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Research Article

The ILHWLAD-MCDM Framework for the Evaluation of Concrete Materials under an Intuitionistic Linguistic Fuzzy Environment

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Concrete, one of the sources of energy consumption and carbon emissions, is widely used in the construction industry. The selection of concrete materials raises the question of energy sustainability and turns it into a complex multicriteria decision-making (MCDM) issue. To address this, we present an MCDM framework based on the intuitionistic linguistic hybrid weighted logarithmic averaging distance (ILHWLAD). To begin with, the intuitionistic linguistic numbers are used to deal with the uncertainty and fuzziness of the decision-making process. In addition, in view of the significance and the ordered position of the input arguments, an intuitionistic linguistic hybrid weighted logarithmic averaging distance (ILHWLAD) operator is defined. We, then, initiate the criteria system and present the MCDM framework based on the ILHWLAD to select the finest concrete. A case study involving four alternative materials, namely, autoclaved aerated concrete (AAC), hollow concrete blocks (HCB), expanded polystyrene (EPS), and lime hemp concrete (LHC), is presented to verify the scientificity of the framework.

1. Introduction

The rapid advance of urbanization has meant that land available for construction is becoming increasingly scarce. However, the number of individuals who crowd into the city to improve their living standards is growing day by day [1]. This has led to an explosion in demand for housing because the existing stock does not meet citizens' needs. Building materials have become an issue of crucial consideration, and because high-rise buildings accommodate more individuals, safety is critical [2]. Concrete, a mixture of paste and aggregate or rocks, is one of the most widely used building materials. Different kinds are used for building external filled walls, frame structured filled walls, non-load-bearing walls, load-bearing walls, roofs, floors, insulation systems, and so on [3–5]. However, as a result, energy consumption is increasing drastically and so is environmental pollution [6]. The United Nations Environment Program (UNEP) reports that the finest concrete materials account for more than 36% of global energy consumption and up to 40% of energy-related carbon dioxide emissions [7]. Therefore, the choice of suitable concrete for construction is of great significance for energy conservation and emissions reduction, manufacturing, composition, innovation, and so on.

Concrete gives buildings strength and durability. The concrete itself must have great compressive strength. Concrete also affects the thermal performance of buildings. Climatic conditions can change enormously [8]; concrete materials consume heat during the summer season, and this is stored and released in the night in winter, which reduces the effect of external temperature variations. In addition, the residential comfort of the building is not adversely affected because concrete is able to balance variations in outdoor humidity and to avoid excessive variations in humidity within the building. Because concrete is widely used in the construction industry, economy and accessibility are especially important in the selection process of the finest types.

It is difficult to use specific data in the analysis of the performance and functionality of specific concrete materials. For example, the energy of concrete material varies according to levels of technology, production conditions, and so on [9]. The intuitionistic linguistic number (ILN) is an effective way to resolve these issues, and it has been frequently used in different fields [10], e.g., energy performance contracting [11], strategy decisions [12], the selection of offshore wind farms [13], and assessment of green building insulation materials [14].

Compared to the value of language evaluation, ILN increases the degree of membership and nonmembership, which reflects the nonmembership degree of the language evaluation value and the magnitude of hesitation of decision makers [15]. We can utilize ILN to characterize the grades of each criterion for concrete materials because the information is hard to measure with specific values.

The ultimate goal of this paper is to select the finest concrete material. Its contribution to the field can be summarized as follows:

(1) The intuitionistic linguistic weighted logarithmic average distance (ILWLAD) operator and the intuitionistic linguistic ordered weighted logarithmic average distance (ILOWLAD) operator are projected by combining the weighted logarithmic and the ordered weighted logarithmic average methods. Furthermore, to address the defects of ILWLAD and ILOWLAD, we introduce a new intuitionistic linguistic hybrid weighted logarithmic average distance (ILHWLAD) operator for better handling of the data.

(2) As mentioned previously, the selection of concrete materials is a comprehensive decision-making problem. To improve the scientificity of the decision-making process, a multidimensional examination of concrete materials is required. Thus, a six-criterion evaluation system for concrete material selection has been developed, and four concrete materials have been graded using ILNs.

(3) The HWLAD-MCDM framework of concrete material selection is presented [16,17], and the ILHWLAD operator is used to select the most suitable material by using the fuzzy concept. To illustrate the rationality of the ILHWLAD operator, we compare the results obtained by using the ILHWLAD operator with those obtained using the ILOWLAD operator, ILOWAD operator, and ILWLAD operator.

The remainder of this paper is arranged as follows: Section 2 introduces the evaluation criteria of concrete materials and briefly reviews the related concepts. Section 3 presents the new ILHWLAD operator and introduces the HWLAD-MCDM framework used to select the most suitable and finest concrete material. In Section 4, we apply the framework to the four alternative concrete materials and display the results. In addition, some comparisons are made and discussed to explain the rationale behind the ILHWALD operator. The conclusions, limitations, and recommendations for further applications are presented in Section 5.

2. Materials and Methods

2.1. Criteria for Concrete Materials Selection. Constructing the evaluation criteria system is a key step in the concrete materials selection process. In accordance with the available literature, four main aspects and six criteria were selected (see Table 1) [18, 23].

(1) Embodied energy (A1): the embodied energy of the concrete materials refers to the exact total energy consumed in the entire process of concrete material production. It includes production, processing, transportation, and construction, that is, is the sum of direct and indirect energy consumption. The lower the energy content, the lower the energy consumption of the concrete material and the more the energy that is saved.

(2) Embodied carbon (A2): the concrete material in production, processing, and other processes expel carbon dioxide into the atmosphere. Carbon dioxide contributes to air pollution and provokes the global greenhouse effect, which is the cause of global climate change. Hence, the less the carbon contained in the concrete material, the lower the carbon dioxide expelled.

(3) Purchase cost (A3): the finest concrete materials are frequently used in the construction business. The purchase cost of concrete changes greatly, and a reduction contributes to economies in construction costs. Therefore, the purchase cost can be regard as an economic criterion for measurement.

(4) Thermal performance (A4): the outdoor temperature of buildings is generally high in the summer. Good thermal performance enables indoor temperatures to reach a lower level than the day's peak temperature, thus improving the comfort of indoor living. In contrast, outdoor temperatures are generally lower in winter and reach their lowest point at the night. Therefore, the indoor temperature is capable of reaching a higher level at the lowest external night-time temperature as a result of the concrete's outstanding thermal performance. In this paper, the highest indoor temperature of the building in summer and the lowest indoor temperature in winter at night-time are combined to measure the thermal performance of the concrete materials.

(5) Ability to balance outdoor humidity fluctuations (A5): a criterion that measures the ability of certain concrete materials to balance outdoor humidity fluctuations is the variation range of indoor humidity within a day. The smaller the range, the better the ability to balance outdoor humidity fluctuations. We combine the indoor humidity variation of the building in the summer and in the winter to measure the ability of the concrete materials to balance fluctuations in outdoor humidity.

(6) Compressive strength (A6): the compressive strength of concrete refers to the strength limit

Table 1: Criteria for concrete material selection.

Aspects	Criteria	Abbreviation	Reference
Energy	Embodied energy	A_1	[8, 18, 19]
Sustainability	Embodied carbon	A_2	[8, 20–22]
Economy	Purchase cost	A_3	[23, 24]
	Thermal performance	A_4	[25–27]
Comfort	Ability to balance outdoor humidity fluctuations	A_5	[28, 29]
Safety	Compressive strength	A_6	[30–33]

applied by external forces, which is obtained by a test of a cube specimen with a side length of 150 mm under the strength of C60. As has been noted, it is one of the factors that influence the stability of a building. The greater the compressive strength, the greater the maximum pressure the material can withstand.

In terms of energy sustainability, embodied energy and embodied carbon are the two main criteria that reflect the energy consumed and carbon dioxide emitted [19,20]. When taking the comfort of the building's interior into account, the thermal performance of the concrete materials and the ability to balance outdoor humidity fluctuations are especially significant [34]. For the economy of the concrete materials, the purchase cost is the critical criterion by which to estimate economic possibilities, given concrete's widespread use in the construction industry. Finally, the criterion of its compressive strength has to be considered because this is what makes buildings strong [30].

2.2. Weighting Method of Criteria. In this section, we briefly review some concepts related to the linguistic approach and the intuitionistic linguistic set (ILS) and present a programming model for calculating the weights of the criteria.

Definition 1. The linguistic approach is an approximate technique that expresses qualitative aspects as linguistic values through the use of linguistic terms [35]. For ease of calculation, let $K = \{k_a | a = 1, 2, \ldots, t\}$ be an ordered linguistic term set, where t is the positive odd value and k_a represents a possible value for a linguistic variable.

For instance, taking $t = 7$, a set K could be expressed as follows: $K = \{k_1, k_2, k_3, k_4, k_5, k_6, k_7\} = \{$*extremely bad*, *quite bad*, *bad*, *medium*, *good*, *quite good*, *extremely good*$\}$.

Any label k_α should satisfy the following operational laws:

(1) $\mathrm{Neg}(k_i) = k_{t-i}$

(2) $k_i \geq k_j \Longleftrightarrow i \geq j$

(3) $\max(k_i, k_j) = k_i$, if $\geq i \geq j$

(4) $\min(k_i, k_j) = k_i$, if $\geq i \leq j$

Considering two linguistic terms $k_\alpha, k_\beta \in K$, and $\mu > 0$, the operations are defined as follows:

(1) $k_\alpha \oplus k_\beta = k_{\alpha+\beta}$

(2) $\mu k_\alpha = k_{\mu\alpha}$

Definition 2. Let X be a nonempty set. An ILS A in X is, then, expressed as

$$A = \left\{ \left\langle x \left[k_{\theta(x)}, \left(\mu_A(x), \nu_A(x) \right) \right] \right\rangle | x \in X \right\}, \quad (1)$$

where $k_\theta \in \overline{K}$ and the $\mu A(x)$ and $\nu_A(x)$ indicate the membership degree and nonmembership degree of the element $x \in X$ to the set A, respectively. Hence, we have $\mu A(x), \nu_A(x) \in [0, 1]$ and $0 \leq \mu A(x) + \nu_A(x) \leq 1$, for all $x \in X$. For convenience, the ILN is generally denoted as $\langle k_{\theta(x)}, (\mu A(x), \nu_A(x)) \rangle$.

More specifically, for each ILS A in X, we have

$$\pi_A(x) = 1 - \mu_A(x) - \nu_A(x), \quad (2)$$

where $\pi_A(a)$ is called the hesitation degree of x to linguistic variable $k_\theta(x)$.

After the notion of the ILN has been presented, we then calculate the weights of criteria. The weight calculation methods commonly used to determine the weights when the information is completely unknown include the analytic hierarchy process (AHP) [36, 37] and entropy method [38, 39]. Here, the criterion information is partially known, so the programming model is preferred to calculate the weights. The steps are as follows:

Step 1: establish a matrix with ILNs $(u \times v)$, which includes u different experts and v different criteria

Step 2: calculate the positive ideal solution (PIS) and negative ideal solution (NIS) for each criterion by using the following equations:

$$A_j^+ = \max_{j \in \mathrm{benefit}} \left(H\left(A_j\right) \right) \mathrm{or} \min_{j \in \mathrm{cost}} \left(H\left(A_j\right) \right), \quad (3)$$

$$A_j^- = \max_{j \in \mathrm{cost}} \left(H\left(A_j\right) \right) \mathrm{or} \min_{j \in \mathrm{benefit}} \left(H\left(A_j\right) \right), \quad (4)$$

where $H(A_i) = (\theta/t - 1) \times (\mu + \nu)$, A_j^+ represents the value of PIS for the j-th criterion, and A_j^- represents the value of NIS for the j-th criterion

Step 3: determine an objective function by using the PIS and NIS values:

$$\min T = \sum_{j=1}^{n} w_j \sum_{i=1}^{m} \left(d\left(A_{ij}, A_j^+\right) - d\left(A_{ij}, A_j^-\right) \right), \quad (5)$$

where $0 \leq w_j \leq 1$ and $\sum_j w_j = 1 \cdot d(\cdot)$ represents the distance between two ILNs

For example, for the two ILNs A_1 and A_2, we have

$$d(A_1, A_2) = \frac{1}{2(t-1)} \times \left(\left| (1 + \mu(A_1) - \nu(A_1))\theta(A_1) - (1 + \mu(A_2) - \nu(A_2))\theta(A_1) \right| \right). \tag{6}$$

2.3. The ILOWAD and the ILWALD Operators. In this section, some related operators are briefly reviewed, including the OWAD [40], the WLAD [41], the OWLAD [42], and the ILOWAD [43] measures.

Definition 3. Let A and B be two intuitionistic linguistic sets; the normalized hamming distance between A and B is given by the mathematical form:

$$d(A, B) = \frac{1}{n} \sum_{i=1}^{n} d_{\mathrm{ILN}}\left(\tilde{a}_i, \tilde{b}_i\right) = \sum_{i=1}^{n} \frac{1}{2n(t-1)} \times \left(\left| (1 + \mu(a_i) - \nu(a_i))\theta(a_i) - (1 + \mu(b_i) - \nu(b_i))\theta(b_i) \right| \right), \tag{7}$$

where $\tilde{a}_i = \langle k_{\theta(ai)}, (\mu(a_i), \nu(a_i)) \rangle$ and $\tilde{b}_i = \langle k_{\theta(bi)}, (\mu(b_i), \nu(b_i)) \rangle$ are the i-th ILN of A and B, respectively, and $\theta(\cdot)$ represents the i-th linguistic value of A or B.

Definition 4. Let $A = \{a_1, a_2, \ldots, a_n\}$ and $B = \{b_1, b_2, \ldots, b_n\}$ be two crisp sets and $d_i = |a_i - b_i|$ the distance between a_i and b_i. The OWAD measure is, then, defined as

$$\mathrm{OWAD}(A, B) = \mathrm{OWAD}\left(d_1, d_2, \ldots, d_n\right) = \sum_{j=1}^{n} w_j d_{\sigma(j)}, \tag{8}$$

where $d_{\sigma(j)}\,(j = 1, 2, \ldots, n)$ is the j-th largest value of $d_j\,(j = 1, 2, \ldots, n)$. $w = \left\{ w_j \middle| \sum_{j=1}^{n} w_j = 1, 0 \leq w_j \leq 1 \right\}$ is the associated weighting vector of *OWAD*.

Definition 5. The WLAD operator of dimension n is a mapping WLAD: $R^n \times R^n \longrightarrow R$ has a relative weighting vector $W = \{w_1, w_2, \ldots, w_n\}$, with $\sum_{i=1}^{n} w_i = 1$ and $w_i \in [0, 1]$.

$$\mathrm{WLAD}(x_1, y_1, x_2, y_2, \ldots, x_n, y_n) = \exp\left\{ \sum_{i=1}^{n} w_i \ln(d_i) \right\}, \tag{9}$$

where $d_i = |x_i - y_i|$ represents the individual distance between x_i and y_i.

Definition 6. Let $X = \{x_1, x_2, \ldots, x_n\}$ and $Y = \{y_1, y_2, \ldots, y_n\}$ be two crisp sets and $d_i = |x_i - y_i|$ be the distance between xi and yi. The OWLAD operator of dimension n is a mapping $OWLAD$: $R^n \times R^n \longrightarrow R$ that has a relative weighting vector $W = \{\omega_1, \omega_2, \ldots, \omega_n\}$, with $\sum_{i=1}^{n} wi = 1$ and $w_j \in [0, 1]$, satisfying

$$\mathrm{OWLAD}(x_1, y_1, x_2, y_2, \ldots, x_n, y_n) = \exp\left\{ \sum_{j=1}^{n} w_j \ln\left(d_{\sigma(j)}\right) \right\}, \tag{10}$$

where $d_{\sigma(j)}$ has the same meaning and value range as Definition 4.

Definition 7. The ILOWAD operator of dimension n is a mapping ILOWAD: $\Omega^n \times \Omega^n \longrightarrow \Omega$ that is defined by an associated weighting vector W. Hence, the sum of weights is equal to 1 and $w_j \in [0, 1]$. Then, we have

$$\mathrm{ILOWAD}\left(\left(\tilde{a}_1, \tilde{b}_1\right), \ldots, \left(\tilde{a}_n, \tilde{b}_n\right)\right) = \sum_{j=1}^{n} w_j d_{\sigma(j)}, \tag{11}$$

where $d_{\sigma(j)}$ is the j-th largest value among the intuitionistic linguistic distance $d_{\mathrm{ILN}}(\tilde{a}_i, \tilde{b}_i)$ and $\tilde{a}_i = \langle k_{\theta(ai)}, (\mu(a_i), \nu(a_i)) \rangle$ and $\tilde{b}_i = \langle k_{\theta(bi)}, (\mu(b_i), \nu(b_i)) \rangle$ are the i-th ILN of A and B, respectively.

3. Proposed Method

3.1. Intuitionistic Linguistic Weighted Logarithmic Distance Measures. In this section, we present the intuitionistic linguistic weighted logarithmic average distance (*ILWLAD*) operator, the *ILOWLAD* operator, and the *ILHWLAD* operator.

Definition 8. The ILWLAD operator of dimension n is a mapping $ILWALD$: $R^n \times R^n \longrightarrow R$. This operator can be formulated as:

$$ILWLAD\left(\left(\tilde{a}_1, \tilde{b}_1\right), \ldots, \left(\tilde{a}_n, \tilde{b}_n\right)\right) = \exp\left\{ \sum_{i=1}^{n} w_i \mathrm{In}(d_i) \right\}, \tag{12}$$

where $W = \{\omega_1, \omega_2, \ldots, \omega_n\}$ is the relative weighting vector of *ILWLAD*, $\sum_{i=1}^{n} wi = 1$, $w_i \in [0, 1]$.

Definition 9. The ILOWLAD operator maps the parameter vector of dimension n to a real number, which has a relative weighting vector $W = \{\omega_1, \omega_2, \ldots, \omega_n\}$, with $\sum_{i=1}^{n} wi = 1$ and $w_i \in [0, 1]$. Hence, we define this operator as follows:

$$\text{ILOWLAD}\left(\left(\tilde{a_1}, \tilde{b_1}\right), \ldots, \left(\tilde{a_n}, \tilde{b_n}\right)\right) = \exp\left\{\sum_{j=1}^{n} w_j \ln\left(d_{\sigma(j)}\right)\right\}, \tag{13}$$

where $d_{\sigma(j)}$ represents the j-th largest value of all intuitionistic linguistic distances $d_{\text{ILN}}(\tilde{a_1}, \tilde{b_1})$.

In the aggregation process, the ILWLAD measure examines the importance of criteria and the ILOWLAD measure examines the importance of the ordered deviation. However, the ILWLAD is unable to perform the aggregation function in order, while the ILOWLAD fails to integrate the criteria in a way that the ILWLAD can. To compensate for this disadvantage, we present the ILHWLAD measure.

Definition 10. Let $\tilde{a_i} = \langle k_{\theta(ai)}, (\mu(a_i), v(a_i))\rangle\, (i = 1, 2, \ldots, n)$ and $\tilde{b_i} = \langle k_{\theta(bi)}, (\mu(b_i), v(b_i))\rangle\ (i = 1, 2, \ldots, n)$ two sets of ILN. An ILHWLAD operator of dimension n is a mapping ILHWLAD: $R^n \times R^n \longrightarrow R$. The ILHWLAD measure is given as follows:

$$\text{ILHWLAD}\left(\left(\tilde{a_1}, \tilde{b_1}\right), \cdots, \left(\tilde{a_n}, \tilde{b_n}\right)\right) = \exp\left\{\sum_{j=1}^{n} w_j \ln\left(\overline{D}_{\sigma(j)}\right)\right\}, \tag{14}$$

where $\overline{D}_{\sigma(j)}$ represents the j-th largest value among $\overline{D}_j$, which is defined as $\overline{D}_j = (nw_j D_j)$, $(j = 1, 2, \ldots, n.)\ w_j = (w_1, w_2, \ldots, w_n)$ is the weight vector corresponding to $\overline{D}_{\sigma(j)}$, and w_j is the associated weight of the unordered value D_j, satisfying $\sum_{i=1}^{n} wi = 1$ and $w_i \in [0, 1]$. N is used as a balancing factor to compensate for the double weighting. Moreover, we can explore a wide range of special cases of the ILHWLAD operator utilizing the similar methods proven in [16, 44].

3.2. The MCDM Framework Based on the ILHWLAD Measure. The selection of concrete materials is a multicriteria decision-making problem. Based on the *ILHWLAD* operator, this section uses a weight programming model to calculate weight, and an MCDM framework is used to select the finest concrete material. The specific steps are shown in Figure 1.

An MCDM problem includes j different alternatives, denoted as $C_1, C_2, \ldots, C_j$, and a total of t experts are invited to evaluate the alternatives under k finite criteria $E_1, E_2, \ldots, E_k$. The process can be summarized into the following steps; Table 2:

Step 1: each expert $e_q\, (q = 1, 2, \ldots, t)$ (the corresponding weight is τ_q, which meets $\tau_q \geq 0$ and $\sum_{q=1}^{t} \tau_q = 1$) measures his or her performance using criteria from the ILNs. Afterwards, the individual decision matrix $R^q = (r_{ij}^{(q)})_{m\leftrightarrow n}$ is obtained, where $r_{ij}(q)$ is the evaluation of the alternative C_i by q-th experts with regard to criterion E_j.

Step 2: calculate the collective decision matrix $R^q = (r_{ij}^{q})_{m\times n}$ to aggregate individual evaluations, where $r_{ij} = \sum_{q=1}^{t} \tau_q r_{ij}^{(q)}$.

Step 3: establish the ideal alternative by setting the ideal performances for each criterion (see Table 2).

Step 4: use the programming model presented to obtain the weights of criteria according to equation (5). Then, the weights of operators can be determined by experts.

Step 5: the distances between the alternative $C_i\, (I = 1, 2, \ldots, j)$ and the ideal alternative I are computed by utilizing the ILHWLAD measure:

$$\begin{aligned}&\text{ILHWLAD}\left(\left(\tilde{a_1}, \tilde{b_1}\right), \cdots, \left(\tilde{a_n}, \tilde{b_n}\right)\right)\\ &\quad = \exp\left\{\sum_{j=1}^{n} w_j \ln\left(\overline{D}_{\sigma(j)}\right)\right\}.\end{aligned} \tag{15}$$

Step 6: based on the value of the distances obtained in the previous steps, we can order the alternatives and select the finest one.

4. Case Study

4.1. Description of Concretes. The concrete materials used in the construction industry are mainly autoclaved aerated concrete (AAC) [10, 45], hollow concrete blocks (HCB) [46, 47], expanded polystyrene (EPS) [48, 49], and lime hemp concrete (LHC) [50].

LHC (C_1) is a new composite material of lime and hemp, which maintains an excellent thermal and moisture processing performance. Because of its lower embodied energy (EE) and embodied carbon (EC), the energy consumption and emission of carbon dioxide are compact during its manufacture. Its low mechanical property means that it is widely used in roofs, walls, slabs, and insulation.

AAC (C_2) forms numerous small air holes in the interior during the production process, so it possesses good heat and sound insulation functions. Moreover, it is relatively light, and the density is about 1/3 of clay brick. It is generally used in the outside filled walls of buildings and non-load-bearing internal partitions.

HCB (C_3) is of low density and possesses a good thermal performance, which are advantageous for masonry. It is commonly used in industrial and civil buildings, particularly in bearing walls and frame structure fill walls of multistorey buildings. It is also frequently adopted to construct fences, flower beds, bridges, and so on.

EPS (C_4) is a lightweight polymer with good thermal insulation. It is commonly used in the heat insulation system of external walls, roofs, and floors of buildings.

4.2. Decision Procedure. In this section, we use the framework to deal with selection problems under IL environments. Four possible concretes $C_i\, (I = 1, 2, 3, 4)$ are evaluated from the following criteria: embodied energy (E1); embodied carbon (E2); purchase cost (E3); thermal performance (E4); ability to balance outdoor humidity

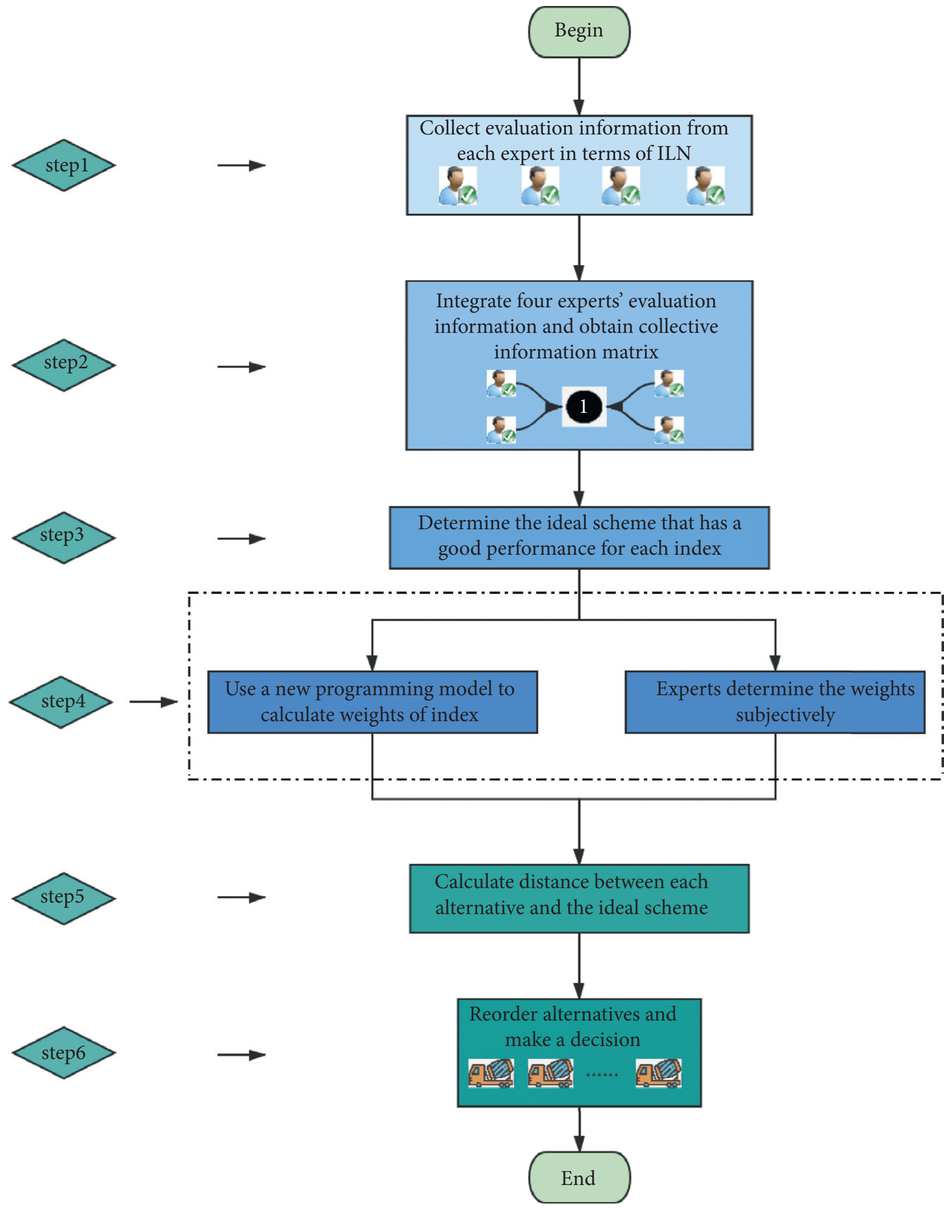

Figure 1: The procedure of the MCDM framework based on ILHWLAD for concrete materials.

Table 2: Ideal alternative.

	E_1	E_2	...	E_k
I	I_1	I_2	...	I_k

fluctuation (E5); and compressive strength (E6). Four experts (expert's weight $\tau = (0.25, 0.3, 0.2, 0.25)$) utilize IL information to evaluate four candidate concretes under six criteria, where the linguistic term set is assumed to be $K = (k_1, k_2, k_3, k_4, k_5, k_6, k_7)$; Tables 3–9 and Table 10.

Step 1: let each expert express evaluation of four concrete materials under given criteria through ILNs. The intuitionistic linguistic individual decision matrixes are shown in Tables 3–6.

Step 2: on the basis of the individual decision matrices and weights of the experts, we can obtain the collective decision matrix; see Table 7.

Step 3: having acquired the relevant information on the four concrete materials, the experts construct the ideal

Table 3: Intuitionistic linguistic matrix-expert 1.

	E_1	E_2	E_3	E_4	E_5	E_6
C_1	$\langle k_6, (0.5, 0.4)\rangle$	$\langle k_6, (0.3, 0.4)\rangle$	$\langle k_3, (0.6, 0.3)\rangle$	$\langle k_6, (0.2, 0.6)\rangle$	$\langle k_6, (0.4, 0.4)\rangle$	$\langle k_6, (0.7, 0.4)\rangle$
C_2	$\langle k_4, (0.3, 0.6)\rangle$	$\langle k_5, (0.5, 0.4)\rangle$	$\langle k_6, (0.7, 0.2)\rangle$	$\langle k_6, (0.5, 0.5)\rangle$	$\langle k_5, (0.5, 0.5)\rangle$	$\langle k_4, (0.2, 0.8)\rangle$
C_3	$\langle k_5, (0.2, 0.7)\rangle$	$\langle k_4, (0.6, 0.2)\rangle$	$\langle k_4, (0.6, 0.3)\rangle$	$\langle k_4, (0.9, 0.1)\rangle$	$\langle k_4, (0.4, 0.4)\rangle$	$\langle k_7, (0.1, 0.9)\rangle$
C_4	$\langle k_3, (0.7, 0.2)\rangle$	$\langle k_3, (0.2, 0.8)\rangle$	$\langle k_5, (0.1, 0.9)\rangle$	$\langle k_3, (0.3, 0.6)\rangle$	$\langle k_2, (0.4, 0.4)\rangle$	$\langle k_2, (0.3, 0.6)\rangle$

Table 4: Intuitionistic linguistic matrix-expert 2.

	E_1	E_2	E_3	E_4	E_5	E_6
C_1	$\langle k_7, (0.7, 0.2)\rangle$	$\langle k_7, (0.8, 0)\rangle$	$\langle k_3, (0.6, 0.3)\rangle$	$\langle k_6, (0.5, 0.5)\rangle$	$\langle k_7, (0.3, 0.6)\rangle$	$\langle k_2, (0.4, 0.5)\rangle$
C_2	$\langle k_5, (0.2, 0.7)\rangle$	$\langle k_5, (0.4, 0.6)\rangle$	$\langle k_6, (0.7, 0.2)\rangle$	$\langle k_6, (0.6, 0.4)\rangle$	$\langle k_5, (0.6, 0.3)\rangle$	$\langle k_3, (0.9, 0)\rangle$
C_3	$\langle k_5, (0.4, 0.5)\rangle$	$\langle k_4, (0.7, 0.3)\rangle$	$\langle k_5, (0.5, 0.3)\rangle$	$\langle k_4, (0.2, 0.7)\rangle$	$\langle k_5, (0.3, 0.6)\rangle$	$\langle k_7, (0.4, 0.5)\rangle$
C_4	$\langle k_3, (0.2, 0.8)\rangle$	$\langle k_4, (0.7, 0.2)\rangle$	$\langle k_5, (0.4, 0.5)\rangle$	$\langle k_3, (0.5, 0.4)\rangle$	$\langle k_2, (0.1, 0.8)\rangle$	$\langle k_2, (0.8, 0.1)\rangle$

Table 5: Intuitionistic linguistic matrix-expert 3.

	E_1	E_2	E_3	E_4	E_5	E_6
C_1	$\langle k_7, (0.3, 0.6)\rangle$	$\langle k_6, (0.4, 0.5)\rangle$	$\langle k_3, (0.3, 0.6)\rangle$	$\langle k_7, (0.8, 0.1)\rangle$	$\langle k_6, (0.8, 0.2)\rangle$	$\langle k_3, (0.7, 0.2)\rangle$
C_2	$\langle k_4, (0.3, 0.7)\rangle$	$\langle k_5, (0.5, 0.4)\rangle$	$\langle k_7, (0.8, 0.1)\rangle$	$\langle k_7, (0.3, 0.6)\rangle$	$\langle k_5, (0.4, 0.5)\rangle$	$\langle k_4, (0.4, 0.6)\rangle$
C_3	$\langle k_6, (0.8, 0.2)\rangle$	$\langle k_5, (0.4, 0.6)\rangle$	$\langle k_5, (0.5, 0.4)\rangle$	$\langle k_5, (0.2, 0.7)\rangle$	$\langle k_4, (0.8, 0.2)\rangle$	$\langle k_7, (0.7, 0.2)\rangle$
C_4	$\langle k_3, (0.4, 0.5)\rangle$	$\langle k_3, (0.7, 0.2)\rangle$	$\langle k_6, (0.5, 0.4)\rangle$	$\langle k_3, (0.6, 0.3)\rangle$	$\langle k_3, (0.6, 0.4)\rangle$	$\langle k_3, (0.6, 0.2)\rangle$

Table 6: Intuitionistic linguistic matrix-expert 4.

	E_1	E_2	E_3	E_4	E_5	E_6
C_1	$\langle k_7, (0.4, 0.5)\rangle$	$\langle k_6, (0.6, 0.3)\rangle$	$\langle k_3, (0.7, 0.2)\rangle$	$\langle k_6, (0.7, 0.2)\rangle$	$\langle k_6, (0.2, 0.7)\rangle$	$\langle k_3, (0.4, 0.4)\rangle$
C_2	$\langle k_4, (0.3, 0.4)\rangle$	$\langle k_4, (0.5, 0.4)\rangle$	$\langle k_6, (0.6, 0.2)\rangle$	$\langle k_6, (0.5, 0.5)\rangle$	$\langle k_4, (0.2, 0.8)\rangle$	$\langle k_4, (0.8, 0.1)\rangle$
C_3	$\langle k_6, (0.6, 0.3)\rangle$	$\langle k_4, (0.7, 0.2)\rangle$	$\langle k_4, (0.6, 0.3)\rangle$	$\langle k_5, (0.3, 0.6)\rangle$	$\langle k_4, (0.1, 0.9)\rangle$	$\langle k_7, (0.4, 0.4)\rangle$
C_4	$\langle k_4, (0.6, 0.2)\rangle$	$\langle k_3, (0.5, 0.5)\rangle$	$\langle k_6, (0.1, 0.9)\rangle$	$\langle k_4, (0.4, 0.5)\rangle$	$\langle k_2, (0.6, 0.3)\rangle$	$\langle k_3, (0.3, 0.5)\rangle$

Table 7: Collective IL decision matrix.

	E_1	E_2	E_3	E_4	E_5	E_6
C_1	$\langle k_{6.46}, (0.52, 0.37)\rangle$	$\langle k_{6.35}, (0.60, 0)\rangle$	$\langle k_{5.27}, (0.58, 0.31)\rangle$	$\langle k_{6.32}, (0.59, 0.30)\rangle$	$\langle k_{6.35}, (0.46, 0.45)\rangle$	$\langle k_{5.11}, (0.56, 0.37)\rangle$
C_2	$\langle k_{5.77}, (0.27, 0.59)\rangle$	$\langle k_{5.91}, (0.47, 0.45)\rangle$	$\langle k_{6.32}, (0.70, 0.17)\rangle$	$\langle k_{6.32}, (0.50, 0.49)\rangle$	$\langle k_{5.91}, (0.46, 0.48)\rangle$	$\langle k_{5.54}, (0.71, 0)\rangle$
C_3	$\langle k_{6.11}, (0.53, 0.40)\rangle$	$\langle k_{5.72}, (0.63, 0.28)\rangle$	$\langle k_{5.83}, (0.55, 0.32)\rangle$	$\langle k_{5.89}, (0.54, 0.41)\rangle$	$\langle k_{5.77}, (0.44, 0.48)\rangle$	$\langle k_{6.52}, (0.42, 0.46)\rangle$
C_4	$\langle k_{5.37}, (0.50, 0.36)\rangle$	$\langle k_{5.39}, (0.56, 0.36)\rangle$	$\langle k_{6.11}, (0.32, 0.64)\rangle$	$\langle k_{5.37}, (0.46, 0.44)\rangle$	$\langle k_{4.86}, (0.44, 0.46)\rangle$	$\langle k_{4.98}, (0.57, 0.33)\rangle$

Table 8: Ideal concrete.

	E_1	E_2	E_3	E_4	E_5	E_6
I_1	$\langle k_7, (0.9, 0.1)\rangle$	$\langle k_7, (0.9, 0)\rangle$	$\langle k_7, (0.8, 0.2)\rangle$	$\langle k_6, (0.9, 0.1)\rangle$	$\langle k_7, (0.8, 0.1)\rangle$	$\langle k_7, (0.9, 0.1)\rangle$

Table 9: Positive ideal solution (PIS) and negative ideal solution (NIS) for each criterion.

	E_1	E_2	E_3	E_4	E_5	E_6
A_j^+	$\langle k_{6.46}, (0.52, 0.37)\rangle$	$\langle k_{5.91}, (0.47, 0.45)\rangle$	$\langle k_{6.11}, (0.32, 0.64)\rangle$	$\langle k_{6.32}, (0.50, 0.49)\rangle$	$\langle k_{6.35}, (0.46, 0.45)\rangle$	$\langle k_{6.52}, (0.42, 0.46)\rangle$
A_j^-	$\langle k_{5.37}, (0.50, 0.36)\rangle$	$\langle k_{6.35}, (0.60, 0)\rangle$	$\langle k_{5.27}, (0.58, 0.31)\rangle$	$\langle k_{5.37}, (0.46, 0.44)\rangle$	$\langle k_{4.86}, (0.44, 0.46)\rangle$	$\langle k_{5.54}, (0.71, 0)\rangle$

Table 10: The total distance of each criterion.

	E_1	E_2	E_3	E_4	E_5	E_6
$\sum_{i=1}^{m}(d(A_{ij}, A_j^+) - d(A_{ij}, A_j^-))$	0.080	-0.320	0.426	-0.161	-0.024	-0.533

Table 11: The ranking orders of different measures.

Measures	Ranking orders
ILHWLAD	$C_1 \succ C_2 \succ C_3 \succ C_4$
ILOWLAD	$C_1 \succ C_2 \succ C_3 \succ C_4$
ILOWAD	$C_1 \succ C_3 \succ C_2 \succ C_4$
ILWLAD	$C_2 \succ C_1 \succ C_3 \succ C_4$

concrete with good performance in each criterion; see Table 8.

Step 4: according to Table 7 and equations (2)–(4), the PIS and NIS of each criterion are determined; see Table 9.

The distance matrix is calculated in accordance with equation (6); see Table 10.

In many real-world situations, the information about criteria weights is incomplete, so we should first determine the criteria weights in Step 4 if the known weight information on the criteria is set as in the following set: $H = \{\omega_2 + \omega_4 + \omega_5 + \omega_6 \le 0.6, \omega_1 \le 0.15, \omega_3 \le 0.25, \omega_2 \le 0.2, \omega_6 \le 0.15, \omega_4 + \omega_6 \le 0.3\}$. The objective function and the constraints are determined by using equation (5). The objective function is given by

$$Z = 0.080\omega_1 - 0.320\omega_2 + 0.426\omega_3 - 0.161\omega_4 - 0.024\omega_5 - 0.533\omega. \tag{16}$$

Finally, the weighting vector of the criteria is obtained as $\omega = (0.15, 0.2, 0.25, 0.15, 0.1, 0.15)^T$ using the Python programming language. In the meantime, the weighting vectors of the *ILHWLAD* are set to be $w = (0.2, 0.15, 0.25, 0.1, 0.15, 0.15)^T$.

Step 5: in accordance with equation (15) and the available information, the distances between the alternatives and the ideal concrete are computed by using the ILHWLAD as follows:

(1) $ILHWLAD\ (C_1, I) = 0.3651$
(2) $ILHWLAD\ (C_2, I) = 0.3717$
(3) $ILHWLAD\ (C_3, I) = 0.4319$
(4) $ILHWLAD\ (C_4, I) = 0.5338$

Step 6: the smaller the value of the $ILHWLAD\ (C_i, I)$, the closer the C_i to the ideal concrete. Therefore, we can rearrange the order of $C_i: C_1 \succ C_2 \succ C_3 \succ C_4$

Hence, the best alternative is C_1.

4.3. Comparisons and Discussion. In this section, to verify the superiority and rationality of the ILHWLAD method, and the results of the ILOWLAD, the ILOWAD, and the ILWLAD measures are compared with those of the ILHWLAD measures in the selection of the concrete materials. According to equation (13), the distances between the alternatives and the ideal concrete are calculated by using the ILOWLAD operator as follows:

(1) $ILOWLAD\ (C_1, I) = 0.3786$
(2) $ILOWLAD\ (C_2, I) = 0.3991$
(3) $ILOWLAD\ (C_3, I) = 0.4445$
(4) $ILOWLAD\ (C_4, I) = 0.5476$

By the *ILOWAD* measure, we have

(1) $ILOWAD\ (C_1, I) = 0.3963$
(2) $ILOWAD\ (C_2, I) = 0.4579$
(3) $ILOWAD\ (C_3, I) = 0.4516$
(4) $ILOWAD\ (C_4, I) = 0.5499$

The results obtained by the *ILWLAD* measure are

(1) $ILWLAD\ (C_1, \mathrm{I}) = 0.3563$
(2) $ILWLAD\ (C_2, I) = 0.3387$
(3) $ILWLAD\ (C_3, \mathrm{I}) = 0.4237$
(4) $ILWLAD\ (C_4, I) = 0.5455$

Thus, the final ranking of the four alternatives according to the *ILOWLAD*, the *ILOWAD*, and the *ILWLAD* measures are $C_1 \succ C_2 \succ C_3 \succ C_4$, $C_1 \succ C_3 \succ C_2 \succ C_4$, and $C_2 \succ C_1 \succ C_3 \succ C_4$, respectively. The final results are shown in Table 11.

The ranking results obtained by the abovementioned four methods are contrasting. As Table 11 shows, LHC is the finest concrete material measured by the ILHWLAD, ILOWLAD, and ILOWAD measures. LHC performs very well in terms of thermal performance, embodied energy, and embodied carbon; it is a high-quality environmentally friendly insulating material. A building constructed with LHC not only reduces carbon dioxide emissions but also cuts down energy consumption. However, according to the measurement results of the

ILWLAD operator, AAC is the finest concrete material. EPS performs poorly under all four measures, mainly because, according to the evaluation criteria system designed for this paper, its compressive strength is low, it consumes more energy, and produces more carbon dioxide in the manufacturing process than the other three materials.

The reasons for the inconsistent results can be summarized as follows:

First, ILOWLAD and ILOWAD take the ordering mechanism of the parameters into account and pay more attention to the importance of ordered deviation. But, ILWLAD considers the importance of the criteria. Under this measure, AAC is superior to the other three concrete materials in the economic aspect. Hence, the distance between AAC and the ideal solution is lowest in terms of the purchase cost criterion. However, during the aggregation process of the ILOWLAD and the ILOWAD operators, the higher weights are coordinated by those larger intuitionistic linguistic distance values, in which LHC performs best. Hence, the distance between it and the ideal solution is the smallest.

Second, unlike the ILOWAD operator, the ILOWLAD operator performs logarithmic transformation of distance. If the evaluation of an alternative is closer to the ideal solution under a certain criterion, the advantage of logarithmic transformation will be clearer. In this case, AAC is the closest to the ideal solution under the purchase cost criterion, which increases the gap between AAC and HCB, so that the second and third place results obtained by the two measures are different.

As has been noted, ILWLAD prioritizes the criteria, whereas the ILOWLAD measure only accounts for the importance of the ordered deviation. Therefore, ILWLAD and ILOWLAD take into account different stages in the assembly process. ILHWLAD makes up for this deficiency by taking input arguments and the ordered position into account simultaneously. Hence, it is the modest among the four operators.

5. Conclusions

Concrete plays a vital role in the construction industry; it helps to determine the strength, thermal performance, and relative humidity of buildings. At the same time, it is one of the major sources of energy consumption and carbon emissions, though certain types of concrete contribute to energy sustainability more than others. In this paper, we proposed an HWLAD-MCDM framework for the selection of the finest concrete materials under an intuitionistic linguistic fuzzy environment. The four alternative concrete materials LHC, AAC, HCB, and EPS were evaluated using six criteria (embodied energy, embodied carbon, purchase cost, thermal performance, ability to balance outdoor humidity fluctuations, and compressive strength), which encompass energy sustainability, economic performance, comfort, and safety. The OWLAD, WLAD, ILOWLAD, and ILWLAD operators were used in combination with an ILS. We, then, presented the new ILHWLAD operator, which addresses the limitations of the latter two. In addition, instead of using the traditional AHP and entropy method, we used a programming model to calculate the weight under incomplete information. The MCDM method based on the ILHWLAD operator was proposed for the selection of the finest concrete material, and the results are compared with those obtained by ILOWLAD, ILOWAD, and ILWLAD.

The MCDM framework based on the ILHWLAD operator allows a new way of making decisions, and its field of application is not limited to the selection of concrete materials. In further research, both methodological developments and new areas of application should be considered. With regard to the former, the expert weighting scheme could be employed in a more objective manner. In addition, we should try to expand further the new operator and implement it in more complex areas.

Data Availability

All data generated and analyzed during this study are included in the published paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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