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ORIGINAL ARTICLE

Intuitionistic fuzzy TOPSIS for ergonomic compatibility evaluation of advanced manufacturing technology

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Abstract Advanced manufacturing technology (AMT) is considered one of the most critical elements in the industrial world to achieve efficiency, productivity, and competitiveness. Evaluation and selection of AMT is a complex problem that involves multiple attributes that are difficult to be taken into account in their totality. In this matter, actual models for AMT evaluation and selection are found scarce of human factors and ergonomics aspects which are commonly neglected among evaluators or decision makers. This paper presents a fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) decision-making model under intuitionistic fuzzy environment that is used for the evaluation of AMT regarding ergonomic compatibility attributes. The methodology includes the description of the ergonomic compatibility attributes and an intuitionistic fuzzy TOPSIS (IFT) procedure applied for a novel evaluation approach of these attributes to support the evaluation and selection of AMT alternatives. As a result, a numerical example is presented for the evaluation and selection of three alternatives of computer numerical controlled milling machines. IFT presents advantages since multiple ergonomic attributes can be effectively integrated when incomplete or vague information is available for evaluators or decision makers.

Keywords Ergonomic compatibility attributes · Intuitionistic fuzzy TOPSIS · AHP · Advanced manufacturing technology

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1 Introduction

Advanced manufacturing technology (AMT) has brought major changes in manufacturing systems in the world's industrial scenery. It is considered one of the main elements towards efficiency and competitiveness of enterprises. It generally includes computer numerical controlled (CNC) equipment, computer-aided design/computer-aided manufacturing (CAD/CAM), flexible manufacturing systems (FMS), robotics, rapid prototyping, environmentally sustainable technologies, etc. [1, 2]. Aiming to optimize manufacturing systems, AMT selection plays an important role in decision making in industries around the world, but an enhanced human–AMT interaction and involvement is also a significant issue [3]. Nowadays, the determination of the best alternative available for AMT implies a large amount of information and uncertainty; decision makers (DMs) continuously deal with the problem of evaluating and selecting equipment among a wide variety of alternatives. Additionally, this involves multiple attributes and conflicting criterion. AMT has been broadly used in modern industries worldwide, and there are evaluation tools and models available to support equipment selection processes even though the publications on this matter are limited [3, 4]. Distinguished authors recognized that AMT's management and decision making constitute a complex problem that involves multiple aspects, which are sometimes difficult to consider in their totality and that it has become a complicated task [5–8]. In this way, evaluation models regarding planning and selection of AMT equipment are found to be scarce of adequate and desirable human factors and ergonomics (HFE) aspects (attributes) and their importance is underestimated among DMs, evaluators, and decision-making models (DMM). Therefore, this paper aims to present an approach that is used to evaluate AMT taking into account in a unique form ergonomic compatibility attributes based on an intuitionistic fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) decision-making model. A numerical example is presented using the approach; in this case, DM faced the problem of selecting CNC milling machines among three alternatives for an AMT training center. It is important for DMs to consider ergonomic and safety aspects as well as economic and technological ones. An ergonomic compatibility survey developed by Maldonado et al. [8, 9] is applied in order to measure the ergonomic compatibility (EC) of these artifacts. Additionally, a fuzzy TOPSIS model under intuitionistic fuzzy sets is used originally to obtain the relative closeness coefficient closeness coefficient (CC) in support of the evaluation or ergonomic compatibility attributes for AMT; the alternative which has the maximum CC is selected as the best for this purpose. The paper is organized as follows. In Section 2, the literature review is presented. Then, the proposed method is explained. In Section 4, results are shown for a numerical example on the evaluation and selection among three models of CNC milling machines. Finally, Section 5 presents the conclusions derived of the study.

2 Literature review

The notions of the theory of fuzzy set were introduced by Zadeh in 1965 [10]. Later on, several works related with fuzzy decision-making problems have been published by applying fuzzy set theory on a broad variety of cases revealing an effective manner to manage human perception like experts' evaluations and opinions among other information where vagueness and imprecise knowledge is obtainable. For instance, some authors have developed a model for equipment selection in a manufacturing system by using fuzzy set theory [4]. Similarly, there are several studies that presented a hybrid of fuzzy set theory with other methodologies such as axiomatic design for a large variety of decision-making problems [5, 11–17]. In addition, fuzzy set theory has been combined with other decision-making techniques such as analytic hierarchical process (AHP). Some works may be found in [7, 18, 19]. Likewise, fuzzy set theory has been used with TOPSIS methodology; related papers are presented in [15, 18–20]. Moreover, several publications that involve the use of fuzzy multiple attribute decision making approaches for selection issues have reported advantages about the effective consideration of vague and incomplete information and the combination of tangible and intangible attributes [1, 21–28].

In 1986, Atanassov introduced, for the first time, the concept of intuitionistic fuzzy sets (IFS) as a generalization of the notion of fuzzy set [29]. In recent years, a large variety of literature for the theory and applications of IFS has been developed. For instance, Szmidt and Kacprzyk presented the use of IFS in some medical applications [30]. Equally, Khatibi and Montazer showed a work in which IFS were used for the detection of intestinal bacteria [31]. Similarly, IFS have been mainly applied to oriented multiattribute evaluation and decision-making problems focusing on AMT selection, supplier selection, equipment selection, equipment performance evaluation, etc. Recent publications about this matter may be found in [28–44]. What these papers have in common is that they have incorporated quantitative attributes in the evaluation of AMT such as cost, time, precision, velocity, reliability, and some other measurements of performance; also, they have integrated qualitative attributes such as reliability, flexibility, and quality improvement. Unlike previous works, the uniqueness of this paper entails the consideration of ergonomic compatibility attributes for the evaluation of AMT under fuzzy environment.

3 Intuitionistic fuzzy sets

A fuzzy set A in $X=\{x\}$ is given by

$$A = \{\langle x, \mu_A(x)\rangle | x \in X\}$$

Where $\mu_A : X \to [0,1]$ is the membership function of the fuzzy set A; $\mu_A(x) \in [0,1]$ is the membership of $x \in X$ in A.

An IFS is proposed by means of two functions expressing the degree of membership and nonmembership of an element x to the set A.

An intuitionistic fuzzy set A in $X=\{x\}$ is defined with the form

$$A = \{\langle x, \mu_A(x), \upsilon_A(x)\rangle | x \in X\}$$

where $\mu_A : X \to [0,1]$; $\upsilon_A : X \to [0,1]$ with the condition

$$0 \le \mu_A(x) + \upsilon_A(x) \le 1 \quad \forall x \in X.$$

The numbers $x, \mu_A(x), \upsilon_A(x) \in [0,1]$ denote respectively the degree of membership and degree of nonmembership of the element x to the set A.

The number

$$\pi_A(x) = 1 - \mu_A(x) - \upsilon_A(x)$$

is called the intuitionistic index of x in A. It is a measure of hesitancy degree of the element x in the set A. It is obvious that $0 \le \pi_A(x) \le 1$ for each $x \in X$.

Hence, an IFS A in $X=\{x\}$ is fully defined with the form

$$A = \{\langle x, \mu_A(x), \upsilon_A(x), \pi_A(x)\rangle | x \in X\}$$

where $\mu_A: X \rightarrow [0,1]; \upsilon_A: X \rightarrow [0,1]$ $\pi_A: X \rightarrow [0,1]$.

4 Methods

The methodology includes the description of the multiple ergonomic compatibility attributes required for AMT evaluation based on the literature and the ergonomic compatibility evaluation model (ECEM) model, and a unique application of fuzzy TOPSIS model under IFS for the evaluation of these attributes.

4.1 Ergonomic compatibility attributes

This section describes the ergonomic compatibility attributes involved in the evaluation of AMT.

4.1.1 Ergonomic compatibility attributes

Ergonomic evaluation of AMT presents difficulties since ergonomic compatibility requirements (attributes) are multiple and are not precisely determined; in addition, it involves the evaluation of multiple quantitative and qualitative aspects. The complexity and vagueness involved makes a problem hard to solve. In the ECEM, ergonomic compatibility attributes are determined from an extensive literature review presented in Maldonado et al. [8, 9, 17] and generally based on ergonomic guidelines for machine design proposed by Corlett and Clark [45]. They are divided into attributes that can be both intangible and tangible. Additionally, on some ergonomic compatibility attributes of the design, it would be ergonomically desirable to maximize its adaptability (positive influence) and maximum values are desirable in the linguistic scale in which case are "benefit" attributes; all of them are intangible. Conversely, the ones which minimize its exposure (negative influence) is ergonomically desirable and minimum values in the linguistic scale will be wanted in which the case are "cost" attributes; all of them are tangible. Attributes are explained in Appendix Table 10. These attributes are human skills compatibility (B1), training compatibility (B2), access to machine and clearances (B3), horizontal and vertical reach zones (B4), adjustability of design (B5), postural comfort of design (B6), physical work and endurance related to the design (B7), controls' design compatibility (B8), controls' physical distribution (B9), visual work space design (B10), information load (B11), error tolerance (B12), man–machine functional allocation (B13), design for maintainability (B14), temperature (B15), vibration (B16), noise (B17), residual materials (B18), compatibility with rate of work (B19), and compatibility with job content (B20). All attributes are benefit attributes excluding (B7, B15, B16, B17, and B18).

4.2 Weighting attributes by analytic hierarchy process

When multiple attributes are taken into account in decision-making problems, a hierarchical structure is a convenient manner of solving it by the assignation of the relative importance of these attributes. This variety of problems is solved effectively by AHP, which is a broadly used multicriteria decision-making method. According to Saaty [46], this method was created to formalize the intuitive understanding of a complex problem using a hierarchical structure. Also, it allows handling qualitative and quantitative data; it helps to acquire expert's knowledge through their opinions using pair-wise comparisons, decomposition, and the priority vector creation and synthesis. This method deals with the priority weights with respect to many items and proposed to determine the priority weight for each item in selecting an alternative. Using AHP, pairwise comparisons are made by means of a preference scale, which assign numerical values to different levels of preference [47]. The standard scale used for AHP is 1–9 scale, where the value 9 indicates that one factor is extremely more important than the other and the value 1/9 indicates that one factor is extremely less important than the other; in other words, reciprocal [48]. Ratio scale and employing of verbal comparisons are used for weighting quantifiable and nonquantifiable elements [49]. AHP is a decision aid to help solve unstructured problems in economics, social, and management sciences; it has been applied in a variety of contexts [49, 50]. In this paper, the method was applied novelty to assign weight to multiple ergonomic compatibility attributes for AMT included in the ECEM proposed by Maldonado and Maldonado et al. [8, 9, 17].

4.3 Intuitionistic fuzzy set TOPSIS procedure

The procedure of the proposed method is described in the following steps:

- Step 1 Determine the alternatives to consider in the evaluation. Where $A_i=\{1,2,\ldots,n\}$ is the number of alternatives.
- Step 2 Determine the attributes to evaluate, establishing the EFRs. Where $B_i=\{1,2,\ldots,m\}$ is the number of attributes.
- Step 3 Constitute the group of experts. Where $E_k=\{1,2,\ldots,p\}$ is the number of experts. Assign a weight to each expert where $W_E = \{w_{E_1}, w_{E_2}, \ldots, w_{E_K}\}$ and $\sum_{k=1}^{p} w_{E_k} = 1$.
- Step 4 Aggregate experts' opinions about the importance of each attribute by obtaining its correspondent weight

Table 1 Linguistic terms for rating alternatives

Linguistic term Intangible/tangible	IFS
Poor (P)/Very Low (VL)	<0.25, 0.60>
Regular (R)/Low (L)	<0.50, 0.40>
Good (G)/Medium (M)	<0.70, 0.20>
Very good (VG)/High (H)	<0.80, 0.10>
Excellent (E)/Very High (VH)	<1.0, 0.0>

from pairwise comparisons of Analytical Hierarchical Process (AHP) methodology and using the geometric mean.

$$W_B = \left(w_{B_1}, w_{B_2}, \ldots, w_{B_j}\right)^{\frac{1}{j}} \tag{1}$$

For this step, the procedure is as follows. According to Entani et al. [51], for m attributes, a decision maker compares a pair of attributes for all possible pairs then a comparison matrix A can be obtained.

$$A = \left[a_{ij}\right] = \begin{pmatrix} 1 & \cdots & a_{1m} \\ \vdots & a_{1m} & \vdots \\ a_{1m} & \cdots & 1 \end{pmatrix} \tag{2}$$

Where a_{ij} shows the priority ratio of attribute i comparing to attribute j. The decision maker gives $m(m-1)/2$ pair-wise comparisons in case of m attributes.

From the given comparison matrix, the priority weights w_{ij} are obtained by the eigenvector method. For this problem, the procedure is as follows:

$$Aw = \lambda w \tag{3}$$

Where λ is an eigenvalue and w is a corresponding eigenvector. By (3), the eigenvector $w = (w_1, \ldots w_n)^t$ corresponding to the principal

Table 2 CNC milling machine alternatives

Alternative	CNC milling machines
X	Bridgeport/EZ vision monitor
Y	Kent/Acurite
Z	Smithy CNC 622 bed mill

Table 3 Weights per sub-attribute

A	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
W_B	0.097	0.1651	0.0499	0.0312	0.0475	0.0303	0.0191	0.0258	0.035	0.0392

A	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
W_B	0.0783	0.0640	0.0471	0.0286	0.0192	0.0296	0.0502	0.0322	0.05	0.07

Table 4 Aggregated intuitionistic fuzzy decision matrix

Alternative Attribute	*X*	*Y*	*Z*
B1	<0.7750, 0.1250>	<0.7250, 0.1750>	<0.5938, 0.3000>
B2	<0.7375, 0.1625>	<0.5125, 03750>	<0.6938, 0.2125>
B3	<0.7625, 0.1500>	<0.7625, 0.1500>	<0.7688, 0.1500>
B4	<0.7375, 0.1750>	<0.7375, 0.1750>	<0.6938, 0.2125>
B5	<0.7500, 0.1625>	<0.7375, 0.1750>	<0.6813, 0.2250>
B6	<0.6813, 0.2375>	<0.6813, 0.2375>	<0.6563, 0.2500>
B7	<0.6000, 0.3000>	<0.6000, 0.3000>	<0.5250, 0.3750>
B8	<0.6875, 0.2125>	<0.6625, 0.2375>	<0.5563, 0.3500>
B9	<0.6563, 0.2500>	<0.6438, 0.2625>	<0.6813, 0.2250>
B10	<0.7125, 0.1875>	<0.7125, 0.2000>	<0.7313, 0.1875>
B11	<0.6875, 0.2125>	<0.6250, 0.2750>	<0.7625, 0.1625>
B12	<0.6313, 0.2625>	<0.6438, 0.2500>	<0.7438, 0.1750>
B13	<0.6750, 0.2250>	<0.6500, 0.2500>	<0.7000, 0.2000>
B14	<0.6375, 0.2625>	<0.6625, 0.2375>	<0.6938, 0.2000>
B15	<0.5250, 0.3625>	<0.5250, 0.3625>	<0.4813, 0.4000>
B16	<0.5188, 0.3750>	<0.5438, 0.3500>	<0.5813, 0.3125>
B17	<0.6375, 0.2625>	<0.6625, 0.2375>	<0.6250, 0.2750>
B18	<0.6375, 0.2625>	<0.6375, 0.2625>	<0.5813, 0.3125>
B19	<0.6875, 0.2250>	<0.6875, 0.2250>	<0.7250, 0.1875>
B20	<0.7125, 0.2000>	<0.6875, 0.2250>	<0.7625, 0.1500>

eigenvalue λ_{max} is obtained as the weight vector. The sum of the obtained weights is normalized to be one: $\sum_i w_{i=}1$. These weights obtained from the given comparison matrix reveal decision-maker's attitude in the actual problem.

When several decision makers emit their opinions using AHP, the geometric means are obtained from (4); the values contained in the final decision matrixes are used as the final weights for each attribute.

$$a_{ijT} = \left(a_{ij1} \times a_{ij2} \times a_{ij3} \times \ldots.. \times a_{ijm}\right)^{1/m} \tag{4}$$

Table 5 Ratings of attribute B1 given by experts

Expert	B1	IFS
1	P	<0.25, 0.60>
2	R	<0.50, 0.40>
3	R	<0.50, 0.40>
4	VG	<0.80, 0.10>
5	R	<0.50, 0.40>
6	VG	<0.80, 0.10>
7	G	<0.70, 0.20>
8	G	<0.70, 0.20>

Table 6 Aggregated weighted intuitionistic fuzzy decision matrix

Alternative Attribute	*X*	*Y*	*Z*
B1	<0.0751, 0.0121>	<0.0703, 0.0170>	<0.0576, 0.0291>
B2	<0.1217, 0.0268>	<0.0846, 0.0619>	<0.1145, 0.0351>
B3	<0.0380, 0.0075>	<0.0380, 0.0075>	<0.0383, 0.0075>
B4	<0.0230, 0.0055>	<0.0230, 0.0055>	<0.0216, 0.0066>
B5	<0.0356, 0.0077>	<0.0351, 0.0083>	<0.0324, 0.0107>
B6	<0.0206, 0.0072>	<0.0206, 0.0072>	<0.0199, 0.0076>
B7	<0.0114, 0.0057>	<0.0114 0.0057>	<0.0100, 0.0071>
B8	<0.0177, 0.0055>	<0.0171, 0.0061>	<0.0143, 0.0090>
B9	<0.0230, 0.0087>	<0.0225, 0.0092>	<0.0238, 0.0079>
B10	<0.0279, 0.0073>	<0.0279, 0.0078>	<0.0286, 0.0073>
B11	<0.0538, 0.0166>	<0.0489, 0.0215>	<0.0596, 0.0127>
B12	<0.0403, 0.0168>	<0.0411, 0.0160>	<0.0475, 0.0112>
B13	<0.0318, 0.0106>	<0.0306, 0.0118>	<0.0329, 0.0094>
B14	<0.0182, 0.0075>	<0.0190, 0.0068>	<0.0199, 0.0057>
B15	<0.0100, 0.0069>	<0.0100, 0.0069>	<0.0092, 0.0076>
B16	<0.0153, 0.0111>	<0.0161, 0.0103>	<0.0172, 0.0092>
B17	<0.0320, 0.0132>	<0.0333, 0.0119>	<0.0314, 0.0138>
B18	<0.0205, 0.0084>	<0.0205, 0.0084>	<0.0187, 0.0101>
B19	<0.0342, 0.0112>	<0.0342, 0.0112>	<0.0361, 0.0093>
B20	<0.0500, 0.0140>	<0.0483, 0.0158>	<0.0535, 0.0105>

Step 5 Construct the IFS decision matrix representing the rating of the alternatives A_i based on the opinions of experts. Linguistic terms are used to rate each alternative as shown in Table 1.

Once every expert has rated every alternative, the next step is to aggregate every opinion to construct the aggregated IFS decision matrix by using a general intuitionistic fuzzy-weighted arithmetic mean (IFWAM) [29] operator with weighting vector W_{E_k} , where W_{E_k} represents the weight associated with every expert, and $\sum_{k=1}^{p} W_{E_k} = 1$.

$$\text{IFWAM}_A = \left\langle \sum\nolimits_{k=1}^{P} W_{E_k}\mu_k, \sum\nolimits_{k=1}^{P} W_{E_k}\upsilon_k, \right\rangle \tag{5}$$

Step 6 Construct the aggregated weighted IFS decision matrix by using the weight vector obtained in step 4.

$$Z = W_B^T \otimes \widetilde{D} = W_B^T \otimes \left\langle \widetilde{\mu}_{ij}, \widetilde{\upsilon}_{ij} \right\rangle = \left\langle \widehat{\mu}_{ij}, \widehat{\upsilon}_{ij} \right\rangle \tag{6}$$

Step 7 Determine intuitionistic fuzzy positive ideal alternative, A^+, and intuitionistic fuzzy negative ideal alternative, A^-.

Table 7 Intuitionistic fuzzy positive and fuzzy negative ideal alternative per sub-attribute

Alternative Attribute	A^+	A^-
B1	<0.0751, 0.0121>	<0.0576, 0.0291>
B2	<0.1217, 0.0268>	<0.0846, 0.0619>
B3	<0.0383, 0.0075>	<0.0380, 0.0075>
B4	<0.0230, 0.0055>	<0.0216, 0.0066>
B5	<0.0356, 0.0077>	<0.0324, 0.0107>
B6	<0.0206, 0.0072>	<0.0199, 0.0076>
B7	<0.0100, 0.0071>	<0.0114 0.0057>
B8	<0.0177, 0.0055>	<0.0143, 0.0090>
B9	<0.0238, 0.0079>	<0.0225, 0.0092>
B10	<0.0286, 0.0073>	<0.0279, 0.0078>
B11	<0.0596, 0.0127>	<0.0489, 0.0215>
B12	<0.0475, 0.0112>	<0.0403, 0.0168>
B13	<0.0329, 0.0094>	<0.0306, 0.0118>
B14	<0.0199, 0.0057>	<0.0182, 0.0075>
B15	<0.0092, 0.0076>	<0.0100, 0.0069>
B16	<0.0153, 0.0111>	<0.0172, 0.0092>
B17	<0.0314, 0.0138>	<0.0333, 0.0119>
B18	<0.0187, 0.0101>	<0.0205, 0.0084>
B19	<0.0361, 0.0093>	<0.0342, 0.0112>
B20	<0.0535, 0.0105>	<0.0483, 0.0158>

All attributes can be classified into two types: benefit and cost. Thus, let BN be a collection of benefit attributes and C is a collection of cost attributes. Therefore, A^+ and A^- can be defined as:

$$A^+ = \{B_j, \left(\left(\max\hat{\mu}_{ij}(B_j)\middle|j\in BN\right), \left(\min\hat{\mu}_{ij}(B_j)\middle|j\in C\right)\right), \left(\left(\min\hat{\upsilon}_{ij}(B_j)\middle|j\in BN\right), \left(\max\hat{\upsilon}_{ij}(B_j)\middle|j\in C\right)\right)\middle|i\in n\} \quad (7)$$

$$A^- = \{B_j, \left(\left(\min\hat{\mu}_{ij}(B_j)\middle|j\in BN\right), \left(\max\hat{\mu}_{ij}(B_j)\middle|j\in C\right)\right), \left(\left(\max\hat{\upsilon}_{ij}(B_j)\middle|j\in BN\right), \left(\min\hat{\upsilon}_{ij}(B_j)\middle|j\in C\right)\right)\middle|i\in n\} \quad (8)$$

Table 8 Distances between A_i and A^+, A^-

Alternatives	$d_{IFS}(A_i, A^+)$	$d_{IFS}(A_i, A^-)$
X	0.0137	0.0576
Y	0.0549	0.0186
Z	0.0278	0.0446

Step 8 Compute the distance of each alternative A_i from A^+ and A^- by using the intuitionistic Euclidean distance.

$$d_{IFS}(A_i, A^+) = \sqrt{\sum_{j=1}^{m}\left[\left(\mu_{A_i}(B_j)-\mu_{A^+}(B_j)\right)^2 + \left(\upsilon_{A_i}(B_j)-\upsilon_{A^+}(B_j)\right)^2 + \left(\pi_{A_i}(B_j)-\pi_{A^+}(B_j)\right)^2\right]} \quad (9)$$

Where

$d_{IFS}(A_i, A^+)$ represents the distance between alternative i with respect to the fuzzy positive ideal alternative.

$\mu_{A_i}(B_j)$ represents the degree of membership of attribute B_j of alternative i

$\mu_{A^+}(B_j)$ represents the degree of membership of attribute B_j of fuzzy positive ideal alternative

$\upsilon_{A_i}(B_j)$ represents the degree of nonmembership of attribute B_j of alternative i

$\upsilon_{A^+}(B_j)$ represents the degree of nonmembership of attribute B_j of fuzzy positive ideal alternative

$\pi_{A_i}(B_j)$ represents the intuitionistic index of attribute B_j of alternative i

$\pi_{A^+}(B_j)$ represents the intuitionistic index of attribute B_j of fuzzy positive ideal alternative

$$d_{IFS}(A_i, A^-) = \sqrt{\sum_{j=1}^{m}\left[\left(\mu_{A_i}(B_j)-\mu_{A^-}(B_j)\right)^2 + \left(\upsilon_{A_i}(B_j)-\upsilon_{A^-}(B_j)\right)^2 + \left(\pi_{A_i}(B_j)-\pi_{A^-}(B_j)\right)^2\right]} \quad (10)$$

Where

$d_{IFS}(A_i, A^-)$ represents the distance between alternative i with respect to the fuzzy negative ideal alternative.

$\mu_{A_i}(B_j)$ represents the degree of membership of attribute B_j of alternative i

$\mu_{A^-}(B_j)$ represents the degree of membership of attribute B_j of fuzzy negative ideal alternative

Table 9 CC and ranking

Alternatives	CC	Rank
X	0.8082	1
Y	0.2531	3
Z	0.6165	2

$\upsilon_{A_i}(B_j)$ represents the degree of nonmembership of attribute B_j of alternative i

$\upsilon_{A^-}(B_j)$ represents the degree of nonmembership of attribute B_j of fuzzy negative ideal alternative

$\pi_{A_i}(B_j)$ represents the intuitionistic index of attribute B_j of alternative i

$\pi_{A^-}(B_j)$ represents the intuitionistic index of attribute B_j of fuzzy negative ideal alternative

Step 9 Compute the relative CC for each alternative, and rank the preference order of all alternatives.

$$\mathrm{CC}_i = \frac{d_{\mathrm{IFS}}(A_i, A^-)}{d_{\mathrm{IFS}}(A_i, A^+) + d_{\mathrm{IFS}}(A_i, A^-)} \tag{11}$$

The best alternative is the one with highest CC value. The larger value shows that an alternative is closer to A^+ and farther from A^- simultaneously.

5 Results

To illustrate the proposed method, a numerical example for three alternatives of CNC milling machines is presented. The procedure is resumed as follows:

Step 1 This case evaluates three alternatives of CNC milling machines which were evaluated in this case of study (Table 2).

Step 2 In this case, 20 attributes were considered. Description of these attributes can be found in Appendix Table 10.

Step 3 Eight experts evaluated the alternatives; all experts had vast experience in the manufacturing and academic fields; therefore, a weight of 0.125 (1/8) to was assigned to each expert.

Step 4 AHP proposed by Saaty using a 1–9 importance scale was used to obtain the importance or weight of each attribute. The results are shown in Table 3.

Step 5 The aggregated ratings for three milling machines with respect to 20 attributes are represented in Table 4. The resulting aggregated IFS decision matrix is obtained by using (5). To illustrate, consider Table 5 which presents alternative Z and attribute $B1$.

$$W_E = (0.125, 0.125, 0.125, 0.125, 0.125, 0.125, 0.125, 0.125)$$

$$B1 = \{\langle 0.25, 0.60\rangle, \langle 0.50, 0.40\rangle, \langle 0.50, 0.40\rangle \langle 0.80, 0.10\rangle \\ \langle 0.50, 04060\rangle \langle 0.80, 160\rangle, \langle 0.70, 0.20\rangle, \langle 0.70, 0.20\rangle\} \tag{12}$$

$\mathrm{IFWAM}_{B1} = \langle 0.5938, 0.3000\rangle$.

The same procedure is followed to construct the aggregated IFS decision matrix.

Step 6 The aggregated weighted IFS decision matrix is calculated with (6), and the resulting matrix is presented in Table 6.

Step 7 All attributes are benefit attributes excluding (B7, B15, B16, B17, and B18). Hence, using Eqs. 7 and 8, the intuitionistic fuzzy positive ideal alternative, A^+, and intuitionistic fuzzy negative ideal alternative, A^-, with respect to each attribute is calculated; it is shown in Table 7.

Step 8 By using Eqs. 9 and 10, the distance between each alternative and the A^+, A^- alternatives is obtained. Table 8 shows the corresponding distance for each alternative.

Step 9 Using Eq. 7, the relative CC is calculated. Results and ranking order are presented in Table 9.

Therefore, the order of ranking is $X>Z>Y$.

6 Conclusions

This paper presents a novel application of a multicriteria group decision-making problem for the evaluation of HFE attributes for the selection of AMT. The use of intuitionistic fuzzy sets was found effective for dealing with uncertainty. The procedure includes the description of ergonomic compatibility attributes; these attributes were evaluated using linguistic terms and weighted using the AHP method. A group of eight experts was conformed for this case. Once the intuitionistic fuzzy positive ideal solution and the intuitionistic fuzzy negative ideal solution were determined, the closeness coefficient was calculated and alternatives were ranked. Since these attributes have been obviated among actual decision-making models for AMT, this model includes them for their evaluation in an effective way. Also, the intuitionistic fuzzy TOPSIS procedure offers advantages when incomplete or vague information is available among evaluators or decision makers.

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Appendix

Table 10 Ergonomic compatibility attributes

Attribute	Description
Set of attributes that define the compatibility of the equipment with technical skills and training of users.	
B1 Skill level compatibility	Attribute of design of equipment regarding its adaptability to differences on technical skills of users. (Allowing safe and efficient operation for expert and novice users).
B2 Training compatibility	Attribute of design of equipment in terms of the training required (quality and duration) that will be available taking into account needs of users.
Set of attributes that define the compatibility of equipment with the physical work space through the allowance of comfortable reaches and postures as well as taking into account the strength and endurance required for its operation promoting safety and effectiveness.	
B3 Access to machine and clearances	Attribute of design of equipment concerning the allowance of mobility and secure access to arms, hands, legs, head, trunk, and knees of the operator through its space and clearances.
B4 Horizontal and vertical reaches	Attribute of design of equipment concerning the allowance of comfortable, safe and effective human vertical and horizontal reaches (upper and lower extremities).
B5 Adjustability of design	Attribute of design of equipment concerning the allowance of adjustment and / or change on its physical structure (size, position, etc.) or on its components that would be satisfactory to operator.
B6 Postural comfort of design	Attribute of design of equipment regarding the allowance of neutral and diverse body postures for a safe and effective operation.
B7 Physical work and endurance of design	Attribute of design of equipment concerning the level of physical work and endurance that will required of operator during interaction.
Set of attributes that promotes easiness of use on design of equipment.	
B8 Compatibility of design of controls	Attribute of design of equipment regarding the type and design of controls and sensors (as buttons, knobs, levers, switches, stoppage sensors of movement, etc.) providing an effective and safe operation.
B9 Physical distribution of controls	Attribute of design of equipment regarding the physical distribution (location) of the controls (buttons, knobs, levers, switches, etc.) providing a safe and effective manipulation.
B10 Visual work space design	Attribute of design of equipment concerning the size and location of screens and displays of information: size and type of characters used, colors, contrast, resolution and brightness facilitating human visual tasks during human-machine interaction.
B11 Information load	Attribute of design of equipment which allows and facilitates a safe and effective operation through a satisfactory human understanding, learning and processing of the information (visual, auditory, sensory) during human-machine interaction.
B12 Error tolerance of design	Attribute of design of equipment which allows and facilitates to the operator the management and prevention of errors, through simple and clear messages and dialogs on the human–machine interface.
B13 Man–machine functional allocation of design	Attribute design of equipment concerning difficult tasks for operator such as quick response, short term storing information, high accuracy and repeatability, among others are allocated in the equipment design preferable to the machine.
B14 Design for maintainability	Attribute of design of equipment considering whether a simple, rapid, effective and safe maintenance tasks will be allowed, during repairing, installation and dismantling, transportation, loading, cleaning, assembling and disassembling among other maintenance activities
Set of attributes related to temperature, vibration, noise and residual materials generated by the equipment and may adversely affect operator and/or environment.	
B15 Temperature	Attribute of design of equipment related to the temperature (hotness/coldness) emitted by the equipment and its components and that may adversely affects operator and/or environment.
B16 Vibration	Attribute of design of equipment which related to the vibration emitted by the equipment and that may adversely affects operator and/or environment.
B17 Noise	Attribute of design of equipment related to the noise emitted by the equipment and its components and that may adversely affects human operators and/or environment.
B18 Residual materials	Attribute of design of equipment related to the amount and kind of residual materials generated by the equipment and its components and that may adversely affect the operator and or environment.

Table 10 (continued)

Attribute	Description
Set of attributes that define the compatibility of equipment with the pace and speed of work as well as with the total content of the work according human limitations and capabilities.	
B19 Rate of work machine compatibility	Attribute of design of equipment considering that it avoids or prevents inappropriate pace and speed of work for operator.
B20 Total work content machine compatibility	Attribute of design of equipment considering the prevention of excessive force application, long term awkward postures, repetitive tasks and high-risk task (i.e., manual handling of loads) on complementary tasks of the machine operation (total content of work).

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