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Sustainability Assessment Framework Incorporating Interval Parameters

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The sustainability assessment framework aims to identify the most sustainable product, or process, or system from a set of alternate options. An appropriate sustainability assessment framework simultaneously handles multi-dimensional sustainable parameters to incorporate aspects such as minimizing the land acquisition, depleting the fossil fuels and materials consumption, reducing the environmental harness, etc. Various multi-criteria decision-making methods such as The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Euclidean Distance Method, etc., are applied to identify the most sustainable option. These assessment methods incorporate precise indicator scores to ascertain the most sustainable option. However, in most applications, sustainable indicator scores are not precise. Imprecise values of parameters may be represented as an interval number with a lower and an upper bound. This paper proposes a generalized framework of sustainability assessment method incorporating interval indicator scores to identify the appropriate option. The significant steps of sustainability assessment methods have been explored from the physical point of view towards sustainability. These steps are extended to an interval scale for retrospective parameters. An extended normalization function and an extended aggregation function are recommended in the proposed method. The proposed framework signifies the appropriate sustainability assessment method and helps to identify the most sustainable system among the systems with imprecise indicator scores. The applicability of the proposed method is illustrated by the sustainability assessment example of deciding the most sustainable electricity generation system. Furthermore, the significance of the proposed approach is discussed.

1. Introduction

Under the pressure of global warming and the limited availability of conventional energy sources (e.g., fossil fuel, and coal), worldwide interest has developed in the usage of non-conventional energy sources to meet the electricity demand. Over the last decade, the share of global CO_2 emissions from the electricity sector has significantly increased by 9 % (IEA, 2021). Conventional energy sources are responsible for more than 70 % of the CO_2 emissions in the electricity sector. From the climate-change perspective, non-conventional energy sources should be preferred for electricity generation compared to conventional energy sources (Desai and Bandyopadhyay, 2017). However, while selecting the power generation system, multiple parameters (such as water footprint, land footprint, and cost of energy) should be involved apart from carbon footprint. These multiple parameters (or indicators) together define the overall relative sustainability of the system.
The quantitative measurement of indicators may lead to imprecise values due to measuring errors or expert estimations (Dawood, 2011). The imprecise numerical value of the indicator for a system provides the solution in a finite interval. For handling the interval numbers, a specific arithmetic is required, which may be incorporated with the sustainability assessment method of the precise indicator. Literature consists of various quantitative approaches to determine the relative sustainability of existing systems with precise indicators, i.e., Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981), Weightage Sum Method, Weightage Product Method (Triantaphyllou, 2000), Geometric Mean Method (Sikdar, 2009), Euclidean Distance Method (Sikdar et al., 2012), and Canberra Distance Method (Brandi et al., 2014). Desai and Bandyopadhyay (2017) highlighted that the different mathematical approaches might lead to different preferences of existing systems. No standard method is available to identify the most sustainable system.

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This paper aims to develop the standard (or appropriate) quantitative method for sustainable decision of multiple systems with imprecise indicators. Rather than making the comparison of existing methods, this paper highlights the newly defined characteristics of mathematical formulations for the sustainability assessment. Defining the framework of the methodology based on the mathematical properties shows the novelty of this paper. In first part, the framework is defined for precise parameters. In second part, the proposed sustainability assessment framework of precise parameters is extended to incorporate interval numbers using normalization and aggregation functions. Among the functions used in the literature, the extended min-max normalization, and extended p-antinorm aggregation functions are determined as the most appropriate, as these functions follow the mathematical properties of the sustainability assessment framework. In this paper, the extended sustainability assessment framework for interval numbers is applied, using the above functions, to identify the most sustainable power generation system. This model represents the nuclear power system to be more sustainable among non-renewable energy sources.

2. Problem statement

The generalized problem of sustainability assessment of multiple systems, involving interval indicators is shown in Table 1. Mathematically, it may be stated as follows:

Table 1: Index formation of multiple systems for sustainability assessment problem

	I_1	I_2	I_3	…	I_n
S_1	$[x^L_{11}, x^U_{11}]$	$[x^L_{12}, x^U_{12}]$	$[x^L_{13}, x^U_{13}]$	…	$[x^L_{1n}, x^U_{1n}]$
S_2	$[x^L_{21}, x^U_{21}]$	$[x^L_{22}, x^U_{22}]$	$[x^L_{23}, x^U_{23}]$	…	$[x^L_{2n}, x^U_{2n}]$
S_3	$[x^L_{31}, x^U_{31}]$	$[x^L_{32}, x^U_{32}]$	$[x^L_{33}, x^U_{33}]$	…	$[x^L_{3n}, x^U_{3n}]$
…	…	…	…	…	…
S_m	$[x^L_{m1}, x^U_{m1}]$	$[x^L_{m2}, x^U_{m2}]$	$[x^L_{m3}, x^U_{m3}]$	…	$[x^L_{mn}, x^U_{mn}]$

- A set of m systems, symbolized by $\{S_1, S_2, \ldots, S_m\}$ is known. Note: the system is also known as an alternative or option.
- A set of n indicators, indicated by $\{I_1, I_2, \ldots, I_n\}$ is known. Note: indicator is also known as parameter or criterion.
- All indicators are represented by numerical performance scores. A quantitative performance score of each system S_i with respect to indicator I_j is given in a closed interval, expressed as $[x^L_{ij}, x^U_{ij}]$. Where, both x^L_{ij} (lower bound) and x^U_{ij} (upper bound) are real numbers (R). A mathematical representation of the interval number is shown in Eq(1).

$$\left[x^L_{ij}, x^U_{ij}\right] = \{g \in R \mid x^L_{ij} \le g \le x^U_{ij}\} \tag{1}$$

- The performance intervals are defined on an inverse scale, i.e., the lower performance values represent the superiority of sustainability.
- The overall objective is to identify the most sustainable system among the systems available to decision-makers, involving performance intervals.

In this paper, an extended mathematical formulation ($f:[R, R]^n \rightarrow [R, R]$) of sustainability assessment is proposed to incorporate the performance intervals. The proposed method of sustainability assessment passes through the appropriate mathematical framework.

3. Sustainability assessment method with precise indicators

The sustainability assessment method aims to define the ranking of existing systems. The quantitative algorithms of sustainability assessment of multiple systems with precise indicators have the following steps:

Step 1: Determine the quantitative performance scores (x_{ij}) of each system S_i with respect to each indicator I_j. In case of qualitative indicators, these need to be converted into quantitative scores. Analytic hierarchy process (Saaty, 1980) can be used to determine the numerical performance score of qualitative indicators for each system S_i. When determining the performance scores, it is suggested that the quantitative performance score should consider the overall impact of alternative on indicator. So that an appropriate comparison of alternatives can be made with appropriate value of indicator.

Step 2: Make all indicators uni-directional. As mentioned in the problem statement, a lower performance score defines the superiority towards sustainability. The performance score, where, a higher numerical value indicates the preference for sustainability, should be multiplied by -1 to reverse the directionality of preference (Sikdar et al., 2017). Reciprocal approach can also be used to reverse the directionality. However, it has limitation. It cannot be used on having the performance score tends to zero (very less).

Step 3: Compute the normalized performance score to make the indicators comparable by making them dimensionless within a given finite range. Normalization function ($N(x_{ij})$ or y_{ij}) should follow the three mathematical characteristics, i.e., finite range, affine invariance, and continuity. Among the existing normalization functions in the literature, the min-max normalization function ($N(x_{ij})$:R→[a, b]) considers all the defined characteristics of the normalization function, as shown in Eq(2).

$$N(x_{ij}) = \left[a + \left(\frac{x_{ij} - \underbrace{\min}_{1\le i\le m}(x_{ij})}{\underbrace{\max}_{1\le i\le m}(x_{ij}) - \underbrace{\min}_{1\le i\le m}(x_{ij})}\right)(b - a)\right] \tag{2}$$

Both a and b are finite positive values with ($0 \le a \le b$). Usually, the normalized performance values are preferred to measure between [0, 1] (a = 0 and b = 1). The proposed normalization function is designed for indicator, that considers the discrete value for alternatives.

Step 4: Compute the sustainable score (or aggregated score) of each system S_i by aggregating all the performance scores ($x_{ij}\ \forall j$) of the system S_i for defining the preference ranking of existing systems. Aggregation function ($f:[0, 1]^n \rightarrow [0, 1]$) should follow the monotonicity, continuity, homogeneity, idempotency, order invariance, and concavity properties. p-antinorm aggregation function, expressed by Eq(3) for i^{th} system, is considered as the most appropriate aggregation function for measuring the sustainable score of each system.

$$f_i(y_{i1}, y_{i2}, \dots, y_{in}) = \left(\frac{\sum_{j=1}^{n} w_j (y_{ij})^p}{\sum_{j=1}^{n} w_j}\right)^{\frac{1}{p}}, (p \le 1) \tag{3}$$

Where, $y_{ij} \in [0, 1]$ is the normalized performance score of i^{th} system for j^{th} indicator. w_j represents the weights of j^{th} indicator as compared to other indicators with $\sum_{j=1}^{n} w_j = 1$ and $w_j > 0\ \forall j$ (*j = 1, 2, …, n*).

Step 5: Identify the most sustainable system with a minimum sustainable score among the existing systems.

The proposed approach of sustainability assessment is defined for deterministic indicators. However, in real-life applications, sustainable indicators are not deterministic. There may be uncertainty in sustainable indicators due to measurement errors (i.e., is called epistemic uncertainty) and expert estimations (Dawood, 2011). Uncertainty expresses the performance scores in imprecise format (or interval number). Interval number requires specific mathematical operations for performing addition, subtraction, multiplication, division, scalar multiplication, and exponentiation, which have been shown in the following equations (Bandyopadhyay, 2020):

$$[x_{ij}^L, x_{ij}^U] + [z_{ij}^L, z_{ij}^U] = [x_{ij}^L + z_{ij}^L, x_{ij}^U + z_{ij}^U] \tag{4}$$

$$[x_{ij}^L, x_{ij}^U] - [z_{ij}^L, z_{ij}^U] = [x_{ij}^L - z_{ij}^U, x_{ij}^U - z_{ij}^L] \tag{5}$$

$$[x_{ij}^L, x_{ij}^U] \times [z_{ij}^L, z_{ij}^U] = [\min(x_{ij}^L z_{ij}^L, x_{ij}^L z_{ij}^U, x_{ij}^U z_{ij}^L, x_{ij}^U z_{ij}^U),\ \max(x_{ij}^L z_{ij}^L, x_{ij}^L z_{ij}^U, x_{ij}^U z_{ij}^L, x_{ij}^U z_{ij}^U)] \tag{6}$$

$$[x_{ij}^L, x_{ij}^U] \div [z_{ij}^L, z_{ij}^U] = [x_{ij}^L, x_{ij}^U] \times \left[\frac{1}{z_{ij}^U}, \frac{1}{z_{ij}^L}\right] \text{ if } 0 \notin [z_{ij}^L, z_{ij}^U] \tag{7}$$

$$h \times [x_{ij}^L, x_{ij}^U] = \begin{cases} [hx_{ij}^L, hx_{ij}^U], h \ge 0 \\ [hx_{ij}^U, hx_{ij}^L], h < 0 \end{cases} \tag{8}$$

$$[x_{ij}^L, x_{ij}^U]^p = [(x_{ij}^L)^p, (x_{ij}^U)^p] \text{ if } x_{ij}^U \ge x_{ij}^L \ge 0 \text{ and } p > 0 \tag{9}$$

In order to assign the preference order of existing systems, interval numbers are needed to be compared. Interval numbers do not follow the well-ordering principle as real numbers follow. There are three cases of inequality constraints for two interval numbers. These cases are stated as follows:

$$x_{ij}^L \le x_{ij}^U \le z_{ij}^L \le z_{ij}^U \Leftrightarrow [x_{ij}^L, x_{ij}^U] \le [z_{ij}^L, z_{ij}^U] \tag{10}$$

$$x_{ij}^L < z_{ij}^L < z_{ij}^U < x_{ij}^U \tag{11}$$

$$x_{ij}^L < z_{ij}^L < x_{ij}^U < z_{ij}^U \tag{12}$$

In the first case, expressed by Eq(10), the system, associated with sustainable interval number $[x_{ij}^L, x_{ij}^U]$, can be determined to be more sustainable as compared to the system, associated with sustainable interval $[z_{ij}^L, z_{ij}^U]$. In the second and third cases, represented by Eq(11) and Eq(12), nothing can be said about the well-ordering principle for identifying the sustainable system. Following arithmetic of interval numbers are used to transform the representation of sustainability assessment method for imprecise indicators.

4. Extension of sustainability assessment method with imprecise indicators

This section extends the sustainability assessment method for imprecise indicators to account for the epistemic uncertainty. The objective of the extended sustainability assessment method is to determine the most sustainable system among the existing systems incorporating the imprecise performance scores. The extended sustainable assessment method involves the following procedures:

Step 1: Determine the quantitative performance interval $[x_{ij}^L, x_{ij}^U]$ of each system S_i for each indicator I_j, as shown in Table 1. The specification of quantitative measurement is already discussed in step 1 of Section 3.

Step 2: Define the uni-directionality of indicators. Indicators, which have higher value as superior, have been multiplied with -1 to reverse the directionality of preferences. Mathematically, It is mentioned in Eq(13):

$$-1 \times [x_{ij}^L, x_{ij}^U] = [-x_{ij}^U, -x_{ij}^L] \tag{13}$$

Step 3: Compute the normalized performance interval $[y_{ij}^L, y_{ij}^U]$ within the finite range [0, 1] by using the following extended normalization function $(N([x_{ij}^L, x_{ij}^U]):[R, R]\rightarrow[[0, 1], [0, 1]])$:

$$N\left([x_{ij}^L, x_{ij}^U]\right) = \frac{[x_{ij}^L, x_{ij}^U] - \underbrace{\min}_{1 \le i \le m}(x_{ij}^L)}{\underbrace{\max}_{1 \le i \le m}(x_{ij}^U) - \underbrace{\min}_{1 \le i \le m}(x_{ij}^L)} \tag{14}$$

Eq(14) may be represented into interval numbers, as defined below:

$$N\left([x_{ij}^L, x_{ij}^U]\right) = \left[\frac{x_{ij}^L - \underbrace{\min}_{1 \le i \le m}(x_{ij}^L)}{\underbrace{\max}_{1 \le i \le m}(x_{ij}^U) - \underbrace{\min}_{1 \le i \le m}(x_{ij}^L)}, \frac{x_{ij}^U - \underbrace{\min}_{1 \le i \le m}(x_{ij}^L)}{\underbrace{\max}_{1 \le i \le m}(x_{ij}^U) - \underbrace{\min}_{1 \le i \le m}(x_{ij}^L)}\right] \tag{15}$$

Step 4: Measure the sustainable interval (or aggregated interval) of each system with the extended aggregation function $(f:[[0, 1], [0, 1]]^n \rightarrow [[0, 1], [0, 1]])$, which is expressed by Eq(16).

$$f_i([y_{i1}^L, y_{i1}^U], [y_{i2}^L, y_{i2}^U], \ldots, [y_{in}^L, y_{in}^U]) = \left(\frac{\sum_{j=1}^n w_j [y_{ij}^L, y_{ij}^U]^p}{\sum_{j=1}^n w_j}\right)^{\frac{1}{p}}, \ (p \le 1) \tag{16}$$

Eq(16) may be expressed in the simplified format for the computation of sustainable internal, as shown in Eq(17).

$$f_i([y_{i1}^L, y_{i1}^U], [y_{i2}^L, y_{i2}^U], \ldots, [y_{in}^L, y_{in}^U]) = \left[\left(\frac{\sum_{j=1}^n w_j (y_{ij}^L)^p}{\sum_{j=1}^n w_j}\right)^{1/p}, \left(\frac{\sum_{j=1}^n w_j (y_{ij}^U)^p}{\sum_{j=1}^n w_j}\right)^{1/p}\right], \ (0 < p \le 1) \tag{17}$$

In Eq(17), weights are considered as $\sum_{j=1}^n w_j = 1$ and $w_j > 0 \ \forall j$ ($j = 1, 2, \ldots, n$) for both a lower and an upper limit. w_j depends upon on decision makers. For simplicity, all indicators can be assumed with equal weights.

Step 5: Identify the most sustainable system with the comparison of sustainable intervals $[f_i^L, f_i^U]$ for each system S_i using the Eq(10-12).

5. Illustrative example

The applicability of the extended sustainability assessment method is shown with the numerical example of the power generation systems. Desai and Bandyopadhyay (2017) reviewed the non-conventional and conventional energy sources for electricity generation with imprecise indicators. The same example has been adopted to know the overall sustainability of power generation systems. Table 2 shows the performance interval of different energy sources for various indicators. These indicators are carbon footprint (C_f), water footprint (W_f), land footprint (L_f), and cost of energy (C_{energy}). The unit of these indicators is mentioned in Table 2. All four indicators are uni-directional. The performance intervals are normalized by Eq(15) to make the indicator dimensionless.

Table 2: Performance interval of sustainable parameters for different power generation systems (Desai and Bandyopadhyay, 2017)

Energy Source	Carbon footprint (C_f) ($g.CO_2$/kWh)	Water footprint (W_f) (gal/kWh)	Land footprint (L_f) (km^2/TWh)	Cost of energy (C_{energy}) (UScents/kWh)
Coal	[834,1026]	[0.16,0.61]	[2.5,17]	[3.77,5.85]
Coal with CCS	[255,442]	[0.16,0.61]	[2.5,17]	[3.77,5.85]
Oil	[657,866]	[4.51,9.04]	[15,75]	[8,10]
Natural gas	[398,499]	[0.55,0.55]	[8,29]	[5.46,11.96]
Biomass	[25,93]	[25,150]	[433,654]	[2,22]
Nuclear	[9,70]	[0.4,0.72]	[1.9,2.8]	[4.55,5.46]
Hydropower	[17,22]	[23,23]	[18,90]	[2,20]
Ocean (Wave and tidal)	[14,113]	[0.001,0.001]	[1,13.9]	[8,30]
Geothermal	[15.1,55]	[0.005,0.005]	[1,13.9]	[3,9]
Solar photovoltaic	[19,59]	[0.042,0.042]	[21,53]	[10,23]
Solar thermal	[8.5,11.3]	[0.037,0.78]	[10,20]	[10,30]
Wind	[2.8,7.4]	[0.001,0.001]	[64,80]	[3,15]

The normalized performance intervals (within the finite range [0, 1]) are shown in Table 3. All indicators are considered to be of equal importance to each other. It defines the weight of each indicator to be 0.25 (w_j $\forall$ *j*). Extended p-antinorm aggregation function (p = 0.5), defined by Eq(17), is used to integrate all the normalized performance intervals of each energy source. Table 3 also shows the sustainable (or aggregated) interval [f_i^L, f_i^U] of each energy source for electricity generation. The lower bound and the upper bound of the sustainable interval of each energy source is represented graphically in Figure 1.

Table 3: Normalized performance interval (within the range [0,1]) of sustainable parameters for different power generation systems, and sustainable (aggregated) interval of various energy sources

Energy Source	C_f	W_f	L_f	C_{energy}	Sustainable interval ([f_i^L, f_i^U])
Coal	[0.81,1]	[0,0]	[0,0.02]	[0.06,0.14]	[0.10,0.16]
Coal with CCS	[0.25,0.43]	[0,0]	[0,0.02]	[0.06,0.14]	[0.04,0.10]
Oil	[0.64,0.84]	[0.03,0.06]	[0.02,0.11]	[0.21,0.29]	[0.16,0.26]
Natural gas	[0.39,0.48]	[0,0]	[0.01,0.04]	[0.12,0.36]	[0.08,0.15]
Biomass	[0.02,0.09]	[0.17,1]	[0.66,1]	[0,0.71]	[0.12,0.62]
Nuclear	[0.01,0.07]	[0,0]	[0,0]	[0.09,0.12]	[0.01,0.03]
Hydropower	[0.01,0.02]	[0.15,0.15]	[0.03,0.14]	[0,0.64]	[0.03,0.18]
Ocean (Wave and tidal)	[0.01,0.11]	[0,0]	[0,0.02]	[0.21,1]	[0.02,0.13]
Geothermal	[0.01,0.05]	[0,0]	[0,0.02]	[0.04,0.25]	[0.01,0.05]
Solar photovoltaic	[0.02,0.05]	[0,0]	[0.03,0.08]	[0.29,0.75]	[0.05,0.12]
Solar thermal	[0.01,0.01]	[0,0.01]	[0.01,0.03]	[0.29,1]	[0.03,0.11]
Wind	[0,0]	[0,0]	[0.10,0.12]	[0.04,0.46]	[0.02,0.08]

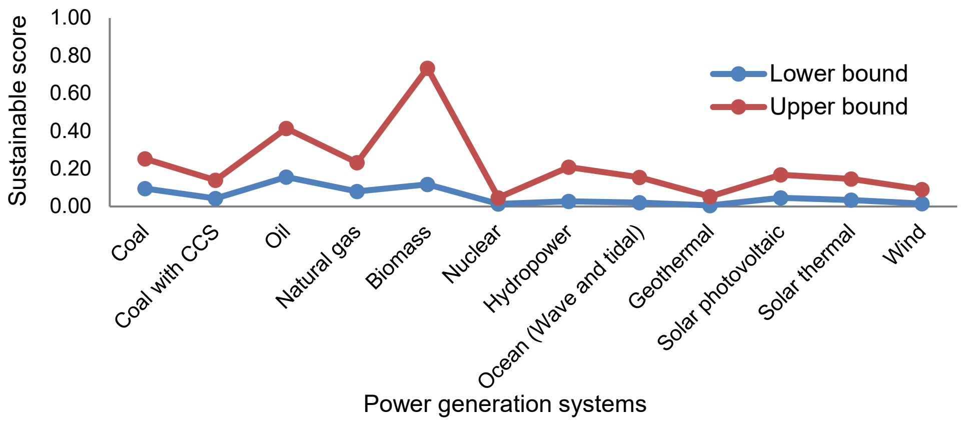

Figure1: Graphical representation of sustainable (aggregated) interval for various energy sources

Due to the inequality constraint (ordering restriction) of interval numbers, as discussed in Eq(11-12), it is hard to identify the most sustainable system in this case study. The sustainable intervals of nuclear, ocean, geothermal, and wind energy sources cannot be compared. However, from Figure 1, it might be concluded that the nuclear-based power system is more sustainable as compared to coal-based, coal-based with CCS, oil-based, natural gas-based, biomass, solar photovoltaic, and solar thermal power systems. The result (nuclear power system is more sustainable as compared to conventional energy sources) is consistent with Desai and Bandyopadhyay (2017). It validates the proposed methodology. The proposed extended sustainability assessment framework for imprecise indicators is significantly able to make the comparison of existing systems to determine the relative sustainable system.

6. Conclusions

An extended sustainability assessment framework, that can be applied on imprecise parameters, is determined for identifying the most sustainable option. This paper shows the transparency to decision makers for using the appropriate methodology. The recommended framework justifies the importance of the min-max normalization function, and defines p-antinorm aggregation function with the help of mathematical properties for the precise indicator value. This paper extends the above-mentioned functions for imprecise indicators (or interval numbers) using well-defined interval arithmetic. The extended framework calculates the sustainable interval of each energy source. The sustainable interval is used to define the ranking of power generation sources. It is observed that the nuclear power generation system, having a sustainable interval [0.01, 0.03], is more sustainable as compared to conventional energy sources. The recommended approach has a limitation, i.e., it measures the sustainable score in interval number. A comparison cannot always be made between two interval numbers. For example, the nuclear power generation system (sustainable interval [0.01, 0.03]) and the geothermal power generation system (sustainable interval [0.01, 0.05]) cannot be compared. Due to having this limitation, this model is not able to provide a clear ranking, only partial ranking can be done. This limitation is considered for further improvement as a future work for making sustainable decision. Further, the mathematical techniques such as fuzzy approach, are needed to incorporate to overcome the limitation.

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