An interval-valued intuitionistic fuzzy-based CODAS for sustainable supplier selection

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Abstract
With the advent of information age, supplier selection has attracted researchers’ attention in the field of supply chain management. Optimal supplier selection meets the competitiveness of industries and satisfaction of customers in the supply chain management. However, considering sustainable factors including environmental and social parameters, alongside customers’ expectations are the main challenge of supplier selection. Moreover, incomplete and hesitation among experts’ judgment result in uncertainty that leads to the more complex assessment of criteria. In this paper, an innovative multi-criteria decision-making method was developed to address supplier selection process and supplier order allocation based on customers’ expectations with respect to the sustainable primers. The proposed method was based on fuzzy combinative distance-based assessment (CODAS) extended with interval-valued intuitionistic fuzzy (IVIF) for multi-criteria sustainable supplier selection. The proposed model was combined with hesitation linguistic set to provide two goals including a: dealing with experts’ hesitation as well as imprecise and vague of decision makers’ knowledge in order to express assessment values. b: coping with missing or nonexistence of attribute assessment values. The proposed method was performed on a steel mill as a case study to illustrate the effectiveness of decision process on four suppliers in detail. The results showed that the presented model could consider conflicting parameters and enhance high-order imprecision and uncertainty.

Keywords Sustainable supplier selection · AHP · CODAS · Interval-valued intuitionist Fuzzy · Hesitation linguistic set

1 Introduction
By increasing competition in business environment, companies should improve their business procedures and performance of supply chain. In fact, supplier selection has been the important challenge of organizations owing to affecting on profitability and maintenance of organizational competitive position (Hosseini and Barker 2016; Ghadimi et al. 2018; Awasthi et al. 2018). Because of increasing outstanding trends of public concerns on environmental problems and sustainable development, considering only economic aspects could not become effective in the optimal supplier selection. Therefore, the efficient approaches should take into account environmental policies, social concerns apart from economic metrics which lead to develop sustainable supplier selection (Fallahpour et al. 2017; Wang et al. 2017; Luthra et al. 2017; Maghsoodi et al. 2018; Liao et al. 2018; Tavana et al. 2017; Daultani et al. 2019).

Sustainable supplier selection is a new management paradigm to capture both commercial profit and environmental performance of organizations. Therefore, engaging different conflicting criteria in selecting sustainable supplier results in complicated decisions which is considered as a multi-criteria decision-making problem. In addition to considering complexity of supplier selection decision, the evaluated metrics may become non-existing because of hesitation among different linguistic term sets in experts’ opinions. Therefore, it is necessary to deal with uncertainty and linguistic problems such as incomplete information for rating the assessment attributes.
Multi-criteria decision methods (MCDMs) are used as the main approaches to evaluate and to select the optimal sustainable supplier. Moreover, fuzzy set theory is integrated with MCDM methods to deal with uncertainty among judgments in order to leverage ambiguity and imprecision among experts’ opinions. In addition to integrating fuzzy and MCDM, hesitation fuzzy linguistic representation developed by Torra (2010) is applied to ignore fixed linguistic term sets MCDM, hesitation fuzzy linguistic representation developed among experts’ opinions. In addition to integrating fuzzy and judgments in order to leverage ambiguity and imprecision integrated with hesitation fuzzy linguistic method to solve uncertainty among sustainable supplier. Moreover, fuzzy set theory is integrated with hesitation fuzzy linguistic method to solve vagueness and uncertainties through capturing fuzziness and uncertainty of assessment information.

The key contributions of the proposed method are summarized as follows:

- To develop a multi-criteria decision model with considering sustainable aspects.
- To utilize linguistic terms for expressing of decision makers’ opinions using hesitation fuzzy language representation.
- To evaluate the weight of different metrics using AHP by integrating hesitation fuzzy language and IVIF.
- To allocate the rank of suppliers using extended CODAS through capturing hesitation fuzzy language and IVIF with considering incomplete information.
- To demonstrate its capability by applying our methodology to steel mill as a real case study.

The rest of the paper is organized as follows: In Sect. 2, the existing approaches are investigated to address sustainable supplier selection problems. Besides, some elementary definitions and operational rules of hesitation linguistic set, IVIF, AHP and fuzzy CODAS are introduced. Section 3 elaborates upon a novel MCDM method based on the IVIF-AHP and the IVIF-CODAS and hesitation fuzzy set for sustainable supplier selection. To demonstrate the efficiency of the proposed method, a steel mill is provided as a real example in Sect. 4. Finally, conclusion is drawn in Sect. 5.

2 Literature review

2.1 Sustainable supplier selection

Selecting the optimal supplier has become the main issue to enhance the performance of supply chain as well as the customers’ expectations. Furthermore, by increasing attention to social and environmental concerns, the development of sustainability should be taken into account in supplier selection which is called as sustainable supplier selection (Awasthi et al. 2018; Gören 2018; Govindan et al. 2018; Liu et al. 2018; Zhou et al. 2016).

Choosing the proper criteria is the important challenge of sustainable supplier selection process. Apart from economic metrics, environmental and social criteria should be considered in sustainable supplier selection. It is necessary that companies capture economic, environmental and social powerful supplier to establish a long-term relationship with it for maintaining competitive advantages.

2.2 Sustainable supplier selection methods

To select the most appropriate sustainable supplier selection, different metrics should be taken into account. The considered metrics are classified into qualitative and quantitative criteria in multi-criteria decision-making (MCDM) problem (Araz and Ozerkaran 2007; de Almeida 2007).

Various studies have been conducted to select the optimal sustainable supplier using different approaches classified by multi-criteria decision making (MCDM), artificial intelligence (AI) and mathematical programming (MP).

Furthermore, existing ambiguity on human being in expressing attributes as well as incomplete information cause that the process of sustainable supplier selection becomes more complex (Chen and Han 2018; Li et al. 2018; Liu and Chen 2018; Wu et al. 2019). Therefore, MCDM requires to be incorporated with uncertainties in different metrics in sustainable supplier selection. The majority of methods for sustainable supplier selection are based on applying fuzzy concept into the traditional MCDM methods (Govindan et al. 2015).

An overview for sustainable supplier selection is summarized in Table 1 to present the applied methods. As shown in Table 1, integrated MCDM methods with different approaches such as fuzzy, gray and so on are also applied to select the optimal sustainable supplier selection.

The introduced models including IVIF, hesitant fuzzy set, IVIF AHP and fuzzy CODAS were collectively utilized to solve sustainable supplier selection. IVIF AHP was used to define the importance weight of criteria. Furthermore, fuzzy CODAS was extended using IVIF to prioritize the alternative suppliers. Furthermore, hesitant fuzzy linguistic representation was used for a subset of the consecutive linguistic variable terms such as “Less than low” or “More than High” or “between Low and High,” etc. Then, the aggregated operator such as IVIF weighted averaging (IIFWA) operator was used to calculate the equivalent IVIF value of a subset of the consecutive linguistic variable set. Therefore, IVIF and hesitant fuzzy linguistic were applied to capture the uncertainty and hesitation among experts’ judgments.
2.3 Preliminary definitions

In this section, basic concepts of IVIF, hesitation fuzzy linguistic representation model, fuzzy AHP and fuzzy CODAS techniques are presented to provide background of the proposed method.

2.4 IVIF and hesitation fuzzy set

In order to solve hesitation among preferences, hesitation fuzzy set similar to an intuitionistic fuzzy set is used. In fact, hesitation fuzzy set is employed to deal with hesitation among judgment of experts’ opinions. Besides, hesitation fuzzy set could be applied as an effective method in different fields of study (Song et al. 2019; Rodríguez et al. 2014; Xu 2014). Furthermore, IVIF is considered as the main representation among hesitation of the present paper. In this sub-section, the essential preliminaries are summarized as follows:

Definition 1 Assuming X, interval-valued intuitionistic fuzzy set (IVIFS) is identified by $\widetilde{A} = \{x, \widetilde{\mu}_A (x), \widetilde{\nu}_A (x) | x \in X \}$ to return a subset of values in $[0, 1]$ where $\widetilde{\mu}_A (x) \subseteq [0, 1]$, and $\widetilde{\nu}_A (x) \subseteq [0, 1]$ are the interval numbers presented by $[t^l_\widehat{A}, t^u_\widehat{A}]$ and $[f^l_\widehat{A}, f^u_\widehat{A}]$ leading to $\widetilde{A} = \{[t^l_\widehat{A}, t^u_\widehat{A}], [f^l_\widehat{A}, f^u_\widehat{A}] \}$ regarding $t^u_\widehat{A} + f^u_\widehat{A} \leq 1$. Visit more details on mathematical operations and Euclidean and Hamming distances on IVIF numbers (Liu et al. 2012; Li 2011; Xue et al. 2016).

Definition 2 Hesitant fuzzy linguistic sets (HFLS) introduced by Rodríguez et al. (2014) are based on the linguistic term set and HFS. It is noted that linguistic expressions are more similar to human beings’ expressions without a context-free grammar.

In fact, HFLS is known as an ordered finite subset of the consecutive linguistic terms of a linguistic term set. For instance, assuming linguistic term set $S = \{s_0, ..., s_8\}$, $H[\{S_i\}] = \{S_j | S_j \in S \}$, $H[\{\text{at most } S_i\}] = \{S_j | S_j \in S \}$, $H[\{\text{lower than } S_i\}] = \{S_j | S_j \in S \}$ and $H[\{\text{between } S_i \text{ and } S_j\}] = \{S_k | S_k \in S \}$. For $S_i \leq S_j$ can be considered as different HFLS (Rodríguez et al. 2014; Chen and Han 2018). HFLS could be transformed into IVIF format.

Example Let $S = \{s_0 : \text{nothing}, s_1 : \text{verylow}, s_2 : \text{low}, s_3 : \text{medium}, s_4 : \text{high}, s_5 : \text{veryhigh}, s_6 : \text{perfect}\}$ as a linguistic term set, therefore, $H[\{\text{at least high}\}] = \{\text{high, veryhigh, perfect}\}$ is HFLS (Rodríguez et al. 2014).
\((I_{A_{\lambda_{i}}}^{f_{h_{i}}}, f_{h_{i}}^{A_{\lambda_{i}}})\) is achieved by IVIF weighted averaging (IFWA) operator in which \(\lambda_{i}\) is the importance of IVIF \(A_{i}\) (Atanassov and Gargov 1989):

\[
IFWA = \left[\left(1 - \prod_{i=1}^{n}(1 - f_{h_{i}}^{A_{\lambda_{i}}})\right), \left(1 - \prod_{i=1}^{n}(1 - f_{h_{i}}^{A_{\lambda_{i}}})\right)\right] - \left[\prod_{i=1}^{n}(f_{h_{i}}^{A_{\lambda_{i}}}) \cdot \prod_{i=1}^{n}(f_{h_{i}}^{A_{\lambda_{i}}})\right]
\]

\[\text{(1)}\]

### 2.5 IVIF AHP

**Step 1.** After determining a matrix of pairwise comparisons for each metric relative to others in one sub criteria presented as \(W = [w_{ij}]_{n,n}\) for \(j \in \{1, 2, 3, ..., n\}\) where \(w_{ij} = (I_{A_{\lambda_{i}}}^{f_{h_{i}}}, f_{h_{i}}^{A_{\lambda_{i}}})\), the score function pairwise judgment matrix \(S = [s_{ij}]_{n,n}\) is defined using equation 2 for each entry of matrix (Wu et al. 2013).

\[
s_{ij} = \left(I_{A_{\lambda_{i}}}^{f_{h_{i}} - f_{h_{i}}^{n}}), (f_{h_{i}}^{A_{\lambda_{i}} - f_{h_{i}}^{n}})\right)
\]

\[\text{(2)}\]

**Step 2.** To form the interval multiplicative matrix expressed as \(\tilde{M} = [\tilde{m}_{ij}]_{n,n}\) for \(j \in \{1, 2, 3, ..., n\}\), each entry of \(\tilde{m}_{ij}\) is calculated by Eq. 3 (Wu et al. 2013):

\[
\tilde{m}_{ij} = \left(\prod_{i=1}^{n} m_{ij}^{1}, m_{ij}^{n}\right)
\]

\[\text{(3)}\]

**Step 3.** To get priority vector of interval multiplicative matrix presented as \(\tilde{P}W = [\tilde{p}_{w}]_{n,n}\) for \(j \in \{1, 2, 3, ..., n\}\) where \(\tilde{p}_{w} = ((p_{w}^{1}, p_{w}^{n})\) is obtained by Eq. 4 (Wu et al. 2013):

\[
p_{w} = \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{j=1}^{n} m_{ij}}
\]

\[\text{(4)}\]

**Step 4.** To calculate possibility degree matrix as \(\tilde{P} = [\tilde{p}_{ij}]_{n,n}\) to compare each \(\tilde{p}_{w}j\) with all of \(\tilde{p}_{w}j\) with the following conditions including \(\tilde{p}_{ij} = 0, \tilde{p}_{ij} + \tilde{p}_{ji} = 1\) and \(\tilde{p}_{ij} = 1/2\) which is computed as follows (Wu et al. 2013):

\[
p(\tilde{p}_{ij} > \tilde{p}_{w}) = \min \left(\frac{\tilde{p}_{ij}}{\tilde{p}_{ij} + \tilde{p}_{w}}, \frac{\tilde{p}_{ij}}{\tilde{p}_{ij} + \tilde{p}_{w}}, \max(\tilde{p}_{ij} - \tilde{p}_{w}, 0)\right)
\]

\[\text{(5)}\]

### 2.6 Fuzzy CODAS

Combinative distance-based assessment (CODAS) method introduced by Ghorabaee et al. (2016) is considered as an efficient method to solve MCDM problems. In fact, CODAS enhances its performance through combining two distances including Euclidean and Taxicab to evaluate the rating of alternatives. Euclidean and Taxicab distances as the primary and secondary measurements are computed based on the negative-ideal point to detect desirability of an alternative. In fact, the greater distance of alternative is considered a more preferred alternative.

A fuzzy extension of CODAS method introduced by Ghorabaee et al. (2017) is taken to address uncertainty in decision-making problems through trapezoidal fuzzy numbers. In fuzzy CODAS, fuzzy-based Euclidean and Hamming distances are used. Fuzzy CODAS method is composed of nine steps as follows (Ghorabaee et al. 2017):

**Step 1.** To form the fuzzy decision matrix as \(\tilde{X} = [x_{ij}]_{m,n}\) for \(i \in \{1, 2, 3, ..., m\}\) and \(j \in \{1, 2, 3, ..., n\}\) and \(k \in \{1, 2, 3, ..., h\}\) which \(x_{ij}^{k}\) is to evaluate the fuzzy performance of \(j^{th}\) alternative with respect to \(i^{th}\) criterion by \(k^{th}\) decision maker.

**Step 2.** To calculate the fuzzy weight vector of criteria as \(\tilde{W} = [\tilde{w}_{ij}]_{1,n}\) for \(j \in \{1, 2, 3, ..., n\}\) to denote the importance of each criteria by decision makers.

**Step 3.** To get the normalized interval-valued intuitionistic fuzzy decision matrix as \(\tilde{N} = [n_{ij}]_{m,n}\).

**Step 4.** To make the fuzzy weighted normalized decision matrix as \(\tilde{R} = [\tilde{r}_{ij}]_{m,n}\) in which \(\tilde{r}_{ij}\) is computed as follows:

\[
\tilde{r}_{ij} = W_{j} \otimes \tilde{N}_{ij}
\]

\[\text{(7)}\]

**Step 5.** To obtain the fuzzy negative ideal solution as \(\tilde{NFS} = [n_{FS}]_{1,m}\) in which \(n_{FS}\) is computed as follows:

\[
n_{FS} = \min(\tilde{r}_{ij}) \text{ when } i = 1, ..., m \text{ for } j \in \{1, 2, 3, ..., n\}
\]

\[\text{(8)}\]

**Step 6.** To compute Euclidean distance (E) and Hamming distance (H) of each alternative from the fuzzy negative ideal solution using Eq. (9):

\[
E = \sqrt{\sum_{j=1}^{n} (\tilde{r}_{ij} - n_{FS})^2}
\]

\[\text{(9)}\]
Fig. 1 The structure of proposed method
\[
E_i = \sum_{j=1}^{m} E(\tilde{r}_{ij}, \tilde{n_1}) \\
H_i = \sum_{j=1}^{m} (\tilde{r}_{ij}, \tilde{n_2})
\] (9)

**Step 7.** To compute the relative assessment matrix as \(RA = [P_{ik}]_{m \times m}\) by Eq. (10)

\[
P_{ik} = (E_i - H_k) + (\zeta(E_i - E_k) \ast (H_i - H_k))
\] (10)

in which \(\zeta\) is a threshold function set by decision maker which is defined by using Eq. (11)

\[
\zeta(x) = \begin{cases} 
1 & \text{if } |x| \geq \theta \\
0 & \text{if } |x| < \theta 
\end{cases}
\] (11)

**Step 8.** To compute the assessment score of each alternative by using Eq. (12):

\[
A_{S_i} = \sum_{k=1}^{m} P_{ik} \text{ for } i \in \{1, 2, 3, \ldots, m\}
\] (12)

**Step 9.** To rank \(A_{S_i}\) for \(i \in \{1, 2, 3, \ldots, m\}\) alternatives according to descending order with considering that the highest assessment score results in the most desirable alternative.

### 3 Methodology

In this section, an extended fuzzy CODAS method integrating with fuzzy AHP using IVIF and hesitant fuzzy linguistic variables is presented to address complicated sustainable supplier selection in the supply chain management with uncertain and incomplete information. To do so, the following assumptions are made:

- A set of \(h\) decision makers \(D = \{D_1, D_2, \ldots, D_h\}\).
- A set of \(m\) possible alternatives \(A = \{A_1, A_2, \ldots, A_m\}\).
- A set of \(n\) decision criteria \(C = \{C_1, C_2, \ldots, C_n\}\).

The structure of the proposed method is given in three main phases as shown in Fig. 1. As depicted in Fig. 1, the first, second and third phases are divided into five, five and seven steps, respectively.

**First phase**

1.1. The first step is to define alternatives and assessment criteria based on previous studies. The main criteria extracted from previous studies in the field of sustainable supplier selection are divided into different groups as follows:

#### Economic criteria

These metrics refer to the service level provided by an industry to satisfy its customers’ expectations. The important economic metrics are divided into five categories including quality, price/cost, delivery time, flexibility and technology (Kannan et al. 2014, 2013; Hashemi et al. 2015; Haeri and Rezaei 2019).

#### Environmental criteria

In order to better fulfill the corporations of environmental metrics into sustainable supplier selection, environmental management system, pollution, energy consumption and recycling should be taken into account which reflects the ability of industries to protect natural resources (Hashemi et al. 2015; Rezaei et al. 2016; Govindan et al. 2013; Kannan et al. 2014; Haeri and Rezaei 2019).

#### Social criteria

This criterion is mainly assessed from two aspects including occupational health and safety, employee right and information disclosure as well as education (Haeri and Rezaei 2019; Govindan et al. 2013).

**1.2.** In this step, decision matrix should be constructed using hesitant fuzzy linguistic expression set. To do so, alternatives with respect to the predefined criteria are evaluated using hesitant linguistic expressions from linguistic variable set in Table 2. It is noted that relative weights are calculated according to the expertise, experience and backgrounds of decision makers.

In addition to assigning relative weight of alternatives with respect to each criterion, criteria relative preference to each other should be evaluated to compute their weights using linguistic variables shown in Table 3 in the second phase.

**1.3.** The linguistic terms of decision matrix for weight importance of alternatives regarding to criteria are transformed into equivalent hesitant IVIF numbers representing by \(\tilde{w}_{ij} = \left(\left[\tilde{w}_{ij}^u, \tilde{w}_{ij}^l\right], \left[\tilde{w}_{ij}^d, \tilde{w}_{ij}^t\right]\right)\) according to Table 2. Assigning IVIF value is performed to define fuzzy weight importance with emphasis on uncertainty. Moreover, importance weight of each criteria relative to each other should be converted into hesitant IVIF set based on Table 3 which is represented by \(\tilde{w}_{ij} = \left(\left[w_{ij}^u, w_{ij}^l\right], \left[w_{ij}^d, w_{ij}^t\right]\right)\).

| Linguistic variable set | IVIF numbers |
|------------------------|--------------|
| Absolutely high (AH)   | (0.85, 0.95), [0.05, 0.15] |
| Very high (VH)         | (0.75, 0.85), [0.15, 0.25] |
| High (H)               | (0.65, 0.75), [0.25, 0.35] |
| Medium high (MH)       | (0.60, 0.65), [0.35, 0.45] |
| Medium (M)             | (0.45, 0.55), [0.45, 0.55] |
| Medium low (ML)        | (0.35, 0.45), [0.55, 0.65] |
| Low (L)                | (0.25, 0.35), [0.65, 0.75] |
| Very low (VL)          | (0.15, 0.25), [0.75, 0.85] |
| Absolutely low (AL)    | (0.05, 0.15), [0.85, 0.95] |

---

Table 2 IVIF weight importance for alternatives regarding each criterion and equivalent linguistic term sets (Abdullah and Najib 2014)
It is important that these two notations including \( \tilde{x}_{ij} = (t^I_{ij}, t^U_{ij}, \{ f^I_{ij}, f^U_{ij} \}) \) and \( \tilde{w}_{ij} = (t^I_{w_{ij}}, t^U_{w_{ij}}, \{ f^I_{w_{ij}}, f^U_{w_{ij}} \}) \) are considered during the rest of paper.

Second phase After performing phase 1, the second phase including five steps is performed to define the significant value of each metric.

2.1-2.2. After forming the matrix of relative weights of criteria with each other, the associated score matrix and the interval multiplicative matrix are obtained using Eqs. 2 and 3.

2.3-2.5. We compute the priority vector and the possibility degree matrix using Eqs. 4 and 5 resulting in determining the weight of each metric through applying Eq. 6.

Third phase After performing phase 2, the third phase including seven steps is carried on.

3.1. After forming the decision matrix, the fuzzy normalized decision matrix as \( \tilde{N} = [\tilde{n}_{ij}]_{m,n} \) for \( i = 1, 2, \ldots, m \) and \( j = 1, 2, \ldots, n \) should be formed in which \( \tilde{n}_{ij} \) is determined using Eq. 13.

\[
\tilde{n}_{ij} = \left[ \frac{t^I_{ij}}{\sqrt{(\sigma^m_{j=1}(t^I_{ij})^2 + (t^U_{ij})^2)}} , \frac{t^U_{ij}}{\sqrt{(\sigma^m_{j=1}(t^I_{ij})^2 + (t^U_{ij})^2)}} \right],
\]

\[
\left[ \frac{f^I_{ij}}{\sqrt{(\sigma^m_{j=1}(f^I_{ij})^2 + (f^U_{ij})^2)}} , \frac{f^U_{ij}}{\sqrt{(\sigma^m_{j=1}(f^I_{ij})^2 + (f^U_{ij})^2)}} \right]
\]

(13)

3.2. In this step, the fuzzy weighted normalized decision matrix values of \( \tilde{R} = [\tilde{r}_{ij}]_{m,n} = w_{ij} \ast \tilde{n}_{ij} \) is developed based on Eq. 14 resulted from the integration of Eq. 7 and IVIF operators.

\[
\tilde{r}_{ij} = \left[ 1 - (1 - t^I_{ij})^{w_i} , 1 - (1 - t^U_{ij})^{w_i} \right],
\]

\[
\left[ (f^I_{ij})^{w_i} , (f^U_{ij})^{w_i} \right]
\]

(14)

3.3. The fuzzy negative ideal solution \( \tilde{N} = [\tilde{n}_{ij} \_ l_{1,m} \) is determined where \( \tilde{n}_{ij} \_ l \) is computed based on Eq. 8. In general, criteria are divided into two main groups including benefit and cost. Regarding the type of metrics, \( \tilde{n}_{ij} \_ l \) is computed as follows:

\[
\tilde{n}_{ij} = \begin{cases} 
\{ \max(t^I_{ij}) , \max(t^U_{ij}) \} & \text{when } i = 1, \ldots, m \text{ for } j \in \{ 1, 2, 3, \ldots, n \} \\
\{ \min(f^I_{ij}) , \min(f^U_{ij}) \} & \text{if criterion } j \text{ is benefit} \\
\{ \min(t^I_{ij}) , \min(t^U_{ij}) \} & \text{when } i = 1, \ldots, m \text{ for } j \in \{ 1, 2, 3, \ldots, n \} \\
\{ \max(f^I_{ij}) , \max(f^U_{ij}) \} & \text{if criterion } j \text{ is cost}
\end{cases}
\]

(15)
3.4. The Euclidean and Hamming distances of each alternative from the fuzzy negative ideal solution are calculated using Eq. 9 and the Euclidean and Hamming distances on IVIF numbers.

3.5. After getting the Euclidean and Hamming distances, the relative assessment matrix is done based on Eq. 10. Threshold function $\zeta$ is defined to measure an equal Euclidean distance between two alternatives. Moreover, threshold parameter ($\theta$) is set to 0.002. In the case of being the Euclidean distance less than $\theta$, the Hamming distance is applied to compare alternatives.

3.6. The assessment score for alternatives is computed according to Eq. 12.

3.7. In the last step, alternatives are ordered according to the decreasing values of the assessment scores calculated in the previous step.

4 An illustrative example

In this section, an illustrative example was applied to select sustainable supplier for steel mill ABC to present the proposed method. The steel mill industry plays an important role in creating employment and driving force for the growth and development of the country’s industries. After a preliminary screen, 4 possible suppliers $A = \{A_1, A_2, A_3, A_4\}$ were selected to evaluate supplying key components of steel mill. To do so, a committee of three decision makers $D = \{D_1, D_2, D_3\}$ evaluated 4 suppliers with respect to metrics shown in Fig. 2 to select the most suitable sustainable supplier. The procedure of selecting the optimal sustainable supplier was conducted in three phases.

**First phase** At first, decision makers evaluated criteria and allocated importance weight to each metric in each sub-criteria (Table 4) using linguistic variables in Table 3.

| Criteria      | C11 | C12 | C13 | C14 | C15 |
|---------------|-----|-----|-----|-----|-----|
| Economic      |     |     |     |     |     |
| Decision Makers |     |     |     |     |     |
| $D_1$         | EI  | SMI | VSMI| VSMI| VSMI|
| $D_2$         | EI  | SMI | SMI | VSMI| SMI |
| $D_3$         | EI  | SMI | SMI | VSMI| SMI |
| Environmental |     |     |     |     |     |
| Decision Makers |     |     |     |     |     |
| $D_1$         | EI  | SMI | VSMI| VSMI| VSMI|
| $D_2$         | EI  | SMI | SMI | VSMI| SMI |
| $D_3$         | EI  | SMI | SMI | VSMI| SMI |
| Social        |     |     |     |     |     |
| Decision Makers |     |     |     |     |     |
| $D_1$         | EI  |     |     |     |     |
| $D_2$         | EI  |     |     |     |     |
| $D_3$         | EI  |     |     |     |     |

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(b) Environmental Decision Makers

| Criteria | \( C_{21} \) | \( C_{22} \) | \( C_{23} \) | \( C_{24} \) |
|----------|-------------|-------------|-------------|-------------|
| \( D_2 \) | \( C_{24} \) | EI          |             |             |
| \( D_3 \) | \( C_{24} \) | EI          |             |             |

(c) Social Decision Makers

| Criteria | \( C_{31} \) | \( C_{32} \) | \( C_{33} \) |
|----------|-------------|-------------|-------------|
| \( D_1 \) | \( C_{31} \) | EI          | SMI         |
| \( D_2 \) | \( C_{31} \) | EI          | SMI         |
| \( D_3 \) | \( C_{31} \) | EI          | VSMI        |
| \( D_1 \) | \( C_{32} \) | EI          | SI          |
| \( D_2 \) | \( C_{32} \) | EI          | VSMI        |
| \( D_3 \) | \( C_{32} \) | EI          | VSSI        |
| \( D_1 \) | \( C_{33} \) | EI          |             |
| \( D_2 \) | \( C_{33} \) | EI          |             |
| \( D_3 \) | \( C_{33} \) | EI          |             |

In order to assess the rating of alternatives with respect to each criterion, decision makers used linguistic variables shown in Table 2 leading to the formation of Table 5.

After evaluating metrics and alternatives regarding criteria, linguistic variable set should be converted into IVIF format by aided of Tables 3 and 2, respectively. In the next step, it is necessary that the group of decision makers’ opinions be aggregate based on Eq. 1 to fill out the incomplete information and to aggregate decision makers’ judgments. Therefore, Table 6 resulted from Table 4 to access relative weight of attributes in different sub-criteria. Besides, Table 7 was the result of equivalent IVIF illustrated in Table 2 to show the importance of each alternative regarding each metric.

By the end of the first phase, relative weight of criteria with each other and the importance of alternatives regarding each criterion were obtained.

**Second phase**

Associated score and interval multiplicative matrix should be performed to obtain economic, environmental and social metrics.

In the next step, through getting priority vector of each metric and possibility degree matrix, normalized weight of each metric in each sub-criteria is presented in Table 8 by considering the same importance of economic, environmental and social in sustainable supplier selection.

**Third phase**

The normalized interval-valued intuitionistic fuzzy decision matrix was calculated using Eq. 13. Moreover, fuzzy normalized weight matrix was constructed using Eq. 14 which is shown in Table 9.

By computing weighted normalized decision matrix, the IVIF negative ideal solution is determined in Table 10. It was formed based on type of metrics including benefit and cost criteria which are represented in Table 8.

Therefore, Hamming and Euclidean distances were calculated for 4 alternatives. At the last step, assessment matrix

| Suppliers | Criteria | \( C_{11} \) | \( C_{12} \) | \( C_{13} \) | \( C_{14} \) | \( C_{15} \) | \( C_{21} \) | \( C_{22} \) | \( C_{23} \) | \( C_{24} \) | \( C_{31} \) | \( C_{32} \) | \( C_{33} \) |
|-----------|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \( D_1 \) | \( A_1 \) | H           | L           | VH          | ML          | M           | M           | M           | ML          | ML          | MH          | M           | M           |
| \( D_2 \) | \( A_1 \) | MH          | ML          | H           | MH          | M           | M           | M           | ML          | Between    | MH          | Between    |
| \( D_3 \) | \( A_1 \) | H           | ML          | H           | M           | M           | MH          | Between    | MH          | MH          | M           | VL          |
| \( D_1 \) | \( A_2 \) | MH          | VL          | MH          | M           | M           | MH          | M           | ML          | ML          | MH          | M           | M           |
| \( D_2 \) | \( A_2 \) | M           | L           | MH          | M           | M           | MH          | M           | MH          | M           | MH          | M           | ML          |
| \( D_3 \) | \( A_2 \) | M           | ML          | M           | M           | MH          | M           | MH          | MH          | MH          | MH          | VH          | ML          |
| \( D_1 \) | \( A_3 \) | VH          | H           | M           | MH          | ML          | M           | MH          | M           | MH          | VH          | VL          |
| \( D_2 \) | \( A_3 \) | M           | MH          | ML          | M           | MH          | ML          | M           | VH          | H           | ML          |
| \( D_3 \) | \( A_3 \) | M           | ML          | ML          | M           | L           | MH          | M           | VH          | MH          |
| \( D_1 \) | \( A_4 \) | At least H  | M           | M           | MH          | L           | L           | M           | Between    | H           | L           |
| \( D_2 \) | \( A_4 \) | VH          | M           | M           | ML          | L           | L           | M           | H           | ML          | VH          | H           |
| \( D_3 \) | \( A_4 \) | MH          | ML          | between H  | –           | MH          | ML          | –           | H           | MH          | VH          | H           | ML          |
Table 6  IVIF relative weight of each metric with others in different sub-criteria assigned by decision makers

(a) Economic Criteria

| Criteria | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ |
|----------|----------|----------|----------|----------|----------|
| $C_{11}$ | (0.378, 0.417], [0.222, 0.583]) | (0.317, 0.617], [0.083, 0.383]) | (0.393, 0.655], [0.082, 0.345]) | (0.522, 0.722], [0.0728, 0.278]) | (0.393, 0.655], [0.082, 0.345]) |
| $C_{12}$ | (0.083, 0.383], [0.317, 0.617]) | (0.378, 0.417], [0.222, 0.583]) | (0.393, 0.655], [0.082, 0.345]) | (1, 1], [0, 0]) | (0.317, 0.617], [0.083, 0.383]) |
| $C_{13}$ | (0.082, 0.350], [0.374, 0.650]) | (0.082, 0.350], [0.374, 0.650]) | (0.378, 0.417], [0.222, 0.583]) | (0.317, 0.617], [0.083, 0.383]) | (0.393, 0.655], [0.082, 0.345]) |
| $C_{14}$ | (0.078, 0.278], [0.522, 0.722]) | (0.034, 0.103], [0.826, 0.897]) | (0.083, 0.383], [0.317, 0.617]) | (0.378, 0.417], [0.222, 0.583]) | (0.393, 0.655], [0.082, 0.345]) |
| $C_{15}$ | (0.081, 0.350], [0.375, 0.650]) | (0.083, 0.383], [0.317, 0.617]) | (0.081, 0.350], [0.375, 0.650]) | (0.081, 0.350], [0.375, 0.650]) | (0.378, 0.417], [0.222, 0.583]) |

(b) Environmental Criteria

| Criteria | $C_{21}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ |
|----------|----------|----------|----------|----------|
| $C_{21}$ | (0.378, 0.417], [0.222, 0.583]) | (0.133, 0.533], [0.067, 0.467]) | (0.461, 0.690], [0.080, 0.310]) | (1, 1], [0, 0]) |
| $C_{22}$ | (0.067, 0.467], [0.133, 0.533]) | (0.378, 0.417], [0.222, 0.583]) | (0.166, 0.442], [0.049, 0.558]) | (0.566, 0.748], [0.069, 0.252]) |
| $C_{23}$ | (0.080, 0.315], [0.442, 0.685]) | (0.061, 0.558], [0.110, 0.442]) | (0.378, 0.417], [0.222, 0.583]) | (0.246, 0.425], [0.077, 0.575]) |
| $C_{24}$ | (0.043, 0.150], [0.732, 0.850]) | (0.070, 0.276], [0.499, 0.724]) | (0.090, 0.574], [0.238, 0.426]) | (0.378, 0.417], [0.222, 0.583]) |

(c) Social Criteria

| Criteria | $C_{21}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ |
|----------|----------|----------|----------|----------|
| $C_{21}$ | (0.378, 0.417], [0.222, 0.583]) | (0.133, 0.533], [0.067, 0.467]) | (0.461, 0.690], [0.080, 0.310]) | (1, 1], [0, 0]) |
| $C_{22}$ | (0.067, 0.467], [0.133, 0.533]) | (0.378, 0.417], [0.222, 0.583]) | (0.166, 0.442], [0.049, 0.558]) | (0.566, 0.748], [0.069, 0.252]) |
| $C_{23}$ | (0.080, 0.315], [0.442, 0.685]) | (0.061, 0.558], [0.110, 0.442]) | (0.378, 0.417], [0.222, 0.583]) | (0.246, 0.425], [0.077, 0.575]) |
| $C_{24}$ | (0.043, 0.150], [0.732, 0.850]) | (0.070, 0.276], [0.499, 0.724]) | (0.090, 0.574], [0.238, 0.426]) | (0.378, 0.417], [0.222, 0.583]) |
and scores were obtained based on Table 11 in order to rank 4 alternatives.

As shown in Table 11, alternative $A_2$ has been selected as the most appropriate sustainable supplier selection due to considering its superior importance of environmental criteria including environmental management system, energy consumption and recycling as well as price from economic criteria. Moreover, it provides relative strong efficiency on social criteria including information disclosure and education followed by alternative $A_4$. Although alternative $A_2$ presents poor impact on quality and flexibility of economic metrics, it is selected as the best sustainable supplier selection owing to high importance of sustainable criteria.

It is also clear that although alternative $A_3$ highlights the superior importance on most of economic criteria in terms of delivery time, flexibility and technology, its importance on environmental and social metrics is weak. Thus, alternative $A_3$ is considered as the last alternative for sustainable supplier selection.

In order to make validation of the proposed method, its results are compared with different methods including IVIF TOPSIS, IVIF VIKOR, fuzzy CODAS shown in Fig. 3.

Moreover, Table 12 indicates the ranking similarity for different methods. It shows that the Spearman’s rank correlation coefficient values of IVIF CODAS and TOPSIS are similar to each other. It is due to the fact that both methods are based on the distance of each alternative from the worst condition of alternatives(anti-ideal solution) for all criteria. However, the similarity ranking value between IVIF CODAS and IVIF VIKOR is located in the low level. Furthermore, since distance each alternative from the best condition of alternatives (ideal solution) for all criteria is considered for calculating utility and regret measurements in IVIF method which is the opposite condition of CODAS and TOPSIS methods, IVIF

| Table 7 | Aggregated IVIF weights for each alternative regarding each metric |
| Criteria | Alternatives | $A_1$ | $A_2$ | $A_3$ | $A_4$ |
|----------|--------------|-------|-------|-------|-------|
| $C_{11}$ | ([0.62, 0.72], [0.28, 0.38]) | ([0.49, 0.59], [0.41, 0.51]) | ([0.58, 0.69], [0.31, 0.42]) | ([0.70, 0.81], [0.19, 0.30]) |
| $C_{12}$ | ([0.32, 0.42], [0.58, 0.68]) | ([0.25, 0.35], [0.65, 0.75]) | ([0.53, 0.64], [0.36, 0.47]) | ([0.42, 0.52], [0.48, 0.58]) |
| $C_{13}$ | ([0.69, 0.79], [0.21, 0.31]) | ([0.52, 0.62], [0.38, 0.48]) | ([0.38, 0.49], [0.51, 0.61]) | ([0.51, 0.62], [0.38, 0.49]) |
| $C_{14}$ | ([0.46, 0.56], [0.44, 0.54]) | ([0.45, 0.55], [0.45, 0.55]) | ([0.49, 0.59], [0.41, 0.51]) | ([0.46, 0.56], [0.45, 0.55]) |
| $C_{15}$ | ([0.45, 0.55], [0.45, 0.55]) | ([0.49, 0.59], [0.41, 0.51]) | ([0.52, 0.62], [0.38, 0.48]) | ([0.37, 0.47], [0.53, 0.63]) |
| $C_{21}$ | ([0.49, 0.59], [0.41, 0.51]) | ([0.52, 0.62], [0.38, 0.48]) | ([0.28, 0.38], [0.62, 0.72]) | ([0.28, 0.38], [0.62, 0.72]) |
| $C_{22}$ | ([0.39, 0.49], [0.51, 0.61]) | ([0.56, 0.66], [0.34, 0.44]) | ([0.46, 0.56], [0.44, 0.54]) | ([0.45, 0.55], [0.45, 0.55]) |
| $C_{23}$ | ([0.62, 0.72], [0.28, 0.38]) | ([0.42, 0.52], [0.48, 0.55]) | ([0.49, 0.59], [0.41, 0.51]) | ([0.65, 0.75], [0.25, 0.35]) |
| $C_{24}$ | ([0.38, 0.49], [0.51, 0.62]) | ([0.53, 0.64], [0.36, 0.47]) | ([0.42, 0.52], [0.48, 0.58]) | ([0.46, 0.56], [0.44, 0.54]) |
| $C_{31}$ | ([0.55, 0.65], [0.35, 0.45]) | ([0.59, 0.69], [0.31, 0.41]) | ([0.70, 0.80], [0.20, 0.30]) | ([0.71, 0.82], [0.18, 0.29]) |
| $C_{32}$ | ([0.45, 0.55], [0.45, 0.55]) | ([0.49, 0.59], [0.41, 0.51]) | ([0.66, 0.76], [0.24, 0.34]) | ([0.65, 0.75], [0.25, 0.35]) |
| $C_{33}$ | ([0.29, 0.40], [0.60, 0.71]) | ([0.29, 0.39], [0.61, 0.71]) | ([0.22, 0.32], [0.68, 0.78]) | ([0.35, 0.46], [0.54, 0.55]) |

| Table 8 | Normalized weight of different metrics |
| Criteria | Type | Weight |
|----------|------|-------|
| $C_{11}$ | B | 0.090 |
| $C_{12}$ | C | 0.078 |
| $C_{13}$ | C | 0.064 |
| $C_{14}$ | B | 0.053 |
| $C_{15}$ | B | 0.048 |
| $C_{21}$ | B | 0.072 |
| $C_{22}$ | C | 0.116 |
| $C_{23}$ | C | 0.087 |
| $C_{24}$ | B | 0.058 |
| $C_{31}$ | B | 0.124 |
| $C_{32}$ | C | 0.118 |
| $C_{33}$ | B | 0.091 |
In the context of sustainable supply chain management, sustainable supplier selection is considered as the main field that influences on the entire operational activities of a company. Since qualitative and quantitative criteria directly affect on the performance of the overall supply chain, the main contribution of paper is to propose a multi-criteria extended intuitionistic fuzzy CODAS approach integrated with fuzzy AHP. Furthermore, the extended fuzzy codas integrating with IVIF and hesitation linguistic set captures imprecise, uncertain, and incomplete information associated with sustainable supplier selection. The proposed model was classified into different phases including a. definition of criteria according to aggregation of the important metrics from customers’ and managers’ viewpoints which affects sustainable supplier selection process, b. extraction of the perceptions of decision makers using IVIF and hesitation linguistic representation to deal with incomplete information and uncertainty and vagueness of decision makers’ judgment, c. definition of the weights of selected criteria with the aid of AHP method integrating with interval-valued intuitionistic fuzzy uncertain linguistic set, d. identification of the order allocation of sustainable supplier selection based on integrating IVIF and fuzzy CODAS technique by a group of decision makers. Finally, a steel mill is provided to illustrate the capability of the proposed method. The results show that using IVIF could select the most appropriate supplier selection with respect to the effective criteria. For instance, in spite of low economic criteria for supplier $A_2$, it has been selected as the best supplier selection because of high consideration to environmental and social criteria. Furthermore, the results show that IVIF can be utilized as an effective method to select the most appropriate supplier with respect to the outlined criteria.

Table 9 Fuzzy normalized weighted decision matrix

| Criteria | Alternatives | $A_1$ | $A_2$ | $A_3$ | $A_4$ |
|----------|--------------|-------|-------|-------|-------|
| $C_{11}$ | (0.036, 0.044), [0.889, 0.914] | (0.027, 0.034), [0.921, 0.939] | (0.033, 0.041), [0.897, 0.922] | (0.042, 0.051), [0.857, 0.894] |
| $C_{12}$ | (0.022, 0.031), [0.922, 0.934] | (0.017, 0.025), [0.930, 0.940] | (0.042, 0.053), [0.889, 0.906] | (0.031, 0.040), [0.908, 0.922] |
| $C_{13}$ | (0.033, 0.040), [0.893, 0.916] | (0.024, 0.029), [0.927, 0.941] | (0.017, 0.022), [0.945, 0.956] | (0.023, 0.029), [0.928, 0.942] |
| $C_{14}$ | (0.020, 0.025), [0.942, 0.952] | (0.019, 0.025), [0.942, 0.952] | (0.021, 0.027), [0.938, 0.949] | (0.020, 0.025), [0.942, 0.952] |
| $C_{15}$ | (0.018, 0.023), [0.947, 0.956] | (0.019, 0.024), [0.943, 0.953] | (0.021, 0.026), [0.939, 0.950] | (0.014, 0.019), [0.954, 0.962] |
| $C_{16}$ | (0.033, 0.042), [0.907, 0.921] | (0.036, 0.045), [0.902, 0.917] | (0.018, 0.025), [0.933, 0.943] | (0.018, 0.025), [0.933, 0.943] |
| $C_{17}$ | (0.035, 0.046), [0.890, 0.909] | (0.054, 0.067), [0.849, 0.875] | (0.042, 0.054), [0.875, 0.896] | (0.042, 0.053), [0.877, 0.898] |
| $C_{18}$ | (0.039, 0.047), [0.881, 0.905] | (0.024, 0.031), [0.924, 0.939] | (0.029, 0.036), [0.912, 0.929] | (0.041, 0.049), [0.873, 0.893] |
| $C_{19}$ | (0.048, 0.052), [0.942, 0.952] | (0.027, 0.034), [0.924, 0.937] | (0.020, 0.026), [0.939, 0.949] | (0.022, 0.028), [0.934, 0.945] |
| $C_{20}$ | (0.048, 0.055), [0.887, 0.915] | (0.043, 0.052), [0.875, 0.906] | (0.053, 0.063), [0.827, 0.872] | (0.054, 0.065), [0.819, 0.866] |
| $C_{21}$ | (0.034, 0.043), [0.896, 0.918] | (0.037, 0.047), [0.887, 0.910] | (0.054, 0.065), [0.830, 0.867] | (0.053, 0.064), [0.836, 0.870] |
| $C_{22}$ | (0.032, 0.046), [0.902, 0.915] | (0.031, 0.045), [0.903, 0.915] | (0.023, 0.036), [0.911, 0.923] | (0.040, 0.055), [0.893, 0.907] |

Table 10 The IVIF negative ideal

| Criteria | IVIF negative ideal |
|----------|---------------------|
| $C_{11}$ | (0.027, 0.034), [0.921, 0.939] |
| $C_{12}$ | (0.042, 0.053), [0.899, 0.906] |
| $C_{13}$ | (0.033, 0.040), [0.893, 0.916] |
| $C_{14}$ | (0.019, 0.025), [0.942, 0.952] |
| $C_{15}$ | (0.014, 0.019), [0.954, 0.962] |
| $C_{16}$ | (0.018, 0.025), [0.933, 0.943] |
| $C_{17}$ | (0.054, 0.067), [0.849, 0.875] |
| $C_{18}$ | (0.041, 0.049), [0.873, 0.899] |
| $C_{19}$ | (0.018, 0.024), [0.942, 0.952] |
| $C_{20}$ | (0.040, 0.049), [0.887, 0.915] |
| $C_{21}$ | (0.054, 0.065), [0.830, 0.867] |
| $C_{22}$ | (0.023, 0.036), [0.911, 0.923] |

Table 11 Assessment matrix, appraisal score and rank of 4 alternatives

| $A_1$ | $A_2$ | $A_3$ | $A_4$ | Appraisal Score | Rank |
|-------|-------|-------|-------|-----------------|------|
| 0     | 0     | 0     | 0     | −0.0528         | 0    | 0.0292 | 0.0072 | −0.0308 | 3     |
| 0.0528| 0     | 0.0820| 0.0456| 0.1804          | 1    |
| −0.0292| 0 | −0.0820| 0     | −0.0364         | 4    |
| 0.0072| −0.0456| 0.0364| 0     | −0.0020         | 2    |

VIKOR represents low value for similarity value to IVIF CODAS method.

It is also shown that fuzzy CODAS is similar with IVIF CODAS. However, considering interval value for belonging and non-belonging to each set makes precise results for ranking alternatives.
For instance, despite the poor performance of supplier A2 in economic criteria, this supplier has been chosen as the best supplier due to its highly rated performance in environmental and social criteria. Furthermore, the results show that there is a similar ranking between IVIF CODAS and TOPSIS values (100%) because they are both anti-ideal solution-based methods. In fact, they are based on the calculation of the distance of each alternative from the worst condition of all alternatives. However, the similarity between ranking of alternatives for IVIF CODAS and IVIF VIKOR (25%) is not considerable. It is due to the fact that IVIF VIKOR considers distance of each alternative from the best condition of all alternatives (ideal solution). Moreover, IVIF CODAS enhances accuracy compared to fuzzy CODAS since IVIF determines belonging and non-belonging of each set. In the future, CODAS method has been integrated with interval type-2 intuitionistic fuzzy (IT2IF) logic to present the comparison of IT2IF CODAS performance with IVIF CODAS. Furthermore, we apply mechanical learning techniques to extend the proposed method for sustainable supplier selection.

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