the weight of the *i*-th criterion can be obtained by Eqs.18-20.. It is worth pointing out that the first part as presented in Eq.18 represents the deviation caused by the elements in the i-th row, and the second part as shown in Eq.18 represents the deviation caused by the elements in the other rows of the deviation matrix

$$\omega_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} \Bigg/ \sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} \tag{17}$$

$$\Delta\omega_i = \Delta\omega_{i1} + \Delta\omega_{i2} \tag{18}$$

$$\Delta\omega_{i1} = \sum_{k=1}^{n} \frac{\frac{1}{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1-n}{n}} \prod_{j=1, j\neq k}^{n} a_{ij}}{\left[\sum_{p=1}^{n}\left(\prod_{j=1}^{n} a_{pj}\right)^{\frac{1}{n}}\right]^2} \sum_{p=1, p\neq i}^{n}\left(\prod_{j=1}^{n} a_{pj}\right)^{\frac{1}{n}} \Delta a_{ik} \tag{19}$$

$$\Delta\omega_{i2} = \sum_{r=1, r\neq i}^{n} \sum_{s=1}^{n} \frac{-\frac{1}{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}\left(\prod_{j=1}^{n} a_{rj}\right)^{\frac{1-n}{n}} \prod_{j=1, j\neq s}^{n} a_{rj}}{\left[\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}\right]^2} \Delta a_{rs} \tag{20}$$

According to Eq.18, it can be deduced that the deviation of the ideal comparison matrix to the interval comparison matrix will fluctuate between some certain intervals; it could be assumed that the data of the deviation obey some certain types of probability distribution, and Monte Carlo method can include any number of different probability distribution for the individual data points. There are several types of probability profiles can be chosen for Monte Carlo simulation, and the most commonly used are: triangular, uniform, normal, and log-normal (Huang and Ma 2009; May and Brennan 2003; Mccleese and Lapuma 2002).

In this study, the normal distribution has been used in Monte Carlo simulation, the deviation of the weights can be calculated when the data points has been generated in Monte Carlo simulation, as shown in Eq.1, the average deviation of the weights can be calculated according to Eqs.21-22; then, the average weight of each criterion can be determined by Eq.23.

$$\Delta W^t = (\Delta\omega_1^t, \Delta\omega_2^t, \cdots, \Delta\omega_n^t) \tag{21}$$

$$\Delta\overline{w}_i = \frac{\sum_{t=1}^{m} \Delta\omega_i^t}{m} \tag{22}$$

$$W = \left(\frac{\omega_1 + \Delta\overline{w}_1}{\sum_{i=1}^{n} \omega_i + \Delta\overline{w}_i}, \frac{\omega_2 + \Delta\overline{w}_2}{\sum_{i=1}^{n} \omega_i + \Delta\overline{w}_i}, \cdots, \frac{\omega_n + \Delta\overline{w}_n}{\sum_{i=1}^{n} \omega_i + \Delta\overline{w}_i}\right) \tag{23}$$

where t represents the t-th time running of the Monte Carlo simulation, M indicates the total times of Monte Carlo simulation, Δw_i^t is deviation of the weight of the i-th criterion in the t-th time running of Monte Carlo simulation, and the $\Delta\overline{w}_i$ represents the average deviation of the weight of the i-th criterion.

3 Case study

In order to illustrate the proposed interval AHP method, an illustrative case about sustainability assessment of six energy and industrial systems has been studied, and this case has been further introduced in part 2. This case study in this study (part 1) aims at determining the weights of the dimensions of sustainability when people use four dimensions including economic performance, technological aspect, social issue and environmental impact to measure sustainability. Five representative groups of stakeholders/decision-makers including engineer group, scholar group, administrator group, worker group, and investor group were invited to participate in the decision-making. It is worth pointing out that a delegate will be selected from each representative group, and he/she will collect the opinions of his/her colleagues to establish the comparison matrix.

Firstly, five delegates established five comparison matrices for comparing each pair of dimensions, as presented in Table 2. The interval comparison matrix can be obtained with Eq.2, as presented in Eq.24. Consequently, the ideal comparison matrix can also be obtained, as presented in Eq.25 by solving the programming model (6); then, the principal eigenvalue and the principal eigenvector of the ideal comparison matrix can be calculated, as presented in in Eq.26 and Eq.27, respectively. The ideal comparison matrix can satisfy the consistency check, as shown in Eqs.28-29; finally, the ideal weights of the four dimensions can be obtained by normalizing the principal eigenvector, as presented in Eq.30.

$$A = \begin{vmatrix} 1 & <2.00,3.00> & <3.20,4.80> & <3.20,4.80> \\ <0.37,0.67> & 1 & <1.80,3> & <2.00,3> \\ <0.22,0.32> & <0.42,0.87> & 1 & <1.40,2.80> \\ <0.21,0.32> & <0.40,0.77> & <0.38,0.8> & 1 \end{vmatrix} \quad (24)$$

$$A^{'} = \begin{vmatrix} 1 & 2 & 3.20 & 3.23 \\ 0.56 & 1 & 1.80 & 2.00 \\ 0.32 & 0.63 & 1 & 1.40 \\ 0.28 & 0.54 & 0.80 & 1 \end{vmatrix} \quad (25)$$

$$\lambda_{\max} = 4.10 \quad (26)$$

$$W_{\max} = (0.8517, 0.4545, 0.2784, 0.2249)^T \quad (27)$$

CI=0.03 (28)

CR=0.04<0.1 (29)

$$W_{A^{'}}^{*} = (0.4599, 0.2563, 0.1570, 0.1268) \quad (30)$$

The positive matrix and negative matrix can also be calculated according to Eqs.9-11, as presented in Eq.31 and Eq.32, respectively. Then, Monte Carlo simulation method has been used to calculate the deviation by running 1000 times, the frequency profile of the deviation of the weight with respect to economic, technological, social and environmental aspects was presented in Figures 1-4, respectively. To some extent, these four profiles obey the normal distribution. Accordingly, the probability of the deviation of the weight with respect to each dimension belonging to some certain intervals can be estimated. The deviation (variance) of the weights with respect to the four dimensions can also be determined, as shown in Fig. 5, and the X-label represents the distribution of the deviation of the weights, and the numbers, namely 1,2,3 and 4 on Y-label represent economic, safety, social and environmental dimensions, respectively. The average deviation of the weight with respect to each dimension can be calculated, as shown in Table 3, and finally, the average weights of the four dimensions can be determined, as shown in Table 4.

$$\Delta A^{+}=\begin{vmatrix} 0 & 1 & 1.60 & 1.57 \\ 0.11 & 0 & 1.20 & 1.00 \\ 0 & 0.24 & 0 & 1.40 \\ 0.04 & 0.23 & 0 & 0 \end{vmatrix} \tag{31}$$

$$\Delta A^{-}=\begin{vmatrix} 0 & 0 & 0 & -0.03 \\ -0.19 & 0 & 0 & 0 \\ -0.10 & -0.21 & 0 & 0 \\ -0.07 & -0.14 & -0.42 & 0 \end{vmatrix} \tag{32}$$

The weights determined by Monte Carlo simulation are more accurate than that determined by the traditional method, and it can reflect the preference of the decision-makers accurately.

4 Conclusions and perspective

This study aims at developing a novel improved AHP method which allows multiple decision-makers/stakeholders to participate in the decision-making and allows them to use interval numbers instead of crisp numbers to express their opinions for establishing the comparison matrices and determining the weights of life cycle indicators. An interval AHP method was proposed for determining the weights of the criteria for sustainability assessment in this study, the proposed method can successfully solve the ambiguity, vagueness and subjectivity problems existed in human judgments when establishing the comparison matrix and the obtained weights can help the decision-makers/stakeholders to aggregate multiple sustainability criteria into a single sustainability index.

The improved AHP with interval comparison matrix can reflect the willingness and preferences of all the decision-makers/stakeholders more accurately than the traditional AHP. The ideal comparison matrix which tends to satisfy the preferences of all the decision-makers can incorporate the willingness and preferences of all the decision-makers/stakeholders. Accordingly, the final weights of the criteria determined by Monte Carlo simulation can reflect the relative importance/priority of the criteria accurately.

Besides the advantages of the proposed interval AHP method, there are also some weak points:

(1) The arithmetic mean method was used to determine the mean interval comparison matrix, but there are some other method (i.e. geometric mean method) for aggregating multiple comparison matrices into a single matrix, but it lacks the comparison of different aggregating

methods;

(2) All the criteria are assumed to be independent, but there are usually various interactions and dependences among these criteria.

Meanwhile, this study only presented a novel modified AHP method for determining the weights of the criteria in multi-actor multi-criteria sustainability assessment of energy and industrial systems , but the multi-actor multi-criteria decision-making method for sustainability assessment has not been discussed in this study, part 2 will present the interval extension theory to address this.

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Tables

Table 1 Comparison scale (Saaty, 1980)

Scale of relative importance	Definition	Note
1	Equal importance	*i* is equally important to *j*
3	Moderate importance	*i* is moderately important to *j*
5	Essential importance	*i* is essentially important to *j*
7	Very Strong importance	*i* is very strongly important to *j*
9	Absolute importance	*i* is very absolutely important to *j*
2,4,6,8	Intermediate value	The relative importance of *i* to *j* is between to adjacent judgment
Reciprocal	Reciprocals of above	One value had been assigned to *i* when compared to *j*, then j has the reciprocal value compared to *i*

Table 2 The comparison matrices determined by the five delegates

	Economic	Technological	Social	Environment
Economic	1	<1,2>,<2,3>,<2,3>, <2,3>,<3,4>	<3,5>,<3,4>,<5,7>, <2,3>,<3,5>	<3,4>,<4,6>,<4,6>, <2,3>, <3,5>
Technological	<1/3,1/2>,<1/2,1>, <1/4,1/3>,<1/2,1>, <1/4,1/2>	1	<1,2>,<2,3>,<2,3>,<3,4>,<1,3>	<1,2>,<2,3>,<2,3>, <2,3>,<3,4>
Social	<1/5,1/4>,<1/3,1/2>, <1/5,1/3>,<1/7,1/6>, <1/5,1/3>	<1/2,1>,<1/2,1>,<1/4,1/3>,<1/3,1>,<1/2,1>	1	<1,2>,<2,3>,<1,2>, <1,2>,<1,2>,,<1,3>
Environmental	<1/4,1/3>,<1/5,1/3>, <1/6,1/4>,<1/4,1/3>, <1/5,1/3>	<1/2,1>,<1/3,1>,<1/2,1/3>,<1/3,1/2>,<1/3,1>	<1/2,1>,<1/3,1>, <1/2,1>,<1/4,1/2>,<1/3,1/2>	1

Table 3 The average deviation of the weights with respect to the four dimensions

Dimensions	Environmental	Technological	Social	Economic
The deviation	0.00260	0.00086	0.00031	-0.0037

Table 4 The average weights of the four dimensions

Dimensions	Environmental	Technological	Social	Economic
Weights	0.4625	0.2571	0.1573	0.1231

Figure Captions

Fig. 1 The frequency profile of the deviation of the weight with respect to economic aspect

Fig. 2 The frequency profile of the deviation of the weight with respect to technological aspect

Fig. 3 The frequency profile of the deviation of the weight with respect to social aspect

Fig. 4 The frequency profile of the deviation of the weight with respect to environmental aspect

Fig. 5 The deviation of the weights

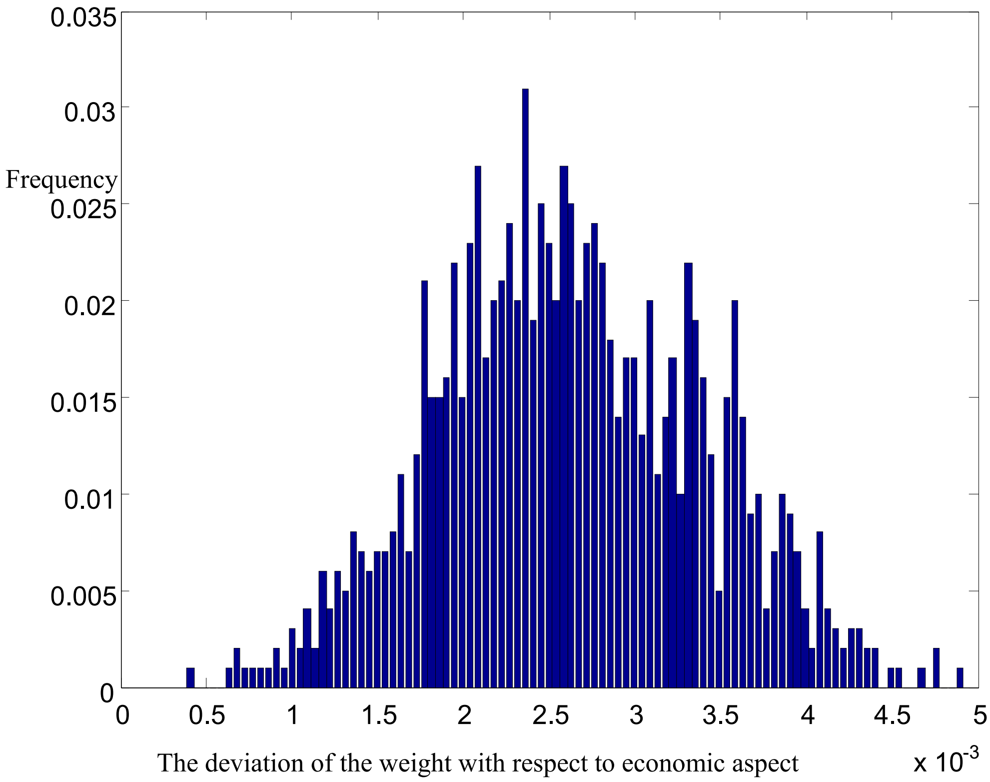

Fig. 1 The frequency profile of the deviation of the weight with respect to economic aspect

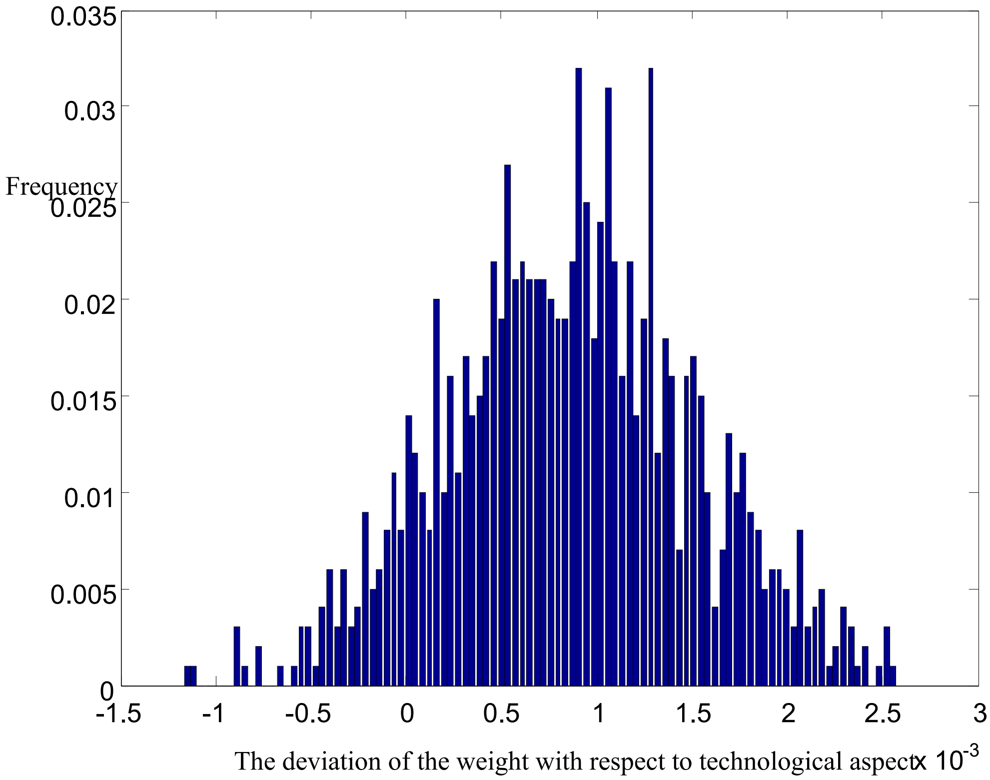

Fig. 2 The frequency profile of the deviation of the weight with respect to technological aspect

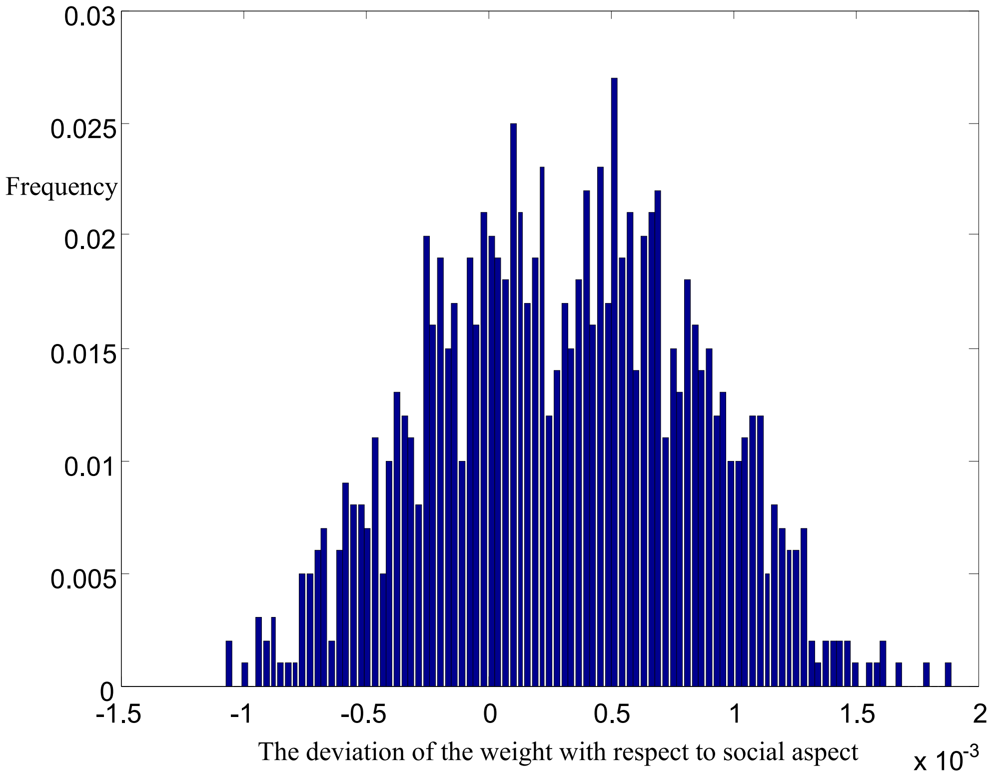

Fig. 3 The frequency profile of the deviation of the weight with respect to social aspect

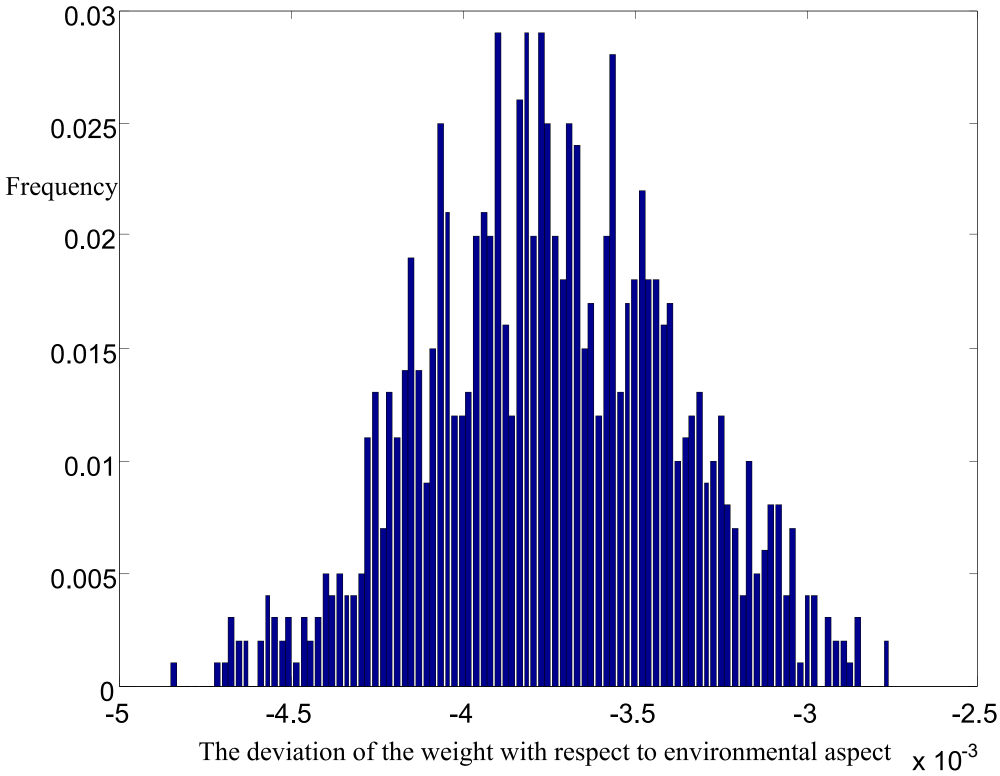

Fig. 4 The frequency profile of the deviation of the weight with respect to environmental aspect

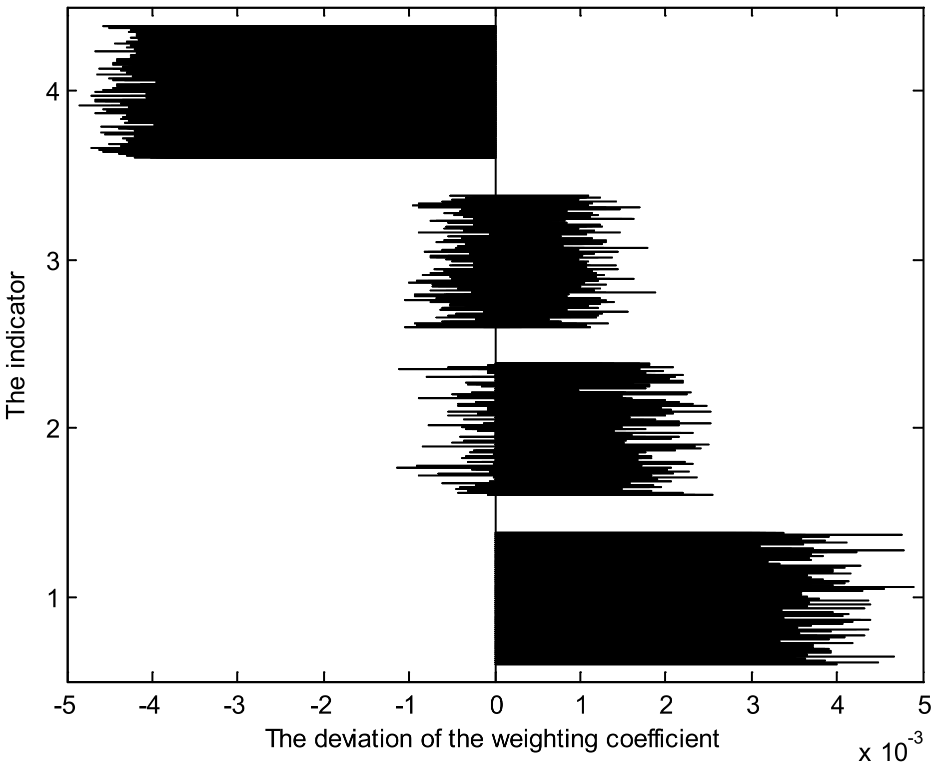

Fig. 5 The deviation of the weights

Note: the numbers, namely 1, 2, 3 and 4 on Y-label represent economic, technological, social and environmental dimensions, respectively