Multi-Actor Multi-Criteria Sustainability Assessment Framework for Energy and Industrial Systems in Life Cycle Perspective under Uncertainties. Part 2: Improved Extension Theory

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Abstract

Purpose The concept of sustainability and sustainable development has been widely incorporated in energy and industrial systems. This paper is the second part of a two-paper series dealing with multi-actor multi-criteria sustainability assessment of alternative energy and industrial systems in life cycle perspective under uncertainties.

Methods The criteria system including four macroscopic aspects (environmental, safety, social and economic aspects) has been developed for sustainability assessment of energy and industrial systems. An improved extension theory which can address interval decision-making matrix has been developed for determining the sustainability degree of the energy and industrial systems.

Results and discussion The weights of the criteria for sustainability assessment in the first part of the two-paper series. An illustrative case has been studied by the proposed multi-criteria decision making method, and the sustainability of six alternative options for the production of 1tonne product was investigated. The sustainability degree of these six alternative options can be determined by the proposed method.

Conclusion and perspective A methodology for multi-actor multi-criteria sustainability assessment of energy and industrial options has been developed in this study, the traditional extension theory has been modified to deal with the uncertainty problems, and the proposed method can rank the alternative energy and industrial systems with the decision-making matrix in which the data of the alternatives with respect the evaluation criteria are intervals. In the improved extension theory, sustainability has been dived into five grades: excellent, good, satisfied, barely adequate, and fail. According to the method for calculating the weights of the criteria for sustainability assessment proposed in part 1, these weights were used to calculate the integrated dependent degree which is a measure of what degree an alternative belongs to the classical fields. An optimal programming model for maximizing the satisfied degree has been developed to rank the sustainability sequence of the alternative options and determine the sustainability degree of each alternative.

Key words: *Sustainability assessment, uncertainty, life cycle thinking, extension theory*

Nomenclature

Indicators	
AJ	Added jobs
AP	Acidification potential
E	The frequency of dangerous incident
GWP	Global warming potential
IC	Investment cost
ILC	Impact on local culture
IRR	Internal rate of return
L	The possibility of accident
LCS	Life cycle safety
NPV	Net present value
PCOP	Photochemical oxidation potential

Parameters	
a_{ij}	The lower bound of scenario i (i=1,2,…,m) with respect to indicator c_j (j=1,2,…,n)
a_{xj}	Lower bound of v_{xj}
α	The interval-converting-coefficient
b_{ij}	The upper bound of scenario i (i=1,2,…,m) with respect to indicator c_j (j=1,2,…,n)
b_{xj}	Upper bound of v_{xj}
ICC	Interval-converting-coefficient
k_{id}	The integrated dependent degree of the (i)th matter element to grade t
k_{id}^L	The lower bound of the integrated dependent degree of scenario i to the grade d
k_{id}^U	The upper bound of the integrated dependent degree of scenario i to the grade d
N_d	The divided grade d
R_d	The classical domain
N_x	The grade of the matter element for assessment
R_x	The matter element for assessment
R_P	Segment field

U	A space of objects
x	A matter element
v_{xj}	the value of x with respect to the characteristic c_j
v_{pj}	The union set of the values with respect to the characteristic c_j in all grades
w_j	The weight of the characteristic (indicator) j
Variables	
z_{pd}	A binary variable, it represents that the matter element p belongs to the grade t when z_{pd} equals 1; on the contrary, it represents that the matter element p does not belong to the grade t when z_{pd} equals 0.

1 Introduction

Due to the increased environmental contamination problems, sustainability development, which has been defined as the development in which the needs of the present generation are met without compromising the ability of future generation to meet their requirements, is the best way to reduce the environmental pollution (Lou et al. 2004). Sustainability assessment which can consider economic prosperity, environmental cleanness and social acceptability, is a powerful tool to select the most sustainable option among multiple different energy and industrial systems. Accordingly, developing a generic sustainability assessment method which can incorporate the preferences and willingness of multiple decision-makers/stakeholders is of vital importance for promoting sustainable development and achieving sustainability transition by selecting the most sustainable scenario among multiple energy and industrial systems.

There are many studies focusing on sustainability assessment of energy and industrial systems, and the criteria for sustainability assessment usually consists of multiple aspects, i.e. resource, environment, economic and social aspects, etc.. Life cycle assessment (LCA) is one of the most popular tools for environmental sustainability assessment which can identify the more environmentally responsible scenarios among different alternatives (Benetto et al. 2004). The data of the alternative energy and industrial systems with respect to the criteria for sustainability assessment was determined in the 'cradle to grave' approach in the life cycle inventory (LCI). However, sustainability assessment in life cycle thinking (LCT) means to assess the sustainability of energy and industrial systems in life cycle perspective, namely from 'cradle to grave', and sustainability usually consists of three pillars, including economic, environmental and social aspects. Consequently, the traditional LCA which focuses on investigating the environmental impacts of products/processes cannot satisfy the requirements of measuring the economic, environmental and social performances simultaneously (Ren et al., 2016). Accordingly, life cycle sustainability assessment (LCSA) which is a tool combines LCA, life cycle costing (LCC), and social life cycle assessment (SLCA) has been widely used for sustainability assessment (Zamagni, 2012).

There are various studies focusing on the applications of LCSA on sustainability assessment of different products/processes. Zhou et al. (2007) developed a life cycle multi-criteria sustainability assessment framework, and this framework was applied on life cycle assessment of six fuels by using four indicators including life cycle costs (LCC), global warming potential (GWP), net energy yield (NE), and non-renewable resource depletion potential (NRDP). Onat et al. (2014) integrated the input–output models and the thoughts of triple bottom line (TBL) into life cycle assessment, and the US buildings have been studied by the proposed method. Stamford and Azapagic (2012) employed the life cycle sustainability assessment framework to investigate the sustainability of four electricity options including gas, nuclear, offshore wind and photovoltaics. Menikpura et al. (2012) proposed a method by using life cycle perspective and a sustainability assessment system which consists of a set of endpoint composite indicators to assess the sustainability of municipal solid waste management systems in Thailand. Schau et al. (2012) applied LCA, LCC and SLCA to quantify the sustainability indicators for sustainability assessment of the three different remanufactured alternators and remanufacturing localization scenarios in life cycle perspective. Hossaini et al. (2015) combined analytic hierarchy process and life cycle sustainability assessment framework to investigate the sustainability of six storey wood frame and concrete frame building in Vancouver. Yu and Halog (2015) used the life cycle sustainability assessment as the tool to study a 1.2 MW flat-roof mounted PV solar array, and the implications regarding to economic, environmental and social aspects have been obtained according to the results of LCSA. Huang and Mauerhofer (2016) developed a sustainability evaluation method based on life cycle theory, and the ground source heat pump in Shanghai was studied. These results of life cycle sustainability assessment are beneficial for the decision-makers/stakeholders to understand the performances of the products/processes with respect to economic, environmental and social aspects; however, it is also difficult for the decision-makers/stakeholders to choose the most sustainable scenario among multiple alternatives, because they usually face many conflict criteria when making a decision. In other words, an alternative performs better in one aspect than the other alternatives, but may perform worse on some other aspects. Accordingly, multi-criteria decision making (MCDM) which aims at ranking multiple alternatives with the consideration of multiple conflict criteria (Ren et al., 2015a), has been widely combined with life cycle thinking.

There are many studies focusing on the combination of MCDM and life cycle sustainability assessment for prioritizing the alternative products/processes, and life cycle sustainability assessment was usually first used to collect the data of the alternatives with respect to economic, environmental and social aspects for establishing the decision-making matrix. Then, MCDM was applied to rank alternatives based on the decision-making matrix established by LCSA. For instance, Ren et al. (2015b) combined the multi-criteria decision making and life cycle sustainability assessment for prioritizing the technologies for bioethanol production, and VIKOR (An et al., 2015) method was employed to rank the alternatives. Akhtar et al. (2015) used analytic hierarchy process (AHP) for selecting the most sustainable sewer pipe with the consideration of eight criteria including resource depletion, energy consumption, global warming, acidification, smog potential, initial cost, and maintenance cost. Fawaz et al. (2016) combined sum weighted method (SWM) and life cycle sustainability assessment to rank the six design alternative of low rise commercial building. Kucukvar et al. (2014) developed a triple bottom line oriented sustainability assessment model to assess the environmental and socio-economic impacts of pavement designs. Besides the combination of MCDM and LCSA, there are some studies focusing the combination of MCDM and LCA. For instance, Liu et al (2012) combined risk assessment, life cycle assessment, and multi-criteria decision making for environmental impact assessment. Myllyviita et al. (2012) integrated the MCDM into life cycle assessment for assessing the environmental impacts of alternative biomasses. Motuziene et al. (2016) developed a life cycle multi-criteria analysis for investigating the three alternative types of envelopes (masonry, log and timber frame) of an energy efficient single-family house by combing COmplex PRoportional ASsesment (COPRAS), life cycle assessment and life cycle cost. Therefore, it is apparent that the combination of MCDM and life cycle thinking can rank the alternatives in life cycle approach.

As discussed above, the combination of MCDM and LCSA as a powerful tool can comprehensively assess the sustainability of alternative energy and industrial systems, but the traditional MCDM methods usually face various uncertainties including both aleatory and epistemic uncertainties (Liu and Huang, 2012), the aleatory uncertainties refer to the variations associate with physical system and/or external environment, and the epistemic uncertainties refer to the variations caused by the lack of information and/or knowledge. Uncertainty is a severe problem existed in multi-criteria decision making, especially the uncertainty factors in human judgments and decision-making matrix. Thus, an improved AHP method which can address the uncertainties existed in human judgments in part 1. However, the uncertainties existed in the decision-making matrix-the uncertainties regarding the data of the alternatives with respect to sustainability criteria cannot be successfully solved by the traditional MCDM method, this is the first research gap. Meanwhile, most of the interval-based MCDM methods can only provide the decision-makers a final score which represents the integrated priority of each alternative, but they cannot tell the decision-makers the sustainability degree/level of the energy and industrial systems, this is the second research gap. In order to fill these research gaps, the improved MCDM method which can address uncertainties for combining with LCSA and determine the sustainability degree is essential.

There are usually three ways for addressing uncertainties in MCDM, including fuzzy set theory (Ren et al., 2013), grey set theory (Chithambaranathan et al., 2015; Manzardo et al., 2012), and interval approach (Jahanshahloo et al., 2006; Sayadi et al., 2009). Accordingly, there are various extended MCDM methods by combining the traditional MCDM with fuzzy theory, grey theory, or interval approach which have been widely used, i.e. fuzzy AHP method (Ren and Lützen, 2015), fuzzy TOPSIS (Chen and Tsao, 2008), fuzzy VOKOR (Kaya and Kahraman, 2010), grey PROMETHEE (Kuang et al., 2015), interval TOPSIS (Tsaur, 2011), and interval VIKOR (Jahan and Edwards, 2013). Among these methods, the MCDM methods based on fuzzy set theory and grey set theory usually need the users to make judgments on the relative performances of the alternatives with respect to evaluation criteria intuitively and subjectively, and the decision-making matrix for MCDM was usually established based on human judgments; however, the data of the alternatives with respect to the evaluation criteria cannot be fully used in the decision making. Accordingly, the interval-based MCDM methods were widely used for addressing uncertainties recently.

This paper presented a method for sustainability assessment of alternative energy and industrial systems based on multi-actor multi-criteria decision making (multi-actor interval extension theory) under uncertainty conditions by modifying the extension theory, and a criteria system including four aspects (environmental, safety, economic, and social) has been established for sustainability assessment. The method for determining the weights of the criteria for sustainability assessment has been provided in the first part of this two-paper series dealing with sustainability assessment of alternative energy and industrial systems under uncertainties. The developed multi-actor multi-criteria decision making method for sustainability assessment of energy and industrial systems can not only allow multiple decision-makers to participate in the decision making, but also address uncertainties.

2 Methods

The criteria system for sustainability assessment was firstly established; secondly, the interval numbers were introduced; subsequently, the method for data processing was proposed; then, the extension theory was presented; and finally, the interval-based extension theory was presented.

2.1 Criteria System for sustainability assessment

Life cycle sustainability assessment is a combination of life cycle assessment, life cycle costing, and social life cycle assessment. LCA can investigate all environmental burdens connected with a product or service from "cradle to grave"-back to the raw materials and down to waste removal (Klöpffer, 1997). The CML 2 baseline 2000 V2.04 characterization is one of the most popular methodologies for characterizing the environmental impacts, and there are ten environmental impact categories including global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation potential (PCOP), acidification potential (AP), human toxicity potential (HTP), abiotic depletion potential (ADP), eutrophication potential (EP), fresh water aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE), and terrestrial ecotoxicity (TE).LCC is a framework for specifying the estimated total incremental cost of developing, producing, using, and retiring a particular item (Asiedu and Gu, 1998), and the concept can be popularized to investigate the economical performances of a product/process in life cycle perspective. Accordingly, some other economic indicators including the investment cost (IC), net present value (NPV) and internal rate of return (IRR) can also be used to measure the life cycle economic sustainability (Ren et al., 2016). SLCA aims at investigating the social impacts from "cradle to grave" approach by integrating the traditional life cycle assessment methodological steps while having social impacts as focus (Sala et al., 2015). Accordingly, many subcategories concerning the impacts on workers, local community, society, value chain actors, and consumers, i.e. fair salary (FS), added jobs (AJ), local employment (LE), impact on local culture (ILC), corruption (C), supplier relationships (SR), and transparency (TR), etc. (Andrews et al., 2009). Therefore, the criteria for life cycle sustainability assessment should also consist of all the indicators used in LCA, LCC and SLCA in the three pillars of sustainability including economic, environmental, and social aspects.

The TBL method has been widely used for sustainability assessment; however, Ren et al. (2013) clarified that the indicators in economic, environmental, and social aspects are not enough for sustainability assessment, because the indicators in technological aspect usually have influences on the indicators in economic, environmental, and social aspects. Thus, the technological aspect should also be incorporated in sustainability assessment. Therefore, the indicators in economic, environmental, social, and technological aspects should be incorporated in life cycle sustainability assessment. The indicators in economic, environmental, and social aspects should contain all the indicators used in LCC, LCA, and SLCA, respectively. As for the indicators in technological aspect, life cycle energy efficiency (LCEE), life cycle safety (LCS), life cycle maturity (LCM), and technology innovation (TI) were used as the criteria in technological aspect based on the work of Ren et al. (2016) in this study. Therefore, there are four macroscopic aspects including environmental, economic, social and technological dimensions for sustainability assessment of energy and industrial systems, and the framework of sustainability assessment has been presented in Fig. 1.

According to the sustainability assessment framework presented in Fig.1, the decision-makers/stakeholders can select the most suitable indicators for sustainability assessment. Meanwhile, they can also add some new indicators or delete some indicators in the criteria system according to their preferences and the actual conditions. Herein, it is worth pointing out that the risk for measuring LCS can be obtained by the LEC method (Feng et al. 2007; Wang et al. 2009), the LEC method was developed based on three components：(i) the possibility of accident (L), (ii) the frequency of dangerous incident(E), (iii) the possible consequences caused by the incidents(C). LCS is the product of L, E and C. The needed area represents the needed land area for the functional unit of product. In addition, investment cost, net present value and internal rate of return are economic indicators that can be used as more appropriate profitability measurement for economic condition and can also reflect a comprehensive economic assessment for alternative options (Othman et al. 2010).

2.2 Interval Numbers

A closed real interval $a=[a^L,a^U]$ is a real interval number, and a^L and a^U ($a^L,a^U \in R$, $a^L < a^U$) are real numbers representing the lower and upper bound of the interval, respectively (Suprajitno and Mohd, 2010).

Suppose that $a_1=[a_1^L,a_1^U]$, $a_2=[a_2^L,a_2^U]$ are two interval numbers, $\lambda \in R$ and $\lambda > 0$.

Definition 1 $a_1 = a_2$ if and only if $a_1^L = a_2^L, a_1^U = a_2^U$.

Definition 2 $a=[a^L,a^U]$ is a point interval number, if $a^L = a^U$.

The interval arithmetic can be presented accordingly to Suprajitno and Mohd (2010), and Alefeld and Herzberger (1983).

$$a_1 + a_2 = [a_1^L + a_2^L, a_1^U + a_2^U] \quad (1)$$

$$a_1 - a_2 = [a_1^L - a_2^U, a_1^U - a_2^L] \quad (2)$$

$$a_1 \bullet a_2 = [\min(a_1^L a_2^L, a_1^L a_2^U, a_1^U a_2^L, a_1^U a_2^U), \max(a_1^L a_2^L, a_1^L a_2^U, a_1^U a_2^L, a_1^U a_2^U)] \quad (3)$$

$$\lambda a_1 = [\lambda a_1^L, \lambda a_1^U] \quad (4)$$

Definition 3 As to an interval number $a=[a^L,a^U]$, the interval-converting-coefficient (ICC) α, is defined in Eq.5.

$$\alpha = \frac{a' - a^L}{a^U - a^L} \quad (5)$$

With the ICC, the crisp value of a' can be calculated in Eq.6.

$$a' = \alpha a^U + (1-\alpha) a^L \quad (6)$$

The interval-converting-coefficient (ICC) $\alpha (0 \le \alpha \le 1)$ can be determined by the users (usually takes the value 0.5), and $\alpha = 0$ represents the most pessimistic aspiration, and $\alpha = 1$ represents the most optimistic aspiration, thus, the greater the value of ICC, the more optimistic the aspiration is.

2.3 Data Processing

As mentioned above, this part aims at developing an interval-based extension theory for assessing the sustainability of the alternative energy and industrial systems under uncertainties, thus, the data of the alternatives with respect to the sustainability indicators are intervals rather than the crisp numbers. The interval decision-making matrix was presented in Eq.7.

$$A = \begin{vmatrix} & Scenario,1 & Scenario,2 & \cdots & Scenario,m \\ Indicator,1 & <a_{11},b_{11}> & <a_{21},b_{21}> & \cdots & <a_{m1},b_{m1}> \\ Indicator,2 & <a_{12},b_{12}> & <a_{22},b_{22}> & \cdots & <a_{m2},b_{m2}> \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ Indicator,n & <a_{1n},b_{1n}> & <a_{2n},b_{2n}> & \cdots & <a_{mn},b_{mn}> \end{vmatrix} \tag{7}$$

where a_{ij} denotes the lower bound of scenario i (i=1,2,…,m) with respect to indicator c_j (j=1,2,…,n), and b_{ij} denotes the upper bound of scenario i (i=1,2,…,m) with respect to indicator c_j (j=1,2,…,n).

In order to make the data dimensionless and make the calculations more convenient (especially for comparing the data in different ranges or with different units), all the data should be normalized. The indicators that will benefit on the priority of the alternative with the increase of its value are beneficial indicator, the set of beneficial indicators is denoted by B. Accordingly, the added jobs (AJ), net present value (NPV) and internal rate of return (IRR) are all beneficial indicators. On the contrary, the indicators should be recognized as negative indicator if the indicators have negative impacts on the priority of the alternatives, and the set of negative index is denoted by N. The data of the alternatives with respect to the positive indicators can be normalized by Eq.8 and Eq.9. After the transformation, the interval $<a_{ij},b_{ij}>$ can be transformed into $<a_{ij}^{'},b_{ij}^{'}>$. In a similar way, the data of the alternatives with respect to the negative indicators can be normalized by Eq.10 and Eq.11. Accordingly, the interval $<a_{ij},b_{ij}>$ can be transformed into $<b_{ij}^{'},a_{ij}^{'}>$

$$a_{ij}^{'} = \frac{a_{ij} - a_j^{\min}}{b_j^{\max} - a_j^{\min}}, j \in P, i = 1,2,\cdots,m \tag{8}$$

$$b_{ij}^{'} = \frac{b_{ij} - a_j^{\min}}{b_j^{\max} - a_j^{\min}}, j \in P, i = 1,2,\cdots,n \tag{9}$$

$$a_{ij}^{'} = \frac{b_j^{\max} - a_{ij}}{b_j^{\max} - a_j^{\min}}, j \in N, i = 1,2,\cdots,m \tag{10}$$

$$b_{ij}^{'} = \frac{b_j^{\max} - b_{ij}}{b_j^{\max} - a_j^{\min}}, j \in N, i = 1,2,\cdots,n \tag{11}$$

where $a_j^{\max} = \max\{a_{ij}\}, i = 1, 2, \cdots, m, a_j^{\min} = \min\{a_{ij}\}, i = 1, 2, \cdots, m$

$b_j^{\max} = \max\{b_{ij}\}, i = 1, 2, \cdots, m, b_j^{\min} = \min\{b_{ij}\}, i = 1, 2, \cdots, m$

2.4 Extension theory

The concept of extension was developed by Cai (1983) to solve contradictions and incompatibility problems. This method has been widely used to deal with the problems which cannot be directly solved by the given conditions. There are usually three kinds of set can be used to describe the objects, namely crisp set, fuzzy set and extension set. Different from the crisp set and the fuzzy set which use {0,1} and [0, 1] to describe the degree an element belongs to a set, the extension set extends the fuzzy set from [0, 1] to [-∞, +∞] for describing the degree of an element belongs to any extension set (Zheng et al. 2009).

2.4.1 Matter-element

The ordered ternary R=（N, C, V）consisting of matter N, characteristic C and the value V of the characteristic C, which represents a fundamental unit to describe the matter N, is called one-dimensional matter element. If the matter N having n characteristics and each characteristic has its value respectively. The array R can be recognized as a n-dimensional matter element, as shown in Eq.12. For instance, Eq.13 can be used to express a box whose length, width and height is 10cm, 8 cm and 5 cm, respectively.

$$R = \begin{bmatrix} N & , & c_1 & , & v_1 \\ & & c_2 & , & v_2 \\ & & \vdots & , & \vdots \\ & & c_n & , & v_n \end{bmatrix} = (N, C, V) \tag{12}$$

where N is a matter-element vector, C is a characteristic vector, and V is a value vector of C.

$$R_{box} = \begin{bmatrix} Box & Length & 10cm \\ & Width & 8cm \\ & Height & 5cm \end{bmatrix} \tag{13}$$

2.4.2 Classical field

$$R_d = (N_d, C, V_{0d}) = \begin{bmatrix} N_d & , & c_{d1} & , & v_{d1} \\ & & c_{d2} & , & v_{d2} \\ & & & , & \\ & & c_{dn} & , & v_{dn} \end{bmatrix} = \begin{bmatrix} N_i & , & c_{d1} & , & <a_{d1}, b_{d1}> \\ & & c_{d2} & , & <a_{d2}, b_{d2}> \\ & & & , & \\ & & c_{dn} & , & <a_{dn}, b_{dn}> \end{bmatrix} \quad (14)$$

where N_d represents the divided grade d, $c_j (j = 1, 2, \cdots, n)$ represents the (*j*) th characteristic of matter-element N_d, $<a_{dj}, b_{dj}>$ represents a domain, namely the value range of the characteristic $c_{dj} (j = 1, 2, \cdots, n)$, a_{dj} and b_{dj} are lower and upper bounds of a classical field respectively, and there are t grades. R_d is classical domain. $d = 1, 2, ..., t$

2.4.3 Segment field

$$R_P = (P, C, V_P) = \begin{bmatrix} N & , & c_1 & , & v_{p1} \\ & & c_2 & , & v_{p2} \\ & & \cdots & , & \cdots \\ & & c_n & , & v_{pn} \end{bmatrix} = \begin{bmatrix} N & , & c_1 & , & <a_{p1}, b_{p1}> \\ & & c_2 & , & <a_{p2}, b_{p2}> \\ & & \cdots & , & \cdots \\ & & c_n & , & <a_{pn}, b_{pn}> \end{bmatrix} \quad (15)$$

where P represents the union set of all the grades, $v_{pj} (j = 1, 2, \cdots, n)$ represents the union set of the values of the characteristic $c_j (j = 1, 2, \cdots, n)$ in all grades, and R_P is the segment field.

2.4.4 The matter element for assessment

$$R_x = (P, C, V_x) = \begin{bmatrix} N_x & , & c_1 & , & v_{x1} \\ & & c_2 & , & v_{x2} \\ & & \vdots & , & \vdots \\ & & c_n & , & v_{xn} \end{bmatrix} = \begin{vmatrix} N_x & c_1 & , & <a_{x1}, b_{x1}> \\ & c_2 & , & <a_{x2}, b_{x2}> \\ & \vdots & , & \\ & c_n & , & <a_{xn}, b_{xn}> \end{vmatrix} \quad (16)$$

where N_x represents the assessed grade of the matter element for assessment, $v_{xj} (j = 1, 2, \cdots, n)$ is the value of characteristic $c_j (j = 1, 2, \cdots, n)$, a_{xj} and b_{xj} were lower and upper bounds of v_{xj}, and R_x which represents the matter element for assessment.

2.4.5 Extended correlation function

Definition 4 The distance between dot x_0 and the interval $X = <a, b>$ is defined in Eq.17.

$$\rho(x_0, X) = \left| x_0 - \frac{a+b}{2} \right| - \frac{b-a}{2} \tag{17}$$

Definition 5 The moment of interval $X = < a, b >$ is defined in Eq.18.

$$|X| = \frac{|b-a|}{2} \tag{18}$$

Suppose U is a space of objects and x is a matter element, then an extension set $\tilde{A}$ in U is defined as a set of ordered pairs.

$$\tilde{A} = \left\{ (x, y) \middle| x \in U, y = K(x) \in (-\infty, +\infty) \right\} \tag{19}$$

where $y = K(x)$ is the correlation function, which can be used to quantify the dependent degree between an element and a set, the dependent degree of the indicator *j* (value v_{xj}) in the matter element for assessment (R_x) subjected to the value field of the indicator *j* in the (*d*) th classical domain can be calculated by the extended correlation function, as shown in Eq.20.

$$k_{dj} = \begin{cases} -\dfrac{\rho(v_{xj}, v_{dj})}{\left| v_{dj} \right|} & v_{xj} \subseteq v_{dj} \\ \dfrac{\rho(v_{xj}, v_{dj})}{\rho(v_{xj}, v_{pj}) - \rho(v_{xj}, v_{dj})} & v_{xj} \not\subset v_{dj} \end{cases} \tag{20}$$

Extended correlation function can used to calculate the integrated correlation degree between v_{xj} and v_{dj}.The extended correlation function indicates the degree of v_{xj} belongs to v_{dj}, and the greater the value, the more dependent it belongs to v_{dj}.

3. Improved Extension Theory

In order to achieve multi-criteria decision making for sustainability assessment of energy and industrial systems under uncertainties, the traditional extension theory has been extended into interval conditions in this section. The improved extension theory can help the decision-makers/stakeholders to determine the sustainability degree of the energy and industrial systems when the data in the decision-making matrix are intervals. Accordingly, the distance of two interval numbers were firstly defined; then, the method for determining the integrated dependent degree of the matter element for assessment to various grades was proposed; finally, an optimal programming for the determination of the sustainably grade of each alternative was proposed.

Assumptions:

(1) the data of the alternatives with respect to the evaluation criteria are intervals rather than the crisp numbers;

(2) the interdependences and interactions among the evaluation criteria and that among the scenarios are neglected.

3.1 Distance of two interval numbers

The distance between two interval numbers $X_1 =< a_1, b_1 >$ and $X_2 =< a_2, b_2 >$ is defined in Eq.21, and this is an extension of the distance between a dot and an interval.

$$\rho(X_1, X_2) = \begin{cases} (\rho(\frac{a_2+b_2}{2}, X_2), \max\left\{\rho(a_1, X_2), \rho(b_1, X_2)\right\}), a_1 \le \frac{a_2+b_2}{2} \le b_1 \\ (\min\left\{\rho(a_1, X_2), \rho(b_1, X_2)\right\}, \max\left\{\rho(a_1, X_2), \rho(b_1, X_2)\right\}), otherwise \end{cases} \quad (21)$$

3.2 Integrated dependent degree

The integrated dependent degree of the matter element p to various grades can be calculated in Eq.22.

$$(k_{i1}, k_{i2}, \cdots, k_{it}) = (w_1, w_2, \cdots, w_n) \begin{bmatrix} k_{11} & k_{21} & \cdots & k_{t1} \\ k_{12} & k_{22} & \cdots & k_{t2} \\ \vdots & \cdots & \ddots & \vdots \\ k_{1n} & k_{2n} & \cdots & k_{tn} \end{bmatrix} \quad (22)$$

where $k_{id} (i = 1, 2, \cdots, m; d == 1, 2, \cdots, t)$ is the integrated dependent degree of the (*i*)th matter element to grade *t*, and $w_j (j = 1, 2, \cdots, n)$ represents the weight of the characteristic(indicator) *j*. The integrated dependent degree reflects the composite influences of all the characteristics on the matter element.

3.3 Optimal Programming for the determination of the grade

According to Eq.22, the integrated dependent degrees of the alternative scenarios to each of the classical domains can be determined, as shown in Eq.23.

$$K = \begin{vmatrix} Grade & Scenario,1 & Scenario,2 & \cdots & Scenario,m \\ 1 & <k_{11}^L,k_{11}^U> & <k_{21}^L,k_{21}^U> & \cdots & <k_{m1}^L,k_{m1}^U> \\ 2 & <k_{12}^L,k_{12}^U> & <k_{22}^L,k_{22}^U> & \cdots & <k_{m2}^L,k_{m2}^U> \\ 3 & <k_{13}^L,k_{13}^U> & <k_{23}^L,k_{23}^U> & \cdots & <k_{m3}^L,k_{n3}^U> \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ t & <k_{1t}^L,k_{1t}^U> & <k_{2t}^L,k_{2t}^U> & \cdots & <k_{mt}^L,k_{mt}^U> \end{vmatrix} \tag{23}$$

where k_{id}^L is the lower bound of the integrated dependent degree of scenario i the (t) grade, k_{id}^U is the upper bound of the integrated dependent degree of scenario i to the grade t.

The satisfied degree (S) was defined in Eq.24 which represents the overall satisfaction of the arrangement of the sustainability levels of these alternatives, and Eq.25 represents the use of the interval-converting-coefficient to transform the interval number to a crisp number, and the interval-converting-coefficient was set by the decision-makers. Eq.26 represents the range of the interval-converting-coefficient. Eq.27 represents that one scenario should be arranged in one grade. Eq.28 represents a binary variable, it represents that the matter element p belongs to the grade d when z_{pd} equals 1; on the contrary, it represents that the matter element p does not belong to the grade d when z_{pd} equals 0.

$$\text{Max}\left\{\text{S}= \sum_{i=1}^{m}\sum_{d=1}^{t} k_{id} z_{id}\right\} \tag{24}$$

$$\alpha = \frac{k_{id} - k_{id}^L}{k_{id}^U - k_{id}^L} \tag{25}$$

$$0 < \alpha < 1 \tag{26}$$

$$\sum_{d=1}^{t} z_{id} = 1 \qquad i = 1,2,\cdots,m \tag{27}$$

$$z_{id}(z_{id} - 1) = 0 \qquad i = 1,2,\cdots,m ; d = 1,2,\cdots,t \tag{28}$$

The programming model is a non-linear mixed-integer programming，and Lingo 11.0 which was introduced in part 1 was applied to address this in this study.

4 Case study

In order to demonstrate the developed interval extension theory for sustainability assessment of different alternative energy and industrial systems, a hypothetical case with six scenarios has been studied in this part. The functional unit is 1 tones product produced by these six different energy and industrial systems, nine criteria including investment cost (IC), net present value (NPV) and internal rate of return (IRR) in economic aspect, life cycle safety (LCS) in technological aspect, photochemical oxidation potential (PCOP), global warming potential (GWP), and acidification potential (AP) in environmental aspect, added jobs (AJ) and impact on local culture (ILC) in social aspect have been employed for sustainability assessment of the energy and industrial systems. The data of all the scenarios with respect to each indicator were presented in Table 1. It is worth pointing out that relative scores of the alternatives with respect to the impact on local culture (ILC) can be obtained by questionnaire survey. For instance, the users can invite ten participants to use the intervals formed by the numbers from 1 to 5 to score these alternatives, and then, the average values of the alternatives with respect to ILC can be determined.

The interval AHP method presented in Part 1 was employed to determine the weights of the four dimensions for sustainability assessment including economic performance, technological aspect, social issue and environmental impact as well as the weights of the indicators in each dimension. 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. According to the method provided in part 1 and the comparison matrices determined by the decision-makers, the weights of the four aspects and the local weights of the indicators in each aspect can be determined (the specific procedures were presented in Appendix A) , as presented in Table 2. The weights of the four dimensions and the weights of the criteria were the average weights determined by the interval AHP presented in part 1. Then, the final weight of each indicator for sustainability assessment can also be determined by calculating the product of the local weight of the criterion and the weight of the dimension to which this criterion belongs to. For instance, the final weight of global warming potential= 0.4625 (the local weight of global warming potential) ×0.2955 (the weight of environmental aspect)= 0.1367. In a similar way, the final weights of other indicators can be determined, as presented in Table 3.

After determining the interval decision-making matrix, the data can be normalized by Eqs.8-11. Then, the improved extension theory was employed to determine the sustainability of these six scenarios.

The sustainability levels of energy and industrial systems were divided into five grades including “excellent”, “good”, “satisfied”, “barely adequate”, and “fail” when using the improved extension theory. Accordingly, the classical fields and segment filed were determined, as presented in Table 4. It is worth pointing out that the classical fields and segment filed were determined according to the normalized interval decision-making matrix. Consequently, the lower and the upper boundaries of the integrated dependent degree of various scenarios to the five grades can be calculated, as presented in in Table 5 and Table 6, respectively.

The interval-converting-coefficient was set as α=0.5 by the decision-makers, the sustainability grade of the six scenarios can be determined by solving the optimal programming (Eqs.24-28), and the results were presented in Table 7. According to the results, it can be concluded that the sustainability of scenario 1 has been ranked at the first place, the sustainability of this scenario has been recognized as “excellent”; the sustainability of scenario 2 and scenario 3 have been recognized as “good”, the sustainability of scenario 4 and scenario 5 have been recognized as “satisfied”, and the sustainability of scenario 6 has been recognized as “barely adequate”. Therefore, the sustainability sequence from the most superior to the least is {scenario 1},{scenario 2, scenario 3},{scenario 4, scenario 5}, and{scenario 6}.

5 Conclusion and perspective

A method for the sustainability assessment of the alternative energy and industrial systems has been developed in this paper by improving the traditional extension theory to uncertainties conditions. The level of the sustainability has been dived into five grades: “excellent”, “good” ,“satisfied” ,“barely adequate”, and “fail”. Extended correlation function which can be used to quantify the dependent degree between an element and a set has been used to calculate the dependent degree of the studied alternative to the classical field with respect to an indicator; then, the integrated dependent degree which can be determined to as a measure of the degrees of an element belongs to the classical fields after determining the weights of the criteria for sustainability assessment according to the method presented in part 1. An optimal programming for maximizing the satisfied degree was developed to rank the sustainability sequence and the sustainability grades of the alternative energy and industrial systems.

All in all, the developed multi-criteria decision making method for sustainability assessment of energy and industrial systems has the following advantages:

(1) It cannot only allow multiple decision-makers to participate in the process of sustainability assessment, but also has the ability to achieve sustainability assessment under uncertainty conditions. In other words, the proposed MCDM method can prioritize the sustainability sequence of the alternative energy and industrial systems when the data of the alternatives with respect to the evaluation criteria are intervals;

(2) It cannot only prioritize the sustainability sequence of the alternative energy and industrial systems, but determine the sustainability levels of the alternatives by using linguistic assessments, i.e. “excellent”, “good”, “satisfied”, “barely adequate”, and “fail”.

Besides these advantages, there are also some weak points in the proposed method:

(1) This study lacks the methods for accurately determining the relative performances of the alternative energy and industrial systems with respect to the soft criteria (i.e. technology innovation and impact on local culture) which cannot be described with units;

(2) This study does not specify the method for determining the classical fields which divide the sustainability into different levels/grades.

The future works of the authors will focus on developing the methods for determining the relative performances of the alternative energy and industrial systems with respect to the soft criteria, and the method for determining the classical fields which divide the sustainability into different levels/grades.

Appendix A

Table A1 The interval comparison matrix of the four aspects in the first hierarchy

	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>
Environment	<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

$$A = \begin{vmatrix} 1 & <2.00,3.00> & <3.20,4.80> & <3.20,4.80> \\ <0.37,0.67> & 1 & <1.80,3> & <2.00,3> \\ <0.22,0.32> & <0.42,0.87> & 1 & <1.40,2.80> \\ <0.21,0.32> & <0.40,0.77> & <0.38,0.8> & 1 \end{vmatrix} \quad \text{(a1)}$$

$$A^* = \begin{vmatrix} 1 & 2 & 3.20 & 3.23 \\ 0.56 & 1 & 1.80 & 2.00 \\ 0.32 & 0.63 & 1 & 1.40 \\ 0.28 & 0.54 & 0.80 & 1 \end{vmatrix} \quad \text{(a2)}$$

$$\lambda_{\max} = 4.10 \quad \text{(a3)}$$

$$W_{\max} = (0.8517, 0.4545, 0.2784, 0.2249)^T \quad \text{(a4)}$$

CI=0.03 (a5)

CR=0.04<0.1 (a6)

$$W_A^* = (0.4599, 0.2563, 0.1570, 0.1268) \quad \text{(a7)}$$

$$\Delta A^{+} = \begin{vmatrix} 0 & 1 & 1.60 & 1.57 \\ 0.11 & 0 & 1.20 & 1.00 \\ 0 & 0.24 & 0 & 1.40 \\ 0.04 & 0.23 & 0 & 0 \end{vmatrix} \tag{a8}$$

$$\Delta A^{-} = \begin{vmatrix} 0 & 0 & 0 & -0.03 \\ -0.19 & 0 & 0 & 0 \\ -0.10 & -0.21 & 0 & 0 \\ -0.07 & -0.14 & -0.42 & 0 \end{vmatrix} \tag{a9}$$

Table A2 The average deviation of the weights of the four aspects

Aspect	Environment	Technological	Social	Economic
The deviation	0.00260	0.00086	0.00031	-0.0037

Table A3 The average weights of the four aspects

Aspect	Environment	Technological	Social	Economic
Weighting coefficient	0.4625	0.2571	0.1573	0.1231

Table A4 The interval comparison matrix of the three indicators in the economic aspect

	IC	NPV	IRR
IC	1	<1/3,1/2>,<1/3,1/2>,<1/3,1/2>, <1/2,1/4>,<1/2,1>	<1,2>,<2,3>,<2,3>,<1,2>, <2,3>
NPV	<1,3>,<1,2>,<2,3>,<2,3>,<1,3>	1	<2,4>,<2,3>,<3,5>,<3,4>, <2,4>
IRR	<1/4,1/2>,<1/2,1>,<1/3,1/2>,<1/3, 1/2>,<1/3,1/2>	<1/4,1/2>,<1/4,1/2>,<1/3,1/2>, <1/4,1/3>,<1/4,1/2>	1

$$B_1 = \begin{vmatrix} 1 & <0.4000, 0.5500> & <1.6000, 2.6000> \\ <1.4, 2.8> & 1 & <2.4, 4> \\ <0.3500, 0.6000> & <0.2667, 0.4667> & 1 \end{vmatrix} \tag{a10}$$

$$B_1^* = \begin{vmatrix} 1 & 0.4793 & 1.7971 \\ 2.0864 & 1 & 3.7495 \\ 0.5564 & 0.2667 & 1 \end{vmatrix} \tag{a11}$$

$$\lambda_{\max} = 3.0000 \tag{a12}$$

$$W_{B_1}^{'} = (0.4202, 0.8768, 0.2338)^T \tag{a13}$$

CI=0 (a14)

CI=0<0.1 (a15)

$$W_{B1}^{*} = (0.2745, 0.5728, 0.1527)^T \tag{a16}$$

$$\Delta B_1^- = \begin{vmatrix} 0 & -0.0793 & -0.1971 \\ -0.6864 & 0 & -1.3495 \\ -0.2064 & 0 & 0 \end{vmatrix} \tag{a17}$$

$$\Delta B_1^+ = \begin{vmatrix} 0 & 0.0707 & 0.8029 \\ 0.7136 & 0 & 0.2505 \\ 0.0436 & 0.2000 & 0 \end{vmatrix} \tag{a18}$$

$$\Delta W = (0.0022, -0.0044, 0.0022)^T \tag{a19}$$

Table A5 The average weights of the three indicators

Indicator	IC	NPV	IRR
Weights	0.2767	0.5684	0.1549

Table A6 The interval comparison matrix of the three aspects in the social aspect

	ILC	AJ
ILC	1	<1/2,1>,<1/3,1>,<1/2,1>,<1/3,1/2><1/2,1>,
AJ	<1,2>,<1,3>,<2,3>,<2,3>,<2,3>	1

$$B_2 = \begin{vmatrix} 1 & <0.4333, 0.9> \\ <1.6, 2.8> & 1 \end{vmatrix} \tag{a20}$$

$$B_2^* = \begin{vmatrix} 1 & 0.4333 \\ 2.3079 & 1 \end{vmatrix} \tag{a21}$$

$$\lambda_{\max} = 2.0000 \tag{a22}$$

$$W_{B_1}^{'} = (3976, 0.9176)^T \tag{a23}$$

CI=0 (a24)

CI=0<0.1 (a25)

$$W_{B2}^{*} = (0.3023, 0.6977)^T \tag{a26}$$

$$\Delta B_1^{-} = \begin{vmatrix} 0 & 0 \\ -0.7079 & 0 \end{vmatrix} \tag{a27}$$

$$\Delta B_1^{+} = \begin{vmatrix} 0 & 0.4667 \\ 0.4921 & 0 \end{vmatrix} \tag{a28}$$

$$\Delta W = (0.0400, -0.0389)^T \tag{a29}$$

$$W_{B_2} = (0.3419, 0.6581)^T \tag{a30}$$

Table A7 The interval comparison matrix of the three aspects in the environment aspect

	PCOP	GWP	AP
PCOP	1	<1/2,1>,<1/3,1/2>,<1/2,1>, <1/2,1/3>,<1/2,1>	<1/3,1/2>,<1/3,1/2>,<1/4, 1/2>,<1/3,1/2>,<1/3,1/2>
GWP	<1,2>,<1,2>,<2,3>,<2,3>,<1,2>	1	<1/2,1>,<1/3,1>,<1/3,1/2> ,<1/4,1/3>,<1/4,1/2>
AP	<2,3>,<1,3>,<2,4>,<1,2>,<2,3>	<1,2>,<1,2>,<2,3>,<1,3>,<1,2>	1

$$B_3 = \begin{vmatrix} 1 & <0.4667, 0.7667> & <0.3167, 0.5000> \\ <1.4, 2.4> & 1 & <0.3333, 0.6667> \\ <1.6, 3> & <1.2, 2.4> & 1 \end{vmatrix} \tag{a31}$$

$$B_3^{*} = \begin{vmatrix} 1 & 0.6427 & 0.3424 \\ 1.5561 & 1 & 0.5328 \\ 2.9207 & 1.8769 & 1 \end{vmatrix} \tag{a32}$$

$$\lambda_{\max} = 3.0000 \tag{a33}$$

$$W_{B_3}^{'} = (0.2893, 0.4501, 0.8118)^T \tag{a34}$$

CI=0.00005 (a35)

CI=0.000086<0.1 (a36)

$$W_{B_3}^* = (0.1865, 0.2902, 0.5233)^T \tag{a37}$$

$$\Delta B_3^- = \begin{vmatrix} 0 & -0.1760 & -0.0257 \\ -0.1561 & 0 & -0.1995 \\ -1.3207 & -0.6769 & 0 \end{vmatrix} \tag{a38}$$

$$\Delta B_3^+ = \begin{vmatrix} 0 & 0.1240 & 0.1576 \\ 0.8439 & 0 & 0.1342 \\ 0.0793 & 0.5231 & 0 \end{vmatrix} \tag{a39}$$

$$\Delta W = (0.0034, 0.0052, -0.0089)^T \tag{a40}$$

Table A8 The average weighting coefficients of the three indicators in environment aspect

Indicator	PCOP	GWP	AP
Weights	0.1900	0.2955	0.5146

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Tables

Table 1 The data of the six scenarios with respect to the indicators for producing 1tones product

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
IC(Yuan.t^{-1})	<568,583>	<476,492>	<625,652>	<542,561>	<494,517>	<587,631>
NPV(Yuan.t^{-1})	<847,866>	<762,771>	<798,834>	<822,859>	<725,748>	<809,834>
IRR(%)	<18.56,18.87>	<15.36,16,03>	<19.12,19.38>	<17.83,18.14>	<17.45,17.62>	<18.06,18.33>
PCOP(kg C_2H_4eq)	<0.029,0.042>	<0.031,0.036	<0.049,0.058>	<0037,0.045>	<.034,0.038>	<.027,0.03>
GWP(kg CO_2eq)	<1.38,2.21>	<4.21,4.36>	<3.82,4.10>	<2.73,2.96>	<1.93,2.31>	<2.68,2.99>
AP(kg SO_2eq)	<0.56,0.65>	<0.89,0.92>	0<0.72,0.81>	<0.49,0.56>	<0.61,0.68>	<0.77,0.82>
ILC	<1.2,1.5>	<.2.7,3.2	<1.9,2.4>	<3.1,3.6>	<0.8,1.0>	<2.2,3.4>
AJ	<28,36>	<22,29>	<32,41>	<17,25>	<19,22>	<33,36>
LCS	<1482,1680>	<1701,1869>	<1722,2053>	<1920,2164>	<1890,2046>	<2424,2684>

Note: AJ represents the number of added jobs when using each scenario for the new plant

Table 2 The weights of the four aspect and the local weights of the indicators in each dimension

First hierarchy	Weighting	Second hierarchy	Weighting
Environmental	0.4625	PCOP	0.1900
		GWP	0.2955
		AP	0.5146
Technological	0.2571	LCS	1
Social	0.1573	ILC	0.3419
		AJ	0.6581
Economic	0.1231	IC	0.2761
		NPV	0.5684
		IRR	0.1549

Table 3 The final weights of the indicators

Indicator	PCOP	GWP	AP	LCS	ILC	AJ	IC	NPV	IRR
Weight	0.0879	0.1367	0.2380	0.2571	0.0538	0.1035	0.0340	0.0700	0.0191

Table 4 Classical field and segment field

	Classical field					Segment field
Grade	Excellent	Good	Satisfied	Barely adequate	Fail	
No.	1	2	3	4	5	
Indicator	<0.80,1.0>	<0.60,0.80>	<0.40,0.60>	<0.20,0.40>	<0,0.20>	<0,1.0>

Table 5 The lower bound of the integrated dependent degree of the six scenarios to various grades

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Excellent	0	-0.1907	-0.3547	-0.1786	-0.1445	-0.3524
Good	-1.4577	-0.0557	-0.1936	-0.1309	-0.0638	-0.4020
Satisfactory	-0.4371	-0.2152	-0.4133	-0.0346	-0.0576	-0.5598
Barely adequate	-0.3544	-0.2334	-0.3171	-0.1526	-0.1425	-0.2571
Fail	-0.3238	-0.2406	-0.2942	-0.1876	-0.1767	-0.2571

Table 6 The upper bound of the integrated dependent degree of the six scenarios to various grades

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Excellent	0.2571	0.0278	0.0004	-0.0528	0.0485	-0.1477
Good	-0.0249	0.3128	0.258	0.0278	0.0558	-0.1208
Satisfactory	-0.1071	-0.0372	0.1548	0.0972	0.0659	-0.0766
Barely adequate	-0.1463	-0.0966	-0.0367	-0.0125	-0.0461	3.1534
Fail	-0.1693	-0.1308	-0.0777	-0.0689	-0.0689	0.1105

Table 7 The results of optimal programming

Parameter	Z_{11}	Z_{22}	Z_{32}	Z_{43}	Z_{53}	Z_{64}
Value	1	1	1	1	1	1

Figure captions

Fig. 1 The framework of sustainability assessment

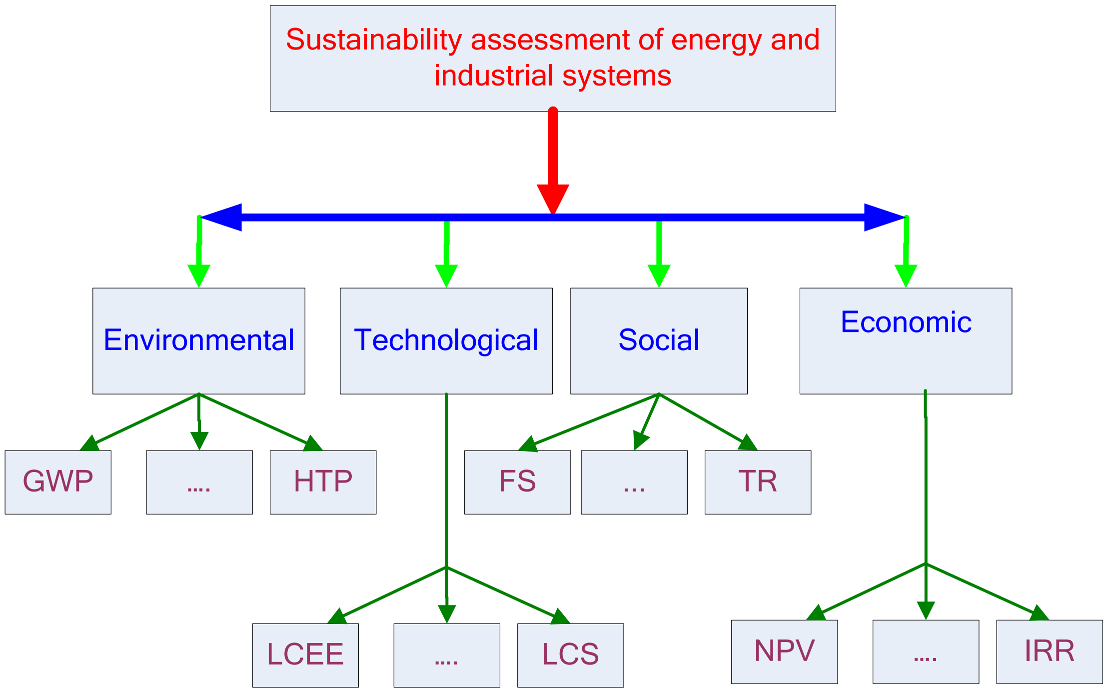

Fig. 1 The framework of sustainability assessment