

# **Life Cycle Aggregated Sustainability Index for the Prioritization of Industrial Systems**

## **Under Data Uncertainties**

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**Abstract:** This study aims at developing a generic method for measuring the sustainability of industrial systems and prioritizing industrial systems under uncertainties. The interval preference relation based goal programming model which can address vagueness and ambiguity existing in human's judgments was employed to determine the weights of the criteria for life cycle sustainability assessment. A life cycle aggregated sustainability index which incorporates both the data of industrial systems with respect to the evaluation criteria and the weights of the criteria was developed to prioritize the industrial systems. An illustrative case including four electricity generation systems were studied by the proposed method, and the results were also validated by another four multi-criteria decision making methods. The results reveal that the developed life cycle aggregated sustainability index can effectively prioritizing industrial systems under data uncertainties.

**Keywords:** life cycle sustainability assessment; sustainability index; multi-criteria decision making; industrial systems; uncertainties

## 1. Introduction

Sustainable development was defined as “the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” in the Brundtland report of 1987 (WBCSD, 1997). As the concept of sustainability development emphasizes the considerations of the influences of development on future generations, it has been an important focal point for the stakeholders/decision-makers of industrial systems and processes (Singh *et al.*, 2012). Sustainability assessment of industrial systems with the objective of sustainability measurement has been recognized as a powerful tool for helping the stakeholders/decision-makers make correct decisions (Ren *et al.*, 2017a). The harmonious development of the three dimensions of sustainability including economy, environment and society simultaneously, so-called “triple bottom line”, has received more and more attentions (Venkatraman and Nayak, 2015). The sustainability assessment of industrial systems usually considered economic sustainability, environmental sustainability, and social sustainability simultaneously (Manara and Zabaniotou, 2014). Economic sustainability represents the economic performances (i.e. the production or manufacturing costs at plant level), environmental sustainability aims at measuring the environmental impacts (usually related to waste reduction, emissions mitigation, lowering energy consumption, improving resource utilization efficiency, and decreasing the frequency of environmental accidents.), and social sustainability is used to measure the social contributions and influences on both internal communities (i.e. operators, workers and engineers) and external society (Gimenez *et al.*, 2012). Therefore, measuring the three pillars of sustainability is the foundation of investigating the sustainability of industrial systems.

There are various studies focusing on developing the metrics for sustainability assessment of industrial systems. Sikdar (2013) pointed out that the improvement of the sustainability characteristics of systems usually focused on the metrics ecological, economic and sociological

aspects. The IChemE Sustainable Development Progress Metrics developed by the Institution of Chemical Engineers (IChemE) consists of three aspects in environmental sustainability including resource usage, emission, effluents and waste, additional environmental items, three aspects in economic sustainability including profit, value and tax, investments, and additional economic items, and three aspects in social sustainability including workplace, society, and additional social items (IChemE, 2012). The GREENSCOPE (Gauging Reaction Effectiveness for the ENvironmental Sustainability of Chemistries with a multi-Objective ProcessEvaluator) tool developed by the U.S. Environmental Protection Agency employed metrics in 4 Es including efficiency, energy, economic and environmental aspects (Ruiz-Mercado *et al.*, 2013; Smith *et al.*, 2015). Othman *et al.* (2010) developed a metric system including fourteen metrics for sustainability assessment of chemical process, namely, net present value (NPV) and discounted cash flow rate of return (DCFRR) in economic pillar, global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), photochemical oxidation potential (PCOP), human toxicity potential by ingestion (HTPI), human toxicity potential by inhalation/dermal exposure (HTPE), aquatic toxicity potential (ATP), and terrestrial toxicity potential (TTP) in environmental pillar, and safety during operation, operability of the plant, safety in start-up and shutdown, and the level of the design for satisfying location specific demands in social pillars. Martins *et al.* (2007) developed a set of four three dimensional (3D) sustainability metrics including material intensity, energy intensity, potential chemical risk, and potential environmental impact for sustainability assessment of chemical processes. Al-Sharrah *et al.* (2010) developed the metrics in three aspects including environmental, economic and safety aspects for sustainability assessment of process industry. All the studies are beneficial for the stakeholders/decision-makers to select the most though the metrics developed by different developers are different. The difference in the metric systems for sustainability assessment was caused by the difference in human's preferences and judgments, and the selection of metrics for

sustainability assessment of industrial systems is an object-oriented problem (Ren *et al.*, 2016a). However, most of these studies only focused on the production stage rather than the whole life cycle of the products. There are several life cycle impact assessment (LCIA) methods, including Eco-indicator 99 (Goedkoop and Spriensma, 2000), CML 2001 (Life Cycle Assessment-An Operational Guide to the ISO Standards 2001) (Guinée *et al.*, 2001), and ReCiPe 2008 method (Goedkoop *et al.*, 2009), etc. Eco-indicator 99 firstly determined the inventory of all the relevant emissions, resources utilization and used land in the whole life cycle of a product, then calculated the damages to Human Health (HH), Ecosystem Quality (EQ) and Resources (R) (Goedkoop and Spriensma, 2000). CML 2001 method employed ten impact categories including Abiotic depletion (AD), acidification (Acid), eutrophication (Eut), global warming potential (GWP), ozone layer depletion (OLD), photochemical oxidation (PO), freshwater ecotoxicity (Fecot), marine ecotoxicity (Mecot), terrestrial ecotoxicity (Tecot), and human toxicity (Htox) to measure the life cycle environmental impacts of a product (Guinée *et al.*, 2001). ReCiPe 2008 method includes two levels of impact categories including midpoint level and endpoint level categories, there are eighteen impact categories at the midpoint level, and they are climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionising radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (ULT), water depletion (WD), mineral resource depletion (MRD), and fossil fuel depletion (FD). These eighteen impact categories can be further aggregated into three endpoint impact categories, and they are damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA) (Goedkoop *et al.*, 2009). All these LCIA methodologies can only investigate the environmental impacts, but the economic performances and social

influences cannot be addressed. Accordingly, the life cycle based sustainability assessment of industrial systems which can investigate the integrated sustainability performances of chemical products from “cradle to grave” perspective was developed. For instance, the life cycle sustainability assessment of bioethanol production pathways in the work of Ren *et al.* (2015), the environmental impacts, economic performances, and social contributions and influences of different bioethanol production methods can be investigated in the life cycle perspective, namely, from the plantation of crops, the harvest, the transportation of crops, bioethanol production from crops, the distribution of bioethanol, and till to the end-use of bioethanol (Ren *et al.*, 2015).

Life cycle sustainability assessment (LCSA) enables the decision-makers/stakeholders to investigate the performances of the products/processes with respect to the three dimensions of sustainability (environmental, economic and social dimensions) from “cradle to grave” perspective (Heijungs *et al.*, 2010). The traditional sustainability assessment methods merely focused on one stage of the life cycle of the products/processes (Ren and Lützen, 2015). The LCSA method can study the sustainability of products/processes by accounting the economic, environmental and social performances of the products/processes in the whole life cycle perspective. Klöpffer (2003) defined the concept of LCSA as the combination of life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (SLCA):  $LCSA = LCA + LCC + SLCA$ . The environmental burdens, economic benefits, and social influences of the products/processes can be investigated by LCA, LCC and SLCA, respectively (Valdivia *et al.*, 2013).

LCSA is a power tool to investigate the sustainability of products/processes. However, there are a limited number of studies using LCSA to analyze products/processes comparing with the studies about sustainability assessment which only focus on the production stage, because there is a great challenge when using life cycle tools for sustainability assessment: the uncertainties in data collection. It is difficult to collect the data with respect to the criteria in economic, environmental

and social dimensions which have the same spatial and temporal characteristics, and the problem of the uncertainties in data collection has become a severe challenge caused by estimation, hypothesis, data variations and systematic uncertainties (Lloyd and Ries, 2007; Caputo *et al.*, 2014).

Besides the challenge of the uncertainties in data collection which was urgent to be resolved, it is usually difficult for the stakeholders/ decision-makers to make correct decision on selecting the most sustainable industrial system among multiple alternatives after LCSA, because there are usually various conflicting criteria in LCSA, and an industrial system is better than another system with respect to one criterion, but it may also perform worse with respect to some other criteria in LCSA (Ren *et al.*, 2017b). Accordingly, developing life cycle based multi-criteria decision making method for prioritizing the alternative industrial systems is of vital importance. There are various studies combining life cycle assessment and multi-criteria decision making for ranking different alternative industrial systems (Hermann, 2007; Linkov and Seager, 2011; Angelo *et al.*, 2017). These methods can help the stakeholders/decision-makers to select the most environmentally sustainable industrial system among multiple alternatives, but the other two pillars of sustainability (economic and social aspects) were usually neglected in these studies. In order to incorporate the three pillars of sustainability simultaneously in the multi-criteria decision making, LCSA and multi-criteria decision making methods were combined to determine the most sustainable industrial system among multiple alternatives in many studies (Azapagic *et al.*, 2016; Hossaini *et al.*, 2015; Galán-Martín *et al.*, 2016). These methods can help the stakeholders/decision-makers to select the most sustainable industrial system among multiple alternatives with the considerations of the three pillars of sustainability simultaneously, but the data uncertainties were neglected in these methods. Uncertainties represent both the aleatory (the variations associated with physical systems and/or the environment) and the epistemic uncertainties (caused by the lack of knowledge and/or information) (Liu and Huang, 2012). It is usually difficult for the users of LCSA to obtain the accurate data in

life cycle inventory (i.e. the consumption of raw materials, energy consumption, and emissions, etc.) for determining the data of industrial systems with respect to the criteria in environmental, economic, and social aspects. There are various ways for addressing data uncertainties, i.e. stochastic theory, fuzzy theory, and interval approach (Ren *et al.*, 2016b). Among these, the interval approach is the most convenient way for addressing uncertainties, because interval approach can use the interval numbers to represent the uncertainties, and the users just need to know upper and lower bounds of the data, but the use of stochastic theory and fuzzy theory has to know the corresponding probability distribution and membership function, respectively. Therefore, interval approach was employed to address the problem of data uncertainties in LCSA in this study.

All in all, there are three research gaps that need to be addressed simultaneously for the prioritization of industrial systems:

- (1) It lacks the method for ranking the alternative industrial systems with the considerations of the three pillars of sustainability (the so-called triple bottom line) and the preferences of the decision-makers/stakeholders simultaneously;
- (2) It lacks the life cycle aggregated sustainability index to measure the life cycle sustainability of industrial systems by aggregating all the indicators in economic, environmental and social pillars of sustainability into an aggregated index; and
- (3) It lacks the method which can address uncertainties when ranking the alternative industrial systems in life cycle sustainability perspective.

In order to overcome the above-mentioned three challenges, a life cycle aggregated sustainability index based on the conditions of data uncertainties and life cycle perspective was developed for ranking the industrial systems in this study.

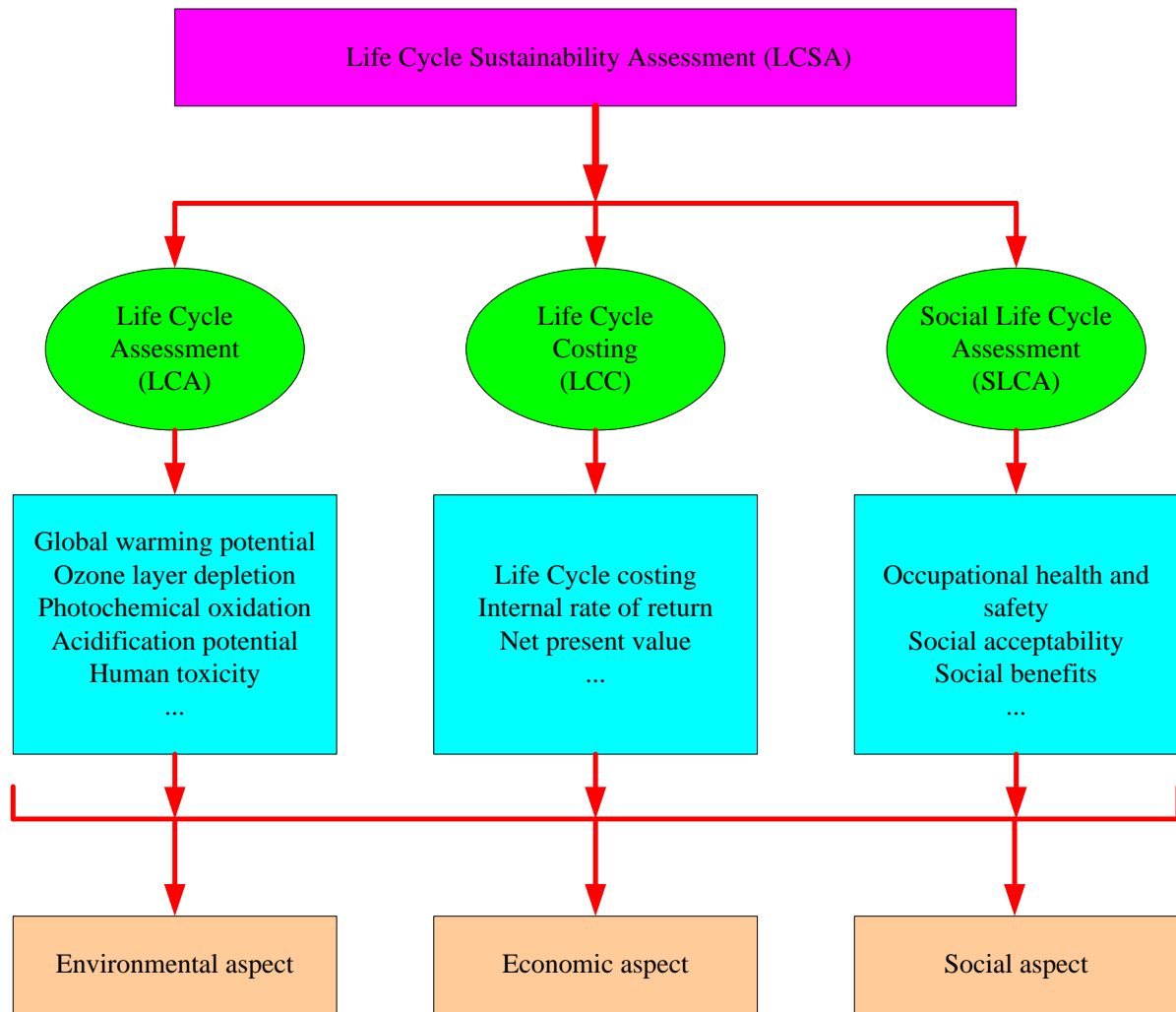


Besides the introduction part, the methods used in this study were presented in section 2, including interval number based LCSA, interval preference relation based goal programming model, and life cycle aggregated sustainability index; an illustrative case was studied in section 3; the results were discussed in section 4 through sensitivity analysis and validations; finally, this study was concluded in section 5.

## **2. Methods**

This section consists of three parts, including the interval number based LCSA, the interval preference relation based goal programming model, and the method for determining life cycle aggregated sustainability index. The interval number based LCSA was employed to determine the life cycle sustainability performance matrix under data uncertainties, the interval preference relation based goal programming model was used to determine the weights of the criteria in LCSA, and finally the life cycle aggregated sustainability index can be determined based on the life cycle sustainability performance matrix and the weights of the criteria for sustainability assessment.

### **2.1 Interval number based LCSA**



**Figure 1:** The framework of sustainability assessment (Ren *et al.*, 2015)

The framework of LCSA was established based on the work of Ren *et al.* (2015). It is apparent that LCA, LCC, and SLCA were combined to investigate the environmental, economic, and social sustainability of products/processes in a life cycle perspective, respectively.

LCA was usually used to investigate the environmental impacts of different products/processes, and the data of the products/processes with respect to the criteria belonging to environmental dimension can be obtained, i.e. global warming potential (GWP), ozone layer depletion (OLD), photochemical oxidation (PO), acidification potential (AP) and human toxicity (HT) based on the

CML 2001 method (Guinée et al., 2001; Hawkins *et al.*, 2013). Note that some other criteria belonging to environmental dimension can also be employed according to the preferences of the decision-makers, i.e. ecological footprint (Huijbregts *et al.*, 2008), emergy index of sustainability (Ren *et al.*, 2013), energy efficiency, and exergy efficiency (Ren *et al.*, 2016a), etc. It is also worth pointing out that all the added criteria to environmental dimension should be investigated in life cycle perspective. LCC which is an effective financial analysis method was widely used for evaluating and comparing different alternative products/processes in terms of initial cost increases against operational cost benefits with a long-term perspective (Ristimäki *et al.*, 2013). LCC can determine the total cost in their life cycles as well as some other economic criteria (i.e. net present value (NPV), internal return rate (IRR), and payback time (PT)). The life cycle cost of a product represents the total cost in its life cycle, including the exploitation of raw materials, the transport of raw materials, the production of the production, the transport of the production, the use of the product, and the recycling and treatment of the wastes. SLCA was defined as a systematic way to collect data and report about the social impacts including both positive and negative influences of a product in its life cycle by UNEP-SETAC in 2009 (UNEP-SETAC, 2009). SLCA can help the decision-makers to understand the social impacts of products/processes in life cycle perspective, and the social impacts were usually measured by both the hard criteria (which can be quantified or measured directly, i.e. created jobs, working hours, and wage, etc.) and the soft criteria (which cannot be quantified or measured directly, i.e. working conditions, job satisfaction and engagement, social acceptability, and discrimination, etc.) (Yıldız-Geyhan *et al.*, 2017).

The variations of the data with respect to the criteria in environmental, economic, and social aspects were incorporated in LCSA process. As for a problem with a total of  $M$  alternative industrial processes ( $A_1, A_2, \dots, A_M$ ),  $K$  criteria ( $EC_1, EC_2, \dots, EC_K$ ) in economic dimension,  $K$  criteria ( $EC_1, EC_2, \dots, EC_K$ ) in economic dimension,  $L$  criteria ( $EN_1, EN_2, \dots, EN_L$ ), and  $N$  criteria ( $S_1,$

$S_2, \dots, S_N$ ), the interval life cycle sustainability performance matrix can be determined, as presented in Table 1.

**Table 1:** The interval life cycle sustainability performance matrix

		$A_1$	$A_2$	...	$A_M$
Economic	$EC_1$	$\begin{bmatrix} x_{1EC_1}^L & x_{1EC_1}^U \end{bmatrix}$	$\begin{bmatrix} x_{2EC_1}^L & x_{2EC_1}^U \end{bmatrix}$		$\begin{bmatrix} x_{MEC_1}^L & x_{MEC_1}^U \end{bmatrix}$
	$EC_2$	$\begin{bmatrix} x_{1EC_2}^L & x_{1EC_2}^U \end{bmatrix}$	$\begin{bmatrix} x_{2EC_2}^L & x_{2EC_2}^U \end{bmatrix}$		$\begin{bmatrix} x_{MEC_2}^L & x_{MEC_2}^U \end{bmatrix}$
	...				
	$EC_K$	$\begin{bmatrix} x_{1EC_K}^L & x_{1EC_K}^U \end{bmatrix}$	$\begin{bmatrix} x_{2EC_K}^L & x_{2EC_K}^U \end{bmatrix}$		$\begin{bmatrix} x_{MEC_K}^L & x_{MEC_K}^U \end{bmatrix}$
Environmental	$EN_1$	$\begin{bmatrix} x_{1EN_1}^L & x_{1EN_1}^U \end{bmatrix}$	$\begin{bmatrix} x_{2EN_1}^L & x_{2EN_1}^U \end{bmatrix}$		$\begin{bmatrix} x_{MEN_1}^L & x_{MEN_1}^U \end{bmatrix}$
	$EN_2$	$\begin{bmatrix} x_{1EN_2}^L & x_{1EN_2}^U \end{bmatrix}$	$\begin{bmatrix} x_{2EN_2}^L & x_{2EN_2}^U \end{bmatrix}$		$\begin{bmatrix} x_{MEN_2}^L & x_{MEN_2}^U \end{bmatrix}$
	...				
	$EN_L$	$\begin{bmatrix} x_{1EN_L}^L & x_{1EN_L}^U \end{bmatrix}$	$\begin{bmatrix} x_{2EN_L}^L & x_{2EN_L}^U \end{bmatrix}$		$\begin{bmatrix} x_{MEC_L}^L & x_{MEC_L}^U \end{bmatrix}$
Social	$S_1$	$\begin{bmatrix} x_{1S_1}^L & x_{1S_1}^U \end{bmatrix}$	$\begin{bmatrix} x_{2S_1}^L & x_{2S_1}^U \end{bmatrix}$		$\begin{bmatrix} x_{MS_1}^L & x_{MS_1}^U \end{bmatrix}$
	$S_2$	$\begin{bmatrix} x_{1S_2}^L & x_{1S_2}^U \end{bmatrix}$	$\begin{bmatrix} x_{2S_2}^L & x_{2S_2}^U \end{bmatrix}$		$\begin{bmatrix} x_{MS_2}^L & x_{MS_2}^U \end{bmatrix}$
	...				
	$S_N$	$\begin{bmatrix} x_{1S_K}^L & x_{1S_K}^U \end{bmatrix}$	$\begin{bmatrix} x_{2S_K}^L & x_{2S_K}^U \end{bmatrix}$		$\begin{bmatrix} x_{MS_K}^L & x_{MS_K}^U \end{bmatrix}$

where  $\begin{bmatrix} x_{iEC_j}^L & x_{iEC_j}^U \end{bmatrix}$   $i = 1, 2, \dots, M ; j = 1, 2, \dots, K$  represents the data of the  $i$ -th alternative with

respect to the  $j$ -th criterion in economic aspect,  $\begin{bmatrix} x_{iEN_j}^L & x_{iEN_j}^U \end{bmatrix}$   $i = 1, 2, \dots, M ; j = 1, 2, \dots, L$

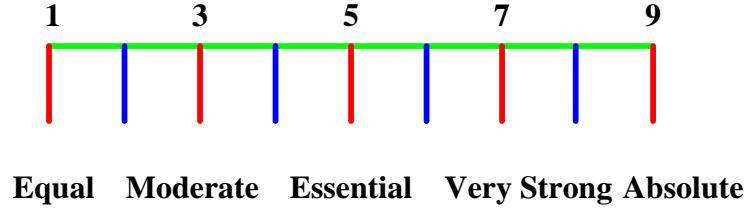
represents the data of the  $i$ -th alternative with respect to the  $j$ -th criterion in environmental aspect,

and  $\begin{bmatrix} x_{is_j}^L & x_{is_j}^U \end{bmatrix} \quad i = 1, 2, \dots, M ; j = 1, 2, \dots, N$  represents the data of the  $i$ -th alternative with respect to the  $j$ -th criterion in social aspect.

## 2.2 Interval preference relation based goal programming model

The interval preference relation based goal programming model allows the users to use interval numbers (rather than crisp numbers) to compare the relative preference of a criterion over another when establishing the comparison matrix. The use of the interval numbers to depict the relative preferences between each pair of criteria can effectively address the ambiguity, vagueness and hesitation existing in human's judgments. The interval preference relation based goal programming model consists of three steps including determining the interval comparison matrix by using the multiplicative preference relation (Step 1), transforming the multiplicative preference relation into fuzzy preference relation (Step 2), and establishing the goal programming for determining the interval weights of the criteria (Step 3), and they were specified as follows based on the work of Zhang (2006).

**Step 1:** Determining the interval comparison matrix by using the multiplicative preference relation. The interval comparison matrix can be determined by using the nice-scale system (see Figure 2) (Saaty, 1978). Note that the decision-makers will be asked to use interval numbers rather than the crisp numbers to establish the comparison matrix. For instance, the decision-makers hold the view that the preference of a criterion over another is between “moderate superiority “ (corresponding to 3) and “essential superiority” (corresponding to 5), then, the interval  $[3 \ 5]$  will used to describe the relative preference. Similarly, the other elements in the comparison matrix can also be determined. As for the problem with  $n$  criteria, and the interval comparison matrix can be determined, as presented in Eq.1.



**Figure 2:** The nice-point scale system for comparison

$$\{T\}_{n \times n} = \begin{bmatrix} 1 & [t_{12}^L, t_{12}^U] & \cdots & [t_{1n}^L, t_{1n}^U] \\ [t_{21}^L, t_{21}^U] & 1 & \cdots & [t_{2n}^L, t_{2n}^U] \\ \vdots & \cdots & \ddots & \vdots \\ [t_{n1}^L, t_{n1}^U] & [t_{n2}^L, t_{n2}^U] & \cdots & 1 \end{bmatrix} \quad (1)$$

where  $[t_{ij}^L, t_{ij}^U] \quad i = 1, 2, \dots, n; j = 1, 2, \dots, n$  represents the relative preference of the  $i$ -th criterion over the  $j$ -th criterion in the multiplicative preference relation, and  $t_{ij}^L$  and  $t_{ij}^U$  are the lower and upper bounds of the element in cell (i,j) of the interval comparison matrix T using multiplicative preference relation, respectively.

**Step 2:** Transforming the multiplicative preference relation into fuzzy preference relation. The multiplicative preference relation  $\{T\}_{n \times n}$  can be transformed into fuzzy preference relation  $\{R\}_{n \times n}$  according to Eqs.2-3.

$$\{R\}_{n \times n} = \begin{bmatrix} 1 & [r_{12}^L, r_{12}^U] & \cdots & [r_{1n}^L, r_{1n}^U] \\ [r_{21}^L, r_{21}^U] & 1 & \cdots & [r_{2n}^L, r_{2n}^U] \\ \vdots & \cdots & \ddots & \vdots \\ [r_{n1}^L, r_{n1}^U] & [r_{n2}^L, r_{n2}^U] & \cdots & 1 \end{bmatrix} \quad (2)$$

$$[r_{ij}^L, r_{ij}^U] = \left[ \frac{t_{ij}^L}{1+t_{ij}^L}, \frac{t_{ij}^U}{1+t_{ij}^U} \right] \quad i = 1, 2, \dots, n; j = 1, 2, \dots, n \quad (3)$$

where  $[r_{ij}^L, r_{ij}^U]$   $i = 1, 2, \dots, n; j = 1, 2, \dots, n$  represents the relative preference of the  $i$ -th criterion over the  $j$ -th criterion in the fuzzy preference relation, and  $r_{ij}^L$  and  $r_{ij}^U$  are the lower and upper bounds of the element in cell (i,j) of the interval comparison matrix R using fuzzy preference relation, respectively.

**Step 3:** Establishing the goal programming for determining the interval weights of the criteria. The goal programming (4) was established to determine the weights of the criteria.

$$\begin{aligned}
Min &= \sum_{i=1}^n (c_i^- + c_i^+ + d_i^- + d_i^+) \\
s.t. & \\
\omega_i^- + \sum_{j=1, j \neq i}^n \omega_j^+ &\geq 1 \quad i = 1, 2, \dots, n \\
\omega_i^+ + \sum_{j=1, j \neq i}^n \omega_j^- &\leq 1 \quad i = 1, 2, \dots, n \\
0 \leq \omega_i^- \leq \omega_i^+ &\leq 1 \quad i = 1, 2, \dots, n \\
\left( \sum_{j=1}^n r_{ij}^- - n + 0.5 \right) \omega_i^- + \sum_{j=1, j \neq i}^n r_{ij}^- \omega_j^+ - c_i^- + c_i^+ &= 0 \quad i = 1, 2, \dots, n \\
\left( \sum_{j=1}^n r_{ij}^+ - n + 0.5 \right) \omega_i^+ + \sum_{j=1, j \neq i}^n r_{ij}^+ \omega_j^- - d_i^- + d_i^+ &= 0 \\
c_i^-, c_i^+, d_i^-, d_i^+ &\quad i = 1, 2, \dots, n
\end{aligned} \tag{4}$$

After solving programming (4), the interval weights of the criteria can be determined.

## 2.3 Life Cycle Aggregated Sustainability Index

### 2.3.1 An projection-based aggregated sustainability index

The sustainability of the industrial process can be represented in the triple-bottom-line approach, and the sustainability performance of an industrial process can be expressed as a vector in the triple-

bottom-line-based 3D space (as presented in Figure 3) (Xu et al., 2017; Aliabadi and Huang, 2015).

$x$ ,  $y$ , and  $z$  are the relative performances of the environmental, economic, and social dimensions,

respectively. The sustainability of an industrial system can be represented in the format of a three

dimensional vector  $\vec{S} = (x, y, z)$ . It is apparent that the original point (0,0,0) which means that the

components of the industrial processes with respect to economic, environmental, and social

dimensions are all zero, and the corresponding sustainability is the lowest. When the sustainability

status reaches to  $\vec{S}_{\max} = (X_{\max}, Y_{\max}, Z_{\max})$ , the sustainability is the greatest, and this is the ideal

solution. The product between  $\vec{S} = (x, y, z)$  and  $\vec{S}_{\max} = (X_{\max}, Y_{\max}, Z_{\max})$  can be determined by Eq.5

and Eq.6:

$$\vec{S} \cdot \vec{S}_{\max} = (x, y, z) \cdot (X_{\max}, Y_{\max}, Z_{\max}) = xX_{\max} + yY_{\max} + zZ_{\max} \quad (5)$$

$$\vec{S} \cdot \vec{S}_{\max} = \|\vec{S}\| \|\vec{S}_{\max}\| \cos \langle \vec{S}, \vec{S}_{\max} \rangle = \|\vec{S}\| P(\vec{S}, \vec{S}_{\max}) \quad (6)$$

where  $\|\vec{S}\|$  represents the norm of  $\vec{S} = (x, y, z)$ ,  $\|\vec{S}_{\max}\|$  represents the norm of

$\vec{S}_{\max} = (X_{\max}, Y_{\max}, Z_{\max})$ ,  $\langle \vec{S}, \vec{S}_{\max} \rangle$  represents the angle between  $\vec{S} = (x, y, z)$  and

$\vec{S}_{\max} = (X_{\max}, Y_{\max}, Z_{\max})$ , and  $P(\vec{S}, \vec{S}_{\max})$  represents the projection of  $\vec{S} = (x, y, z)$  on

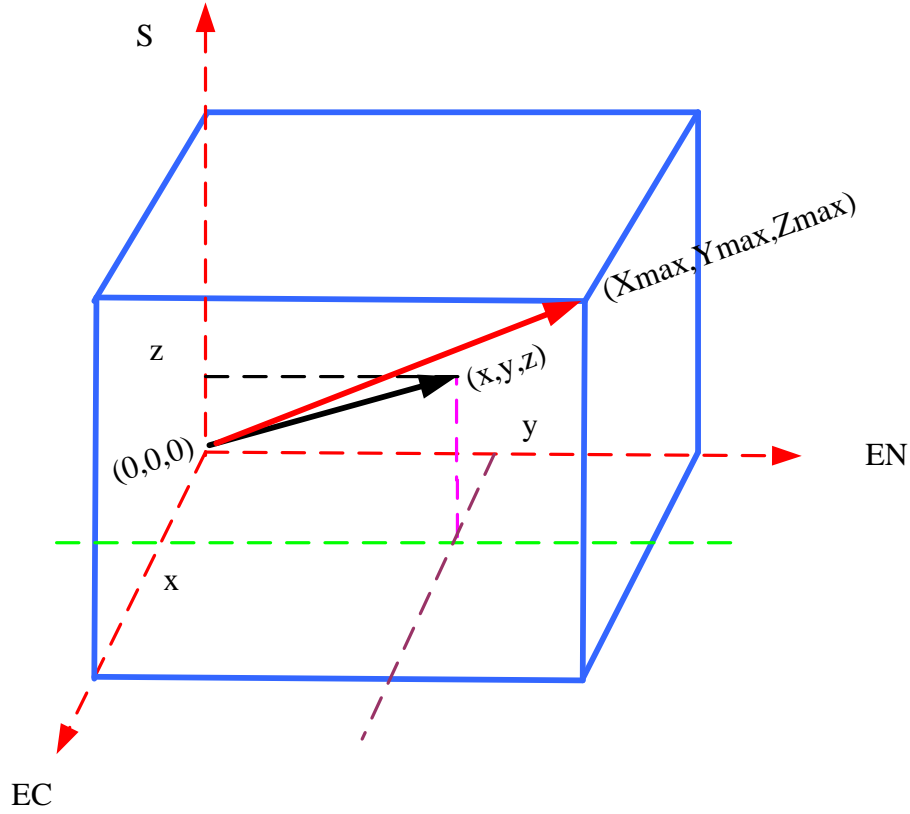
$\vec{S}_{\max} = (X_{\max}, Y_{\max}, Z_{\max})$ .

Integrating Eqs.5-6, the projection of an industrial system with the sustainability status  $(x, y, z)$  on

the ideal solution with the sustainability status  $(X_{\max}, Y_{\max}, Z_{\max})$  can be determined by Eq.7



$$P(\vec{S}, \vec{S}_{\max}) = \frac{\vec{S} \cdot \vec{S}_{\max}}{\|\vec{S}_{\max}\|} = \frac{xX_{\max} + yY_{\max} + zZ_{\max}}{\sqrt{(X_{\max})^2 + (Y_{\max})^2 + (Z_{\max})^2}} \quad (7)$$



**Figure 3:** The Triple-Bottom-Line based sustainability (Xu et al., 2017; Aliabadi and Huang, 2015)

The projection of an industrial system with the sustainability status  $(x, y, z)$  on the ideal solution with the sustainability status  $(X_{\max}, Y_{\max}, Z_{\max})$  denotes by  $P(\vec{S}, \vec{S}_{\max})$ , can be recognized as an aggregated index which represents the integrated sustainability performance of the corresponding industrial system. The aggregated sustainability index based on projection was extended to uncertainty and multiple dimensional conditions in section 2.3.2.

### 2.3.2 A life cycle aggregated sustainability index

After determining the life cycle sustainability performance matrix, the data of the alternative industrial processes with respect to the criteria in economic, environmental and social dimensions can be normalized by Eq. 8 and Eq.9.

As for the data with respect to the benefit-type criteria (the greater the value of the alternative industrial processes with respect to these criteria, the most sustainable the alternative industrial processes will be):

$$\begin{bmatrix} r_{ij}^L & r_{ij}^U \end{bmatrix} = \begin{bmatrix} \frac{x_{ij}^L - \min_{i=1,2,\dots,M} \{x_{ij}^L\}}{\max_{i=1,2,\dots,M} \{x_{ij}^U\} - \min_{i=1,2,\dots,M} \{x_{ij}^L\}} & \frac{x_{ij}^U - \min_{i=1,2,\dots,M} \{x_{ij}^L\}}{\max_{i=1,2,\dots,M} \{x_{ij}^U\} - \min_{i=1,2,\dots,M} \{x_{ij}^L\}} \end{bmatrix} \quad (8)$$

As for the data with respect to the cost-type criteria (the smaller the value of the alternative industrial processes with respect to these criteria, the most sustainable the alternative industrial processes will be):

$$\begin{bmatrix} r_{ij}^L & r_{ij}^U \end{bmatrix} = \begin{bmatrix} \frac{\max_{i=1,2,\dots,M} \{x_{ij}^U\} - x_{ij}^U}{\max_{i=1,2,\dots,M} \{x_{ij}^U\} - \min_{i=1,2,\dots,M} \{x_{ij}^L\}} & \frac{\max_{i=1,2,\dots,M} \{x_{ij}^U\} - x_{ij}^L}{\max_{i=1,2,\dots,M} \{x_{ij}^U\} - \min_{i=1,2,\dots,M} \{x_{ij}^L\}} \end{bmatrix} \quad (9)$$

where  $\begin{bmatrix} x_{ij}^L & x_{ij}^U \end{bmatrix}$  represents the value of the  $i$ -th alternative industrial process with respect to the  $j$ -th criterion, and  $\begin{bmatrix} r_{ij}^L & r_{ij}^U \end{bmatrix}$  represents the normalized value of the  $i$ -th alternative industrial process with respect to the  $j$ -th criterion.

After the normalization processes, the normalized life cycle sustainability performance matrix can be weighted by Eq.10, and the weighted normalized life cycle sustainability performance matrix was presented in Table 2.

$$\begin{bmatrix} y_{ij}^L & y_{ij}^U \end{bmatrix} = \begin{bmatrix} r_{ij}^L & r_{ij}^U \end{bmatrix} \times \begin{bmatrix} \omega_j^L & \omega_j^U \end{bmatrix} = \begin{bmatrix} \omega_j^L r_{ij}^L & \omega_j^U r_{ij}^U \end{bmatrix} \quad (10)$$

**Table 2:** The weighted normalized life cycle sustainability performance matrix

		A <sub>1</sub>	A <sub>2</sub>	...	A <sub>M</sub>
Economic	EC <sub>1</sub>	$\begin{bmatrix} y_{1EC_1}^L & y_{1EC_1}^U \end{bmatrix}$	$\begin{bmatrix} y_{2EC_1}^L & y_{2EC_1}^U \end{bmatrix}$		$\begin{bmatrix} y_{MEC_1}^L & y_{MEC_1}^U \end{bmatrix}$
	EC <sub>2</sub>	$\begin{bmatrix} y_{1EC_2}^L & y_{1EC_2}^U \end{bmatrix}$	$\begin{bmatrix} y_{2EC_2}^L & y_{2EC_2}^U \end{bmatrix}$		$\begin{bmatrix} y_{MEC_2}^L & y_{MEC_2}^U \end{bmatrix}$
	...				
	EC <sub>K</sub>	$\begin{bmatrix} y_{1EC_K}^L & y_{1EC_K}^U \end{bmatrix}$	$\begin{bmatrix} y_{2EC_K}^L & y_{2EC_K}^U \end{bmatrix}$		$\begin{bmatrix} y_{MEC_K}^L & y_{MEC_K}^U \end{bmatrix}$
Environmental	EN <sub>1</sub>	$\begin{bmatrix} y_{1EN_1}^L & y_{1EN_1}^U \end{bmatrix}$	$\begin{bmatrix} y_{2EN_1}^L & y_{2EN_1}^U \end{bmatrix}$		$\begin{bmatrix} y_{MEN_1}^L & y_{MEN_1}^U \end{bmatrix}$
	EN <sub>2</sub>	$\begin{bmatrix} y_{1EN_2}^L & y_{1EN_2}^U \end{bmatrix}$	$\begin{bmatrix} y_{2EN_2}^L & y_{2EN_2}^U \end{bmatrix}$		$\begin{bmatrix} y_{MEN_2}^L & y_{MEN_2}^U \end{bmatrix}$
	...				
	EN <sub>L</sub>	$\begin{bmatrix} y_{1EN_L}^L & y_{1EN_L}^U \end{bmatrix}$	$\begin{bmatrix} y_{2EN_L}^L & y_{2EN_L}^U \end{bmatrix}$		$\begin{bmatrix} y_{MEC_L}^L & y_{MEC_L}^U \end{bmatrix}$
Social	S <sub>1</sub>	$\begin{bmatrix} y_{1S_1}^L & y_{1S_1}^U \end{bmatrix}$	$\begin{bmatrix} y_{2S_1}^L & y_{2S_1}^U \end{bmatrix}$		$\begin{bmatrix} y_{MS_1}^L & y_{MS_1}^U \end{bmatrix}$
	S <sub>2</sub>	$\begin{bmatrix} y_{1S_2}^L & y_{1S_2}^U \end{bmatrix}$	$\begin{bmatrix} y_{2S_2}^L & y_{2S_2}^U \end{bmatrix}$		$\begin{bmatrix} y_{MS_2}^L & y_{MS_2}^U \end{bmatrix}$
	...				
	S <sub>N</sub>	$\begin{bmatrix} y_{1S_K}^L & y_{1S_K}^U \end{bmatrix}$	$\begin{bmatrix} y_{2S_K}^L & y_{2S_K}^U \end{bmatrix}$		$\begin{bmatrix} y_{MS_K}^L & y_{MS_K}^U \end{bmatrix}$

where  $\begin{bmatrix} y_{iEC_j}^L & y_{iEC_j}^U \end{bmatrix} \quad i = 1, 2, \dots, M ; j = 1, 2, \dots, K$  represents the data of the  $i$ -th alternative with

respect to the  $j$ -th criterion in economic aspect,  $\begin{bmatrix} y_{iEN_j}^L & y_{iEN_j}^U \end{bmatrix} \quad i = 1, 2, \dots, M ; j = 1, 2, \dots, L$

represents the data of the  $i$ -th alternative with respect to the  $j$ -th criterion in environmental aspect,

and  $\begin{bmatrix} y_{iS_j}^L & y_{iS_j}^U \end{bmatrix} \quad i = 1, 2, \dots, M ; j = 1, 2, \dots, N$  represents the data of the  $i$ -th alternative with

respect to the  $j$ -th criterion in social aspect.

The ideal solutions which represent the ideal best solutions performing the best on all the criteria can be determined by Eq.11.

$$\vec{Y}_{ID} = \{y_j^o\}_{1 \times (K+L+N)} = \left[ \max_{i=1,2,\dots,M} y_{iEC_1}^U, \dots, \max_{i=1,2,\dots,M} y_{iEC_K}^U, \max_{i=1,2,\dots,M} y_{iEN_1}^U, \dots, \max_{i=1,2,\dots,M} y_{iEN_L}^U, \max_{i=1,2,\dots,M} y_{iS_1}^U, \dots, \max_{i=1,2,\dots,M} y_{iS_N}^U \right] \quad (11)$$

where  $\vec{Y}_{ID}$  represents the ideal solution, and  $y_j^o$  represents the value of the  $j$ -th criterion in the ideal solution.

The sustainability performances of the  $i$ -th alternative industrial process can also be represented in the vector format, as presented in Eq.12.

$$\vec{Y}_i = \left[ \begin{bmatrix} y_{iEC_1}^L & y_{iEC_1}^U \end{bmatrix}, \dots, \begin{bmatrix} y_{iEC_K}^L & y_{iEC_K}^U \end{bmatrix}, \begin{bmatrix} y_{iEN_1}^L & y_{iEN_1}^U \end{bmatrix}, \dots, \begin{bmatrix} y_{iEN_L}^L & y_{iEN_L}^U \end{bmatrix}, \begin{bmatrix} y_{iS_1}^L & y_{iS_1}^U \end{bmatrix}, \dots, \begin{bmatrix} y_{iS_N}^L & y_{iS_N}^U \end{bmatrix} \right] \quad (12)$$

where  $\vec{Y}_i$  represents the sustainability performance of the  $i$ -th alternative industrial process.

The product between  $\vec{Y}_i$  and  $\vec{Y}_{ID}$  can be determined by Eq.13, and the product between these two vectors is an interval number.

$$\vec{Y}_i \cdot \vec{Y}_{ID} = \left[ \sum_{j=1}^K y_j^o y_{iEC_j}^L + \sum_{j=K+1}^{K+L} y_j^o y_{iEN_{j-K}}^L + \sum_{j=K+L+1}^{K+L+N} y_j^o y_{iS_{j-K-L}}^L, \sum_{j=1}^K y_j^o y_{iEC_j}^U + \sum_{j=K+1}^{K+L} y_j^o y_{iEN_{j-K}}^U + \sum_{j=K+L+1}^{K+L+N} y_j^o y_{iS_{j-K-L}}^U \right] \quad (13)$$

The product between  $\vec{Y}_i$  and  $\vec{Y}_{ID}$  can also be rewritten as Eq.14.

$$\vec{Y}_i \cdot \vec{Y}_{ID} = \left\| \vec{Y}_i \right\| \left\| \vec{Y}_{ID} \right\| \cos \left\langle \vec{Y}_i, \vec{Y}_{ID} \right\rangle = \left\| \vec{Y}_{ID} \right\| P(\vec{Y}_i, \vec{Y}_{ID}) \quad (14)$$

where  $\|\vec{Y}_i\|$  represents the norm of  $\vec{Y}_i$ ,  $\|\vec{Y}_{ID}\|$  represents the norm of  $\vec{Y}_{ID}$ ,  $\langle \vec{Y}_i, \vec{Y}_{ID} \rangle$  represents the angle between  $\vec{Y}_{ID}$  and  $\vec{Y}_i$ , and  $P(\vec{Y}_i, \vec{Y}_{ID})$  represents the projection of  $\vec{Y}_i$  on  $\vec{Y}_{ID}$ .

The norm of  $\vec{Y}_i$  can be determined by Eq.15, and it is also an interval number.

$$\|\vec{Y}_{ID}\| = \sqrt{\sum_{j=1}^{K+L+N} (y_j^0)^2} \quad (15)$$

Integrating Eqs.13-15, the projection of  $\vec{Y}_i$  on  $\vec{Y}_{ID}$  can be determined by Eq.16, and it is also an interval number.  $P(\vec{Y}_i, \vec{Y}_{ID})$  can be recognized as the integrated sustainability of the  $i$ -th industrial system. It is apparent that  $P(\vec{Y}_i, \vec{Y}_{ID})$  degenerates into crisp number when  $\vec{Y}_i$  is a vector composed by crisp numbers.

$$P(\vec{Y}_i, \vec{Y}_{ID}) = \frac{\vec{Y}_i \cdot \vec{Y}_{ID}}{\|\vec{Y}_{ID}\|} = \begin{bmatrix} P_i^L & P_i^U \end{bmatrix} \quad (16)$$

$$= \begin{bmatrix} \frac{\sum_{j=1}^K y_j^o y_{iEC_j}^L + \sum_{j=K+1}^{K+L} y_j^o y_{iEN_{j-K}}^L + \sum_{j=K+L+1}^{K+L+N} y_j^o y_{iS_{j-K-L}}^L}{\sqrt{\sum_{j=1}^{K+L+N} (y_j^0)^2}} & \frac{\sum_{j=1}^K y_j^o y_{iEC_j}^U + \sum_{j=K+1}^{K+L} y_j^o y_{iEN_{j-K}}^U + \sum_{j=K+L+1}^{K+L+N} y_j^o y_{iS_{j-K-L}}^U}{\sqrt{\sum_{j=1}^{K+L+N} (y_j^0)^2}} \end{bmatrix}$$

where  $P_i^L$  and  $P_i^U$  represents the lower and upper bounds of the projection of  $\vec{Y}_i$  on  $\vec{Y}_{ID}$ .

After determining the projection of each industrial system on the ideal solution, they can be ranked according to their projections and the greater the projection, the more sustainable the alternative industrial system will be. The projection of the  $i$ -th alternative industrial system

$P(\vec{Y}_i, \vec{Y}_{ID}) = \begin{bmatrix} P_i^L & P_i^U \end{bmatrix}$  and that of the  $j$ -th alternative industrial system  $P(\vec{Y}_j, \vec{Y}_{ID}) = \begin{bmatrix} P_j^L & P_j^U \end{bmatrix}$  can

be compared by Eq.17 according to the work of Zhou *et al.* (2012). The probability of

$P(\vec{Y}_i, \vec{Y}_{ID}) = \begin{bmatrix} P_i^L & P_i^U \end{bmatrix}$  be greater than  $P(\vec{Y}_j, \vec{Y}_{ID}) = \begin{bmatrix} P_j^L & P_j^U \end{bmatrix}$  can be determined by Eq.17.

$$\Pr \left\{ P(\vec{Y}_i, \vec{Y}_{ID}) \geq P(\vec{Y}_j, \vec{Y}_{ID}) \right\} = \Pr_{ij} = \max \left\{ 1 - \frac{1}{2} \max \left( \frac{(P_j^L + P_j^U) - (P_i^L + P_i^U)}{P_i^U - P_i^L + P_j^U - P_j^L} + 1, 0 \right), 0 \right\} \quad (17)$$

Herein, we define  $\Pr \{0 \geq 0\} = \Pr_{ij} = 0.50$ .

where  $\Pr \left\{ P(\vec{Y}_i, \vec{Y}_{ID}) \geq P(\vec{Y}_j, \vec{Y}_{ID}) \right\} = \Pr_{ij}$  represents the probability  $P(\vec{Y}_i, \vec{Y}_{ID}) = \begin{bmatrix} P_i^L & P_i^U \end{bmatrix}$  be greater

than  $P(\vec{Y}_j, \vec{Y}_{ID}) = \begin{bmatrix} P_j^L & P_j^U \end{bmatrix}$ .

After comparing the projections of each pair of the industrial systems, the probability matrix (PR) can be determined, as presented in Eq.18.

$$PR = \begin{bmatrix} \Pr_{11} & \Pr_{12} & \cdots & \Pr_{1M} \\ \Pr_{21} & \Pr_{22} & \cdots & \Pr_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \Pr_{M1} & \Pr_{M2} & \cdots & \Pr_{MM} \end{bmatrix} \quad (18)$$

where  $PR$  represents the probability matrix, and  $\Pr_{ij} (i = 1, 2, \dots, M; j = 1, 2, \dots, M)$  represents the probability of the projection of the  $i$ -th alternative industrial system on the ideal solution be greater than that of the  $j$ -th alternative industrial system on the ideal solution.

The integrated priority of the  $i$ -th industrial system with respect to its sustainability can be determined by Eq.19 according to the work of Xu (2015). Then, the sustainability ranking of the M

industrial systems can be determined according to the rule that the greater the integrated priority, the more sustainable the industrial system will be.

$$V_i = \frac{\sum_{j=1}^n \text{Pr}_{ij} + \frac{n}{2} - 1}{n(n-1)} \quad (19)$$

where  $V_i$  represents the sustainability index of the  $i$ -th industrial system with respect to its sustainability.

The main novelty of developed method for life cycle sustainability prioritization of industrial systems in this study is that a life cycle aggregated sustainability index under uncertainties and life cycle sustainability perspective was proposed, and all the indicators in the three pillars of sustainability can be aggregated into an aggregated index, Meanwhile, the uncertainties in life cycle sustainability assessment and prioritization of industrial systems can be incorporated by using interval numbers to substitute crisp numbers. Different from the previous life cycle sustainability ranking methods which firstly used the life cycle sustainability assessment to collect the data of the alternative industrial systems with respect to the indicators in the three pillars of sustainability and then used the multi-criteria decision making methods to rank the alternative industrial systems, the life cycle aggregated sustainability index developed based on the thoughts of “triple bottom line” represents the aggregation of economic, environmental and social sustainability. Although the uncertainties can be address in some the previous studies, but it lacks a method which can provide the decision-makers/stakeholders an aggregated index which has sustainability meaning and can aggregated all the indicators for sustainability assessment into a generic index.

### 3. Case study

In order to illustrate the developed life cycle sustainability aggregated index for ranking the industrial systems under uncertainties, the sustainability of four scenarios for electricity generation under the conditions of UK was ranked by using the life cycle sustainability aggregated index method, and the four scenarios are coal-pulverised ( $A_1$ ), combined cycle gas turbines ( $A_2$ ), nuclear-pressurised water reactor ( $A_3$ ), offshore wind power based electricity ( $A_4$ ). The objective of the work carried out by Stamford and Azapagic (2012) is to identify the most sustainable option for electricity generation and provide some policy implications for the UK. The scope is from extraction, processing of raw materials (including fuels), power generation, waste disposal, construction of power plant, and decommissioning of power plant (Atilgan and Azapagic, 2016; Stamford and Azapagic, 2012). The data of the data with respect to the criteria in environmental, economic, and social aspects were derived from the work of Stamford and Azapagic (2012). Four criteria including global warming potential (GWP), acidification potential (AP), photochemical smog (PS), and land occupation (LO) investigated by LCA were employed to measure the environmental sustainability of the four scenarios for electricity generation. There are three criteria in economic dimension, namely, capital cost (CC), operation and maintenance cost (OMC), and fuel cost (FC). The social sustainability dimension consists of three criteria, and they are employment (EM), human toxicity potential (HTP), and total health impacts from radiation (THIR). The interval life cycle sustainability performance matrix was presented in Table 3.



**Table 3:** The interval life cycle sustainability performance matrix

		A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	A <sub>4</sub>
CC	GBP.MWh <sup>-1</sup>	[28.40 61.70]	[11.10 12.40]	[51.30 79.40]	[88.50 144.60]
OMC	GBP.MWh <sup>-1</sup>	[10.70 13.10]	[6.00 6.00]	[10.90 14.30]	[23.00 45.80]
FC	GBP.MWh <sup>-1</sup>	[13.00 24.40]	[25.40 66.40]	[4.20 6.30]	[0 0]
GWP	kg CO <sub>2</sub> eq.kWh <sup>-1</sup>	[9.65E-01 1.48E+00]	[3.66E-01 4.96E-01]	[5.13E-03 1.31E-02]	[4.73E-03 1.42E-02]
AP	kg SO <sub>2</sub> eq.kWh <sup>-1</sup>	[1.66E-03 9.80E-03]	[1.22E-04 3.70E-04]	[3.76E-05 9.34E-05]	[3.35E-05 8.41E-05]
PS	kg C <sub>2</sub> H <sub>4</sub> eq.kWh <sup>-1</sup>	[1.33E-04 4.57E-04]	[2.31E-05 6.30E-05]	[4.50E-06 8.08E-06]	[3.47E-06 9.81E-06]
LO	m <sup>2</sup> yr	[2.07E-02 4.04E-02]	[2.76E-04 3.79E-03]	[5.28E-04 7.71E-04]	[1.56E-04 4.61E-04]
EM	person- years.MWh <sup>-1</sup>	[5.56E+01 1.91E+02]	[2.66E+01 6.24E+01]	[5.59E+01 8.08E+01]	[3.11E+01 3.68E+01]
HTP	kg DCB eq.kWh <sup>-1</sup>	[7.28E-02 4.58E-01]	[3.68E-03 1.41E-02]	[1.35E-02 1.35E-01]	[3.03E-02 7.52E-02]
THIR	DALY.kWh <sup>-1</sup>	[2.15E-10 2.21E-09]	[1.16E-11 2.53E-09]	[2.03E-08 3.19E-08]	[1.86E-11 6.66E-11]

**Reference:** the data were derived from Stamford and Azapagic (2012)

All the criteria are cost-type except employment (EM), the normalized life cycle sustainability performance can also be determined according to Eq.8-9, and the results were presented in Table 4.

**Table 4:** The normalized interval life cycle sustainability performance matrix

	A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	A <sub>4</sub>
CC	[0.6210 0.8704]	[0.9903 1.0000]	[0.4884 0.6989]	[0 0.4202]
OMC	[0.8216 0.8819]	[1.0000 1.0000]	[0.7915 0.8769]	[0 0.5729]
FC	[0.6325 0.8042]	[0 0.6175]	[0.9051 0.9367]	[1.0000 1.0000]
GWP	[0 0.3491]	[0.6670 0.7551]	[0.9943 0.9997]	[0.9936 1.0000]
AP	[0 0.8335]	[0.9655 0.9909]	[0.9939 0.9996]	[0.9948 1.0000]
PS	[0 0.7144]	[0.8687 0.9567]	[0.9898 0.9977]	[0.9860 1.0000]
LO	[0 0.4895]	[0.9097 0.9970]	[0.9847 0.9908]	[0.9924 1.0000]
EM	[0.1764 1.0000]	[0 0.2178]	[0.1782 0.3297]	[0.0274 0.0620]
HTP	[0 0.8479]	[0.9771 1.0000]	[0.7110 0.9784]	[0.8426 0.9414]
THIR	[0.9311 0.9936]	[0.9210 1.0000]	[0 0.3638]	[0.9983 0.9998]

The interval preference relation based goal programming model was employed to determine the weights of the three pillars and the local weights of the criteria in each pillar. The results of the weights of the three pillars of sustainability and the local weights of the criteria in each pillar of sustainability were presented in Table 5. The global weights of the ten criteria can also be determined by calculating the product between of the local weight of each criterion and the weight of the pillar to which the corresponding criterion belongs to, and the results were presented in Table 6.

**Table 5:** The comparison matrices for determining the weights of the three pillars of sustainability and the local weights of the criteria in each pillar of sustainability

Multiplicative preference relation	EC	EN	S
EC	[1 1]	[1 2]	[4 6]
EN	[1/2 1]	[1 1]	[2 5]
S	[1/6 1/4]	[1/5 1/2]	[1 1]
Fuzzy preference relation	EC	EN	S
EC	[1/2 1/2]	[1/2 2/3]	[4/5 6/7]
EN	[1/3 1/2]	[1/2 1/2]	[2/3 5/6]
S	[1/7 1/5]	[1/6 1/3]	[1/2 1/2]
Weights	[0.4464 0.6181]	[0.2616 0.4564]	[0.0972 0.1203]
Multiplicative preference relation	CC	OMC	FC
CC	[1 1]	[2 3]	[4 5]
OMC	[1/3 1/2]	[1 1]	[2 3]
FC	[1/5 1/4]	[1/3 1/2]	[1 1]
Fuzzy preference relation	CC	OMC	FC
CC	[1/2 1/2]	[2/3 3/4]	[4/5 5/6]

OMC	[1/4 1/3]	[1/2 1/2]	[2/3 3/4]	
FC	[1/6 1/5]	[1/4 1/3]	[1/2 1/2]	
Weights	[0.5745 0.6416]	[0.2282 0.3034]	[0.1154 0.1302]	
Multiplicative preference relation	GWP	AP	PS	LO
GWP	[1 1]	[2 3]	[5 7]	[1 3]
AP	[1/3 1/2]	[1 1]	[2 4]	[1 3]
PS	[1/7 1/5]	[1/4 1/2]	[1 1]	[1/5 1/3]
LO	[1/3 1]	[1/3 1]	[3 5]	[1 1]
Fuzzy preference relation	GWP	AP	PS	LO
GWP	[1/2 1/2]	[2/3 3/4]	[5/6 7/8]	[1/2 3/4]
AP	[1/4 1/3]	[1/2 1/2]	[2/3 4/5]	[1/2 3/4]
PS	[1/8 1/6]	[1/5 1/3]	[1/2 1/2]	[1/6 1/4]
LO	[1/4 1/2]	[1/4 1/2]	[3/4 5/6]	[1/2 1/2]
Weights	[0.1405 0.5593]	[0 0.4188]	[0 0.0193]	[0.0027 0.4215]
Multiplicative preference relation	EM	HTP	THIR	
EM	[1 1]	[1 3]	[2 4]	
HTP	[1/3 1]	[1 1]	[1 4]	
THIR	[1/4 1/2]	[1/4 1]	[1 1]	
Fuzzy preference	EM	HTP	THIR	

relation			
EM	[1/2 1/2]	[1/2 3/4]	[2/3 4/5]
HTP	[1/4 1/2]	[1/2 1/2]	[1/2 4/5]
THIR	[1/5 1/3]	[1/5 1/2]	[1/2 1/2]
Weights	[0.4317 0.5886]	[0.2016 0.4398]	[0.1286 0.2097]

**Table 6:** The global weights of the ten criteria for life cycle sustainability assessment of electricity generation systems

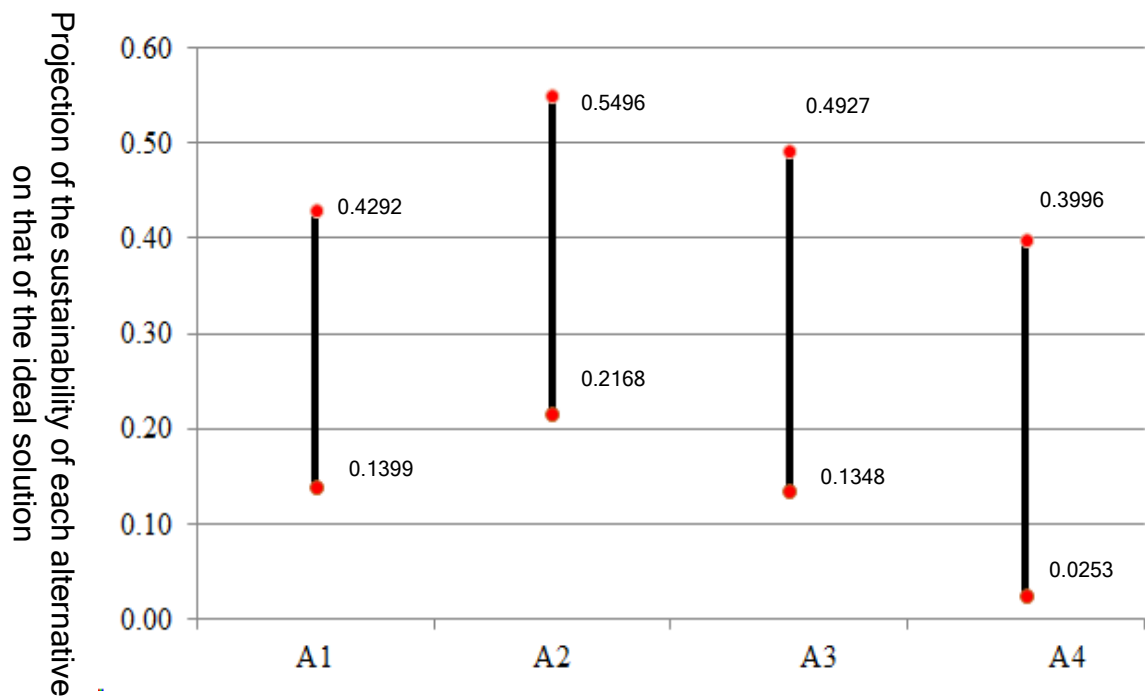
Pillar	Criteria	Local weights	Global weights
Economic ([0.4464 0.6181])	CC	[0.5745 0.6416]	[0.2565 0.3966]
	OMC	[0.2282 0.3034]	[0.1019 0.1875]
	FC	[0.1154 0.1302]	[0.0515 0.0805]
Environmental ([0.2616 0.4564])	GWP	[0.1405 0.5593]	[0.0368 0.2553]
	AP	[0 0.4188]	[0 0.1911]
	PS	[0 0.0193]	[0 0.0088]
	LO	[0.0027 0.4215]	[0.0007 0.1924]
Social ([0.0972 0.1203])	EM	[0.4317 0.5886]	[0.0420 0.0708]
	HTP	[0.2016 0.4398]	[0.0196 0.0529]
	THIR	[0.1286 0.2097]	[0.0125 0.0252]

The weighted normalized life cycle sustainability performance matrix can subsequently then determined by Eq.10, and the results were presented in Table 7. The ideal solutions also be

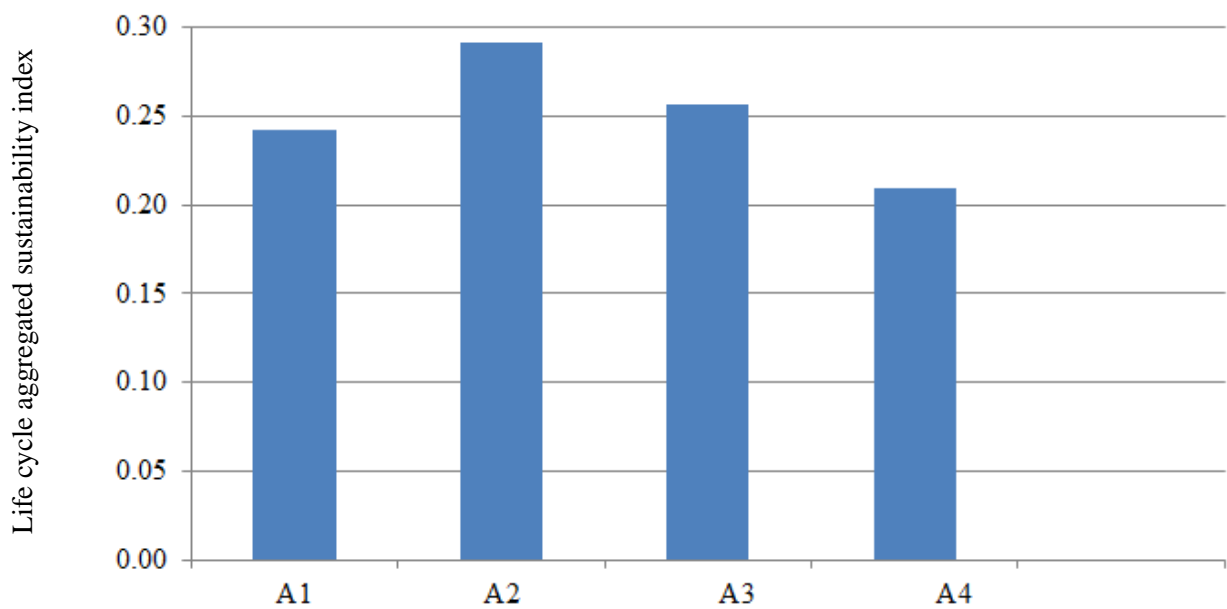
determined by Eq.11, and the results were also presented in Table 7. According to Eq.16, the projection of the sustainability of the four alternative electricity generation systems on that of the ideal solution can be determined, and the results were presented in Figure 4. Finally, the life cycle aggregated sustainability index of each electricity generation systems can be determined, and the results were presented in Figure 5.

**Table 7:** The weighted normalized life cycle sustainability performance matrix for ranking the four electricity generation systems

	A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	A <sub>4</sub>	Ideal solutions
CC	[0.1593 0.3452]	[0.2540 0.3966]	[0.1253 0.2772]	[0 0.1667]	0.3966
OMC	[0.0837 0.1654]	[0.1019 0.1875]	[0.0806 0.1644]	[0 0.1074]	0.1875
FC	[0.0326 0.0647]	[0 0.0497]	[0.0466 0.0754]	[0.0515 0.0805]	0.0805
GWP	[0 0.0891]	[0.0245 0.1928]	[0.0366 0.2552]	[0.0366 0.2553]	0.2553
AP	[0 0.1593]	[0 0.1894]	[0 0.1910]	[0 0.1911]	0.1911
PS	[0 0.0063]	[0 0.0084]	[0 0.0088]	[0 0.0088]	0.0088
LO	[0 0.0942]	[0.0006 0.1918]	[0.0007 0.1906]	[0.0007 0.1924]	0.1924
EM	[0.0074 0.0708]	[0 0.0154]	[0.0075 0.0233]	[0.0011 0.0044]	0.0233
HTP	[0 0.0449]	[0.0192 0.0529]	[0.0139 0.0518]	[0.0165 0.0498]	0.0529
THIR	[0.0116 0.0250]	[0.0115 0.0252]	[0 0.0092]	[0.0125 0.0252]	0.0252



**Figure 4:** The projections of the sustainability of the four electricity generations systems on that of the ideal solution



**Figure 5:** The life cycle aggregated sustainability index of each electricity generations system

According to the life cycle aggregated sustainability index of each electricity generations system presented in Figure 5, the sustainability order from the most sustainable to the least is combined cycle gas turbines ( $A_2$ ), nuclear-pressurised water reactor ( $A_3$ ), coal-pulverised ( $A_1$ ), offshore wind powder based electricity ( $A_4$ ). However, it is worth pointing out that the sustainability order of the four electricity generation systems may change when changing the evaluation criteria. In addition, the change of the weights of the criteria for life cycle sustainability assessment of electricity generation systems may also change the sustainability order of the four electricity generation systems (see section 4 for more details).

#### **4. Discussions**

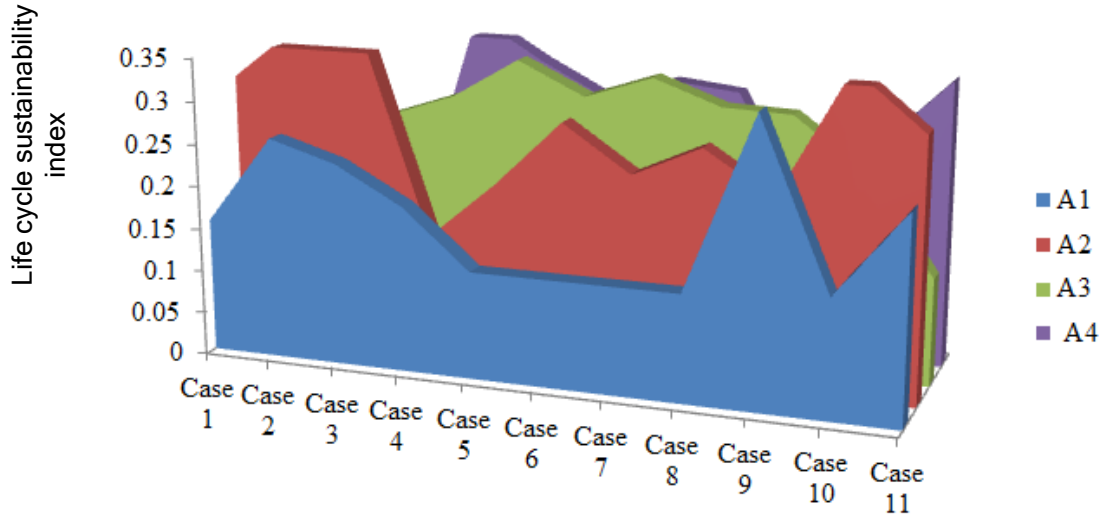
In order to investigate the effects of the weights on the sustainability order of industrial processes, the following scenarios were studied by changing the weights of the ten criteria for life cycle sustainability assessment:

**Case 1:** equal weights-an equal weight (0.1000) was assigned to the ten criteria;

**Case 2-11:** a dominant weight (0.3700) was assigned to the  $(i-1)$ -th criterion, and an equal weight (0.0700) was assigned to the other nine criteria.

The results of sensitivity analysis were presented in Figure 6. It is apparent that the weights of the criteria have significant effects on life cycle ranking of the four electricity generation systems, and the change of the weights of the criteria for life cycle sustainability assessment may lead to the change the sustainability order of the four electricity generation systems.





**Figure 6:** The results of sensitivity analysis for investigating the effects of the weights of the criteria on life cycle ranking of the four electricity generation systems

In order to validate the sustainability order of the four electricity generation systems, four interval multi-criteria decision making methods including interval sum weighted method (SWM), two different interval TOPSIS methods, and an interval multi-attribute decision analysis (IMADA) method were also employed to rank the four electricity generation systems.

The interval sum weighted method determined the sustainability order based on the weighted normalized life cycle sustainability performance matrix, and the integrated priority of each industrial can be determined by Eq. 35.

$$P_i = \left[ \sum_{j=1}^K y_{iEC_j}^L + \sum_{j=1}^L y_{iEN_j}^L + \sum_{j=1}^N y_{iS_j}^L \quad \sum_{j=1}^K y_{iEC_j}^U + \sum_{j=1}^L y_{iEN_j}^U + \sum_{j=1}^N y_{iS_j}^U \right] \quad i = 1, 2, \dots, M \quad (35)$$

After determining the integrated priority of each alternative electricity generation system, the four electricity generation systems can be ranked according to Eqs.17-19. As for the interval

TOPSIS methods, both the one developed by He *et al.* (2017) and another developed by Wang *et al.* (2017) were employed in this study. However, the IMADA method derived from the work of Ren and Ren (2018) cannot use the interval weights of the criteria for life cycle sustainability assessment directly, and the midpoint of the weight of each criterion was used in the IMADA method.

The comparison results of the developed life cycle aggregated sustainability index method with that determined by interval SWM, the two interval TOPSIS methods and the IMADA method based on the weights determined by the interval preference relation based goal programming model were presented in Table 8. It is apparent that the sustainability order of the four electricity generation systems determined by the life cycle aggregated sustainability index method developed in this study is absolutely the same to that determined by the interval SWM method and the interval TOPSIS method developed by Wang *et al.* (2017). However, the results determined by the proposed method in this study is slightly different from that developed by the interval TOPSIS method proposed by He *et al.* (2017) and that determined by the IMADA (Ren and Ren, 2018). The most sustainable and the least sustainable electricity generation determined by these two methods are the same with that determined by the proposed method in this study. To some extent, these comparisons demonstrate that the developed life cycle aggregated sustainability index is valid and feasible for ranking alternative industrial systems under data uncertainties in life cycle sustainability perspective.

**Table 8:** The sustainability order of the four electricity generation systems

		A <sub>1</sub>	A <sub>2</sub>	A <sub>3</sub>	A <sub>4</sub>	
This study		3	1	2	4	
Integrated priorities	SWM	[0.2946 1.0649]	[0.4117 1.3097]	[0.3112 1.2469]	[0.1189 1.0816]	
Ranking		3	1	2	4	
Closeness coefficient	Interval TOPSIS	[0.1116 0.1805]	[0.1334 0.2158]	[0.0567 0.0917]	[0.0427 0.0690]	He <i>et al.</i> (2017)
Ranking		2	1	3	4	
Closeness coefficients	Interval TOPSIS	0.4884	0.5971	0.5227	0.4141	Wang <i>et al.</i> (2017)
Ranking		3	1	2	4	
Ranking	IMADA	2	1	3	4	Ren and Ren (2008)

## 5. Conclusions

This study developed a life cycle aggregated sustainability index for measuring the integrated sustainability performances of industrial systems under data uncertainties. Life cycle sustainability assessment which combines life cycle assessment, life cycle costing, and social life cycle assessment was employed to determine the data of the industrial systems with respect to the criteria in the three pillars of sustainability. The data uncertainties can be incorporated in life cycle sustainability assessment by using interval numbers to represent data uncertainties. Accordingly, the

life cycle sustainability performance matrix which was used as the decision-making matrix was composed by interval numbers. The interval preference relation based goal programming model which allows the decision-makers to use interval numbers to establish the pair-wise comparison matrix was employed to determine the relative weights of the criteria for life cycle sustainability assessment. A life cycle aggregated sustainability index which incorporates the weights of the criteria for life cycle sustainability assessment and the life cycle environmental, economic and social performances of the industrial systems was developed for measuring the integrated sustainability based on projection theory. An industrial case (four electricity generation systems) were investigated by the developed life cycle aggregated sustainability index method, and the results reveal that the proposed method is feasible and valid for ranking industrial systems according to their sustainability.

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