An Integrated EDAS-ELECTRE Method with Picture Fuzzy Information for Cleaner Production Evaluation in Gold Mines

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ABSTRACT Faced with the contradiction between economic growth and environmental pollution, implementing cleaner production has become a good choice for many mining companies to achieve sustainable development. This study aims to evaluate the cleaner production for gold mines by exploring applicable decision making methods. First, the PFNs (picture fuzzy numbers) with four membership degrees are adopted to describe experts’ assessment information under complicated fuzzy environment. Thereafter, the extended SWARA (stepwise weight assessment ratio analysis) and mean-squared deviation models are combined to obtain the comprehensive criteria weights. Meanwhile, a novel evaluation method, which integrates the EDAS (evaluation based on distance from average solution) with ELECTRE (elimination and choice translating reality) module, is proposed to judge the cleaner production level. Subsequently, according to the characteristics of gold mines, an evaluation criteria system of cleaner production is constructed. Finally, a case of evaluating the cleaner production performance for four gold mines is provided to explain the application of the proposed method. Besides, a systematic comparison analysis with other existent methods is conducted to reveal the advantages of our method. Results indicate that the integrated EDAS-ELECTRE method is suitable and effective for gold mines to evaluate their cleaner production performance, and has important reference values for the cleaner production management and implementation.

INDEX TERMS Cleaner production evaluation, combined weights, EDAS (evaluation based on distance from average solution) approach, ELECTRE (elimination and choice translating reality) approach, PFNs (picture fuzzy numbers).

I. INTRODUCTION
In recent years, the industrial developments and expanding global population have led to increasing demands for mineral resources [1,2]. However, with the continuous large-scale exploitations of resources, serious environmental problems occur at the same time. Especially, huge quantities of waste residue [3], waste water [4] and waste gas [5] are generated with traditional production pattern in gold mines. The biggest flaw of the old production mode is that it achieves the economic growth at the expense of environmental disruption. In consequence, terrible adverse impacts are made not only on the ecological environment, but also on the health of surrounding people [6,7]. In order to resolve the contradiction between economic growth and environmental damage, a novel idea, the cleaner production, has been widely accepted and adopted. The implementation of cleaner production can help mining enterprises improve economic efficiency with the premise of environmental protection. As a crucial stage for realizing cleaner production, assessing the cleaner production performance is necessary for any company [8].

Due to the variety of evaluation criteria, the evaluation of cleaner production can be deemed as a multi-criteria decision making problem. Several evaluation methods have been developed to tackle such problems in different enterprises. Dong et al. [9] made some quantitative assessment of cleaner production with AHP (analytic hierarchy process) method for...
phosphorus chemical companies; Gong et al. [10] coalesced ER (the evidential reasoning) and DEA (data envelopment analysis) means to appraise cleaner production for iron and steel companies; Basappaji and Nagasaka [11] adopted the fuzzy logic to judge the cleaner production gradation for agro-based industries; Peng and Li [12] suggested a comprehensive evaluation model under interval-valued intuitionist fuzzy environment for assessing the cleaner production in aviation firms; Tseng et al. [13] extended the AHP with triangular fuzzy numbers to discriminate dissimilar criteria for printed wire board manufacturing enterprises. Nevertheless, evaluation information in these methods is expressed by crisp numbers, triangular fuzzy numbers or intuitionistic fuzzy extensions. Since the evaluation environment is complex, more suitable fuzzy extensions should be investigated to avoid the loss or distortion of assessment information.

In 2014, Cuong and Kreinovich [14] came up with the concept of PFNs (picture fuzzy sets) to extend the fuzzy set theory. Unlike other types of fuzzy numbers, there are four membership degrees (i.e., the positive, neutral, negative and refusal membership degrees) in aPFN (picture fuzzy number) [15]. Thus, different formats of DMs’ (decision makers’) opinion expressions, like certainty, abstain, negation and refusal, can all be depicted correspondingly with these degrees [16,17]. Owing to the great advantage of sufficiently depicting experts’ preference or behaviors with PFNs, numerous researchers manifested strong interest in the decision making methods based on PFNs [18]. For instance, Wang et al. [19] put forward the weighted geometric aggregation operator and ordered weighted geometric aggregation operator under picture fuzzy conditions; Wei et al. [20] proposed a projection model on the basis of PFNs (picture fuzzy numbers) to deal with emerging technology commercialization evaluation issues; Wang et al. [21] extended the MABAC (multi-attributive border approximation area comparison) approach within picture fuzzy environment to construct a decision making framework; Ashraf et al. [22] suggested some multi-criteria group decision making models under picture fuzzy conditions; Wei and Gao [23] provided the generalized Dice similarity measures for PFNs.

Recently, Ghorabae et al. [24] recommended an innovative technique, the EDAS (evaluation based on distance from average solution) approach in the inventory classification process. Since only the distance from the average solution needs to be determined, the EDAS has the characteristic of simple calculation and high efficiency. Many scholars investigated the EDAS method in various fuzzy cases. Ghorabae et al. [25] extended the EDAS method with trapezoidal fuzzy numbers to tackle practical problems, like supplier selection; Kahraman et al. [26] picked out the solid waste disposal sites with an intuitionistic fuzzy EDAS approach; Peng and Liu [27] established an EDAS model under single-valued neutrosophic soft environment;

Keshavarz-Ghorabae et al. [28] suggested a dynamic fuzzy decision making method with EDAS to assess the subcontractor in the construction project; Ecer [29] combined the EDAS with AHP to choose the best third-party logistics provider. So far, the EDAS approach has not been modified to address decision making issues in picture fuzzy situations.

Even though the EDAS is a powerful module, it is still limited by its hypothesis that the evaluation criteria are compensatory. This assumption is unreasonable when some assessment criteria are non-compensatory in reality. For example, little resource or energy consumption cannot be regarded as the compensation for bad ecological environment in the cleaner production assessment process for gold mines. In this case, the ELECTRE (elimination and choice translating reality) approach [30] is combined with EDAS to get the ranking results in this study. As outranking methods, the ELECTRE family shows excellent performance in dealing with non-complementary criteria [31,32]. Meanwhile, numerous of ELECTRE models have been extended with various fuzzy extensions, such as the interval-valued intuitionistic fuzzy sets [33], interval 2-tuple linguistic sets [34], hesitant fuzzy linguistic term sets [35] and so on. Nevertheless, the ELECTRE method based on PFNs has not been researched.

On the other hand, because the evaluation environment is usually complicated and the knowledge of DMs is restrained, assigning the criteria weights directly in advance is tricky. Hence, determining the weight of each criterion is a necessary and vital step in the cleaner production evaluation process. Plenty of useful weights determination techniques have been developed in existing literature, like the AHP [36], entropy weight ways [37], mean-squared deviation approach [38], SWARA (stepwise weight assessment ratio analysis) [39] and combination calculation models [40,41]. Among them, mean-squared deviation approach is a useful objective criteria weights determination method. By contrast, SWARA is developed for identifying importance of criteria and relative weight of each criterion subjectively. It gives the chance for decision and policy makers to select their priority based on the current situation of environment and economy. And the largest advantage of the combination calculation models is that not only the objective facts but also the subjective preferences of DMs are taken into consideration. Thus, this study introduces a new combination calculation model by integrating the extended SWARA and mean-squared deviation approaches to get the comprehensive criteria weights for cleaner production.

According to the analyses above, this study aims to integrate the EDAS with ELECTRE approaches for assessing the cleaner production of gold mines. The main novelties and contributions of this study are illustrated as follows:

First, the evaluation criteria of cleaner production for gold mines are distinguished. And the assessment information of DMs is expressed by PFNs, so that their behaviors or attitudes can be conveyed properly.
Second, a combination criteria weight determination technique is suggested. The subjective weights of evaluation criteria are obtained by using an extended SWARA model. Meanwhile, the objective criteria weights are calculated through the mean-squared deviation model. Then, the comprehensive weight vector is determined with their linear combination.

Third, a combined decision making method, the EDAS-ELECTRE method, is proposed. Different with the classical EDAS approach, the integrated method merges the idea of ELECTRE III approach to deal with the non-compensatory problem of cleaner production evaluation criteria.

Fourth, an example of cleaner production evaluation for four gold mines is illustrated to demonstrate the application of the proposed method. And an in-depth comparative analysis is also provided to reveal the advantages of our method.

The rest of this study is designed as follows. Section II briefly introduces the basic knowledge of PFNs. An integrated EDAS-ELECTRE method is presented in Section III. Four phases, like constructing assessment matrix, calculating overall criteria weights, establishing difference matrix and getting ranking results, are included. In Section IV, the detailed evaluation procedures of the proposed method are displayed by a case study after the evaluation criteria system is built. Section V makes some discussions through a comparison analysis. And essential conclusions are drawn in Section VI.

II. PRELIMINARIES
The definition, operations, aggregation operators, comparison method and distance measures of PFNs are reviewed in this section.

Definition 1 [14]: If an object can be denoted as \( A(y) = \{ y, u_A(y), h_A(y), v_A(y) | y \in Y \} \), it is called a PFS (picture fuzzy set) , where \( u_A(y) \in [0,1] \) is the positive membership degree of \( z \) in \( S \), \( h_A(y) \in [0,1] \) is the neutral membership degree of \( z \) in \( S \), and \( v_A(y) \in [0,1] \) is the negative membership degree of \( z \) in \( S \), and \( g_A(y) = 1 - u_A(y) - h_A(y) - v_A(y) \in [0,1] \) is the refusal membership degree of \( z \) in \( S \).

Specially, if only one element exists in the PFS \( A(y) \), \( A \) is degenerated to a PFN \( A = \langle u_A, h_A, v_A \rangle \).

Definition 2 [19]: Let \( A = \langle u_A, h_A, v_A \rangle \) and \( B = \langle u_B, h_B, v_B \rangle \) be two arbitrary PFNs, \( \sigma > 0 \), their operations are defined as
\[
A \oplus B = 1 - (1 - u_A)(1 - u_B), h_Ah_B, (v_A + h_A + h_B + h_A + h_B - h_Ah_B, h_A + h_B, v_A + h_A + h_B + h_A + h_B - h_Ah_B; \quad (1)
\]
\[
A \ominus B = (u_A + h_A)(u_B + h_B), h_A + h_B, (v_A + h_A + h_B, h_A + h_B, (1 - v_A)(1 - v_B); \quad (2)
\]
\[
\partial A = 1 - (1 - u_A)^\sigma, (h_A)^\sigma, (v_A + h_A)^\sigma - (h_A)^\sigma, \quad (3)
\]
\[
A^c = (u_A + h_A)^\sigma - (h_A)^\sigma, (h_A)^\sigma, (1 - v_A)^\sigma. \quad (4)
\]

Definition 3 [18]: Given a group of PFNs \( A_i = \langle u_{A_i}, h_{A_i}, v_{A_i} \rangle \), the PFWAA (picture fuzzy weighted arithmetic average) operator is defined as
\[
PFWAA(A_1, A_2, ..., A_n) = \sum_{i=1}^{n} \omega_i \cdot A_i = 1 - \prod_{i=1}^{n} (1 - u_{A_i}), \prod_{i=1}^{n} (h_{A_i})^\sigma, \prod_{i=1}^{n} (v_{A_i} + h_{A_i})^\sigma - \prod_{i=1}^{n} (h_{A_i})^\sigma > \quad (5)
\]
where \( \omega_i \in [0,1] \) is the weight of \( A_i \) and \( \sum_{i=1}^{n} \omega_i = 1 \).

Definition 4 [19]: Given a group of PFNs \( A_i = \langle u_{A_i}, h_{A_i}, v_{A_i} \rangle \), the PFWGA (picture fuzzy weighted geometric average) operator is defined as
\[
PFWGA(A_1, A_2, ..., A_n) = \prod_{i=1}^{n} (A_i) = <\prod_{i=1}^{n} (u_{A_i} + h_{A_i}), \prod_{i=1}^{n} (h_{A_i})^\sigma, 1 - \prod_{i=1}^{n} (1 - v_{A_i}), > \quad (6)
\]
where \( \omega_i \in [0,1] \) is the weight of \( A_i \) and \( \sum_{i=1}^{n} \omega_i = 1 \).

Definition 5 [19]: Suppose \( A = \langle u_A, h_A, v_A \rangle > \) is a PFN, then the score function and accuracy function of \( A \) are respectively defined as follows:
\[
\alpha(A) = u_A - v_A, \quad (7)
\]
\[
\beta(A) = u_A + h_A + v_A. \quad (8)
\]

Definition 6 [19]: Assume \( A = \langle u_A, h_A, v_A \rangle \) and \( B = \langle u_B, h_B, v_B \rangle \) are two PFNs, the comparison method between \( A \) and \( B \) is

(1) if \( \alpha(A) > \alpha(B) \), then \( A > B \);

(2) if \( \alpha(A) = \alpha(B) \), then \( \beta(A)/\beta(B) \Rightarrow A > B \).

Definition 7 [21]: Given two PFNs \( A = \langle u_A, h_A, v_A \rangle \) and \( B = \langle u_B, h_B, v_B \rangle \), the generalized distance between \( A \) and \( B \) is measured with
\[
d(A, B) = \sqrt{\left| u_A - u_B \right|^\theta + \left| h_A - h_B \right|^\theta + \left| v_A - v_B \right|^\theta + \left| g_A - g_B \right|^\theta} \quad (9)
\]
where \( \theta > 0 \).

Particularly, a Hamming distance is calculated if \( \theta = 1 \) in the following:
\[
d_1(A, B) = \left| u_A - u_B \right| + \left| h_A - h_B \right| + \left| v_A - v_B \right| + \left| g_A - g_B \right| \quad (10)
\]
and an Euclidean distance is computed if \( \theta = 2 \) in the following:
\[
d_2(A, B) = \sqrt{\left| u_A - u_B \right|^2 + \left| h_A - h_B \right|^2 + \left| v_A - v_B \right|^2 + \left| g_A - g_B \right|^2} \quad (11)
\]

III. INTEGRATED EDAS-ELECTRE METHOD
In this section, an integrated EDAS-ELECTRE method is proposed to solve multi-criteria decision making problems under picture fuzzy circumstances. The framework of the proposed method is depicted in Fig. 1. It can be seen that the integrated EDAS-ELECTRE method contains four phases: Construct the decision making matrix, determine the
comprehensive criteria weights, establish the difference matrix using EDAS approach and obtain the ranking orders employing ELECTRE III approach.

A. PHASE I: Construct the decision making matrix
In this phase, a normalized decision making matrix is established. Taking into account the uncertainty and inconsistency of DMs' preference, PFNs are utilized to describe evaluation information in this study.

In this case, a voting mechanism is adopted among a certain number of DMs. For example, given that there are five DMs and the assessment benchmarks are separated into three levels: “high”, “medium” and “low”. Then the PFN \( z_{ij} = (0.2, 0.4, 0.2) \) can depict a situation as follows: An expert believes that high grade can be assigned to alternative \( \varphi_i \) against criterion \( \pi_j \), two DMs hold that the level of \( \varphi_i \) against \( \pi_j \) is medium, one specialist thinks that the rank of \( \varphi_i \) against \( \pi_j \) is low, and one DM refuses to provide a judgment.

By using this voting technique for each alternative under each criterion, an initial decision making matrix can be obtained as

\[
Z = \varphi_1 \left[ \begin{array}{cccc} z_{11} & z_{12} & \cdots & z_{1m} \\
\vdots & \vdots & \ddots & \vdots \\
z_{n1} & z_{n2} & \cdots & z_{nm} \end{array} \right],
\]

(12)

where \( z_{ij} = (u_i, h_i, v_i) \) is a PFN for alternative \( \varphi_i \) \((i = 1, 2, \ldots, n)\) against criterion \( \pi_j \) \((j = 1, 2, \ldots, m)\).

Considering that both benefit and cost criteria may exist in an evaluation matrix, a normalization equation is given as follows [21]:

\[
x_j = \begin{cases} (u_j, h_j, v_j) & \text{under benefit criteria} \\ (v_j, h_j, u_j) & \text{under cost criteria} \end{cases}
\]

(13)

Then, a normalized assessment matrix is constructed as

\[
X = \varphi_2 \left[ \begin{array}{cccc} x_{11} & x_{12} & \cdots & x_{1m} \\
\vdots & \vdots & \ddots & \vdots \\
x_{n1} & x_{n2} & \cdots & x_{nm} \end{array} \right].
\]

(14)

B. Phase II: Determine the comprehensive criteria weights
In this phase, the criteria weight vector is obtained through combining the extended SWARA (subjective weights determination manner) and mean-squared deviation models (objective weights). The detailed calculation steps are provided as follows.

Step 1: Calculate the subjective weight values with extended SWARA model.

In this Step, the modified SWARA model recommended by Liang et al. [42] is used to obtain the subjective weight values. At first, on the basis of importance degree, the assessment criteria are ranked in descending order \( \pi_{(1)} \succ \pi_{(2)} \succ \cdots \succ \pi_{(n)} \). Then, a linguistic value is used to describe the relative importance degree of criterion \( \pi_{(j)} \) over \( \pi_{(j-1)} \), and the value of the relative importance index \( p_j \) is acquired based on Table 1.

Thereafter, the importance degree of each criterion can be computed by

\[
c_{(j)} = c_{(j-1)} f(p_j + 1), \quad (j = 2, 3, \ldots, m). \quad (15)
\]

In particular, the \( c_{(j)} \) value of the most important criterion \( \pi_{(1)} \) is \( c_{(1)} = 1 \).

Thus, the subjective criteria weights are determined by

\[
o_{(j)} = c_{(j)} f\left(\sum_{j=2}^{m} c_{(j)}\right), \quad (j = 1, 2, \ldots, m). \quad (16)
\]

Note that: \( o_{(j)} \) is the subjective criterion weight \( o_j \) ranked by descending order.

Step 2: Compute the objective weight values with mean-squared deviation model.

At first, the mean value \( x_j \) under each criterion is calculated by using the PFWGA operator as follows:

\[
x_j = \text{PFWGA}(x_{j1}, x_{j2}, \ldots, x_{jm}) = \prod_{i=1}^{m} (x_{ij})^{w_i} \quad (j = 1, 2, \ldots, m),
\]

(17)

where \( w_1 = w_2 = \cdots = w_n = 1/n \).

Subsequently, the mean-squared deviation value under each criterion is computed by

\[
msq(x_j) = \sqrt{\sum_{i=1}^{m} \left( d_{ij}(x_j - x_i) \right)^2} \quad (j = 1, 2, \ldots, m),
\]

(18)

where \( d_{ij}(x_j - x_i) \), defined in Definition 7, is the picture fuzzy distance measure between \( x_j \) and \( x_i \).

As a result, the objective criteria weights are determined by

\[
o_{(j)} = msq(x_j) f\left(\sum_{j=2}^{m} msq(x_j)\right), \quad (j = 1, 2, \ldots, m). \quad (19)
\]

Step 3: Obtain the combined criteria weights.

Since both the subjective and objective weight vectors are determined, the comprehensive criteria weights are computed with their linear combination as follows:

\[
o_j = \lambda \cdot o_{(j)} + (1-\lambda) \cdot o_j,
\]

(20)

where \( \lambda \in [0,1] \) is an adjustment parameter to indicate the relative importance between subjective and objective criteria weights. Generally, \( \lambda = 0.5 \).

C. Phase III: Establish the difference matrix using EDAS approach
In this phase, the idea of EDAS approach is accepted to establish a difference matrix. The followings are the computation processes in detail.

Step 1: Attain the average solutions under criteria.
According to (5), the average solution $\Gamma_j$ under criterion $\pi_j$ is obtained as

$$\Gamma_j = PFWAA(x_{ij}, x_{2j}, \ldots, x_{nj}) = \sum_{i=1}^{n} (w_i \cdot x_{ij}) \quad (j = 1, 2, \ldots, m),$$

where $w_1 = w_2 = \cdots = w_n = 1/n$.

Step 2: Compute both the positive and negative distance from average matrices.

The positive distance $P_{ij}$ from average is calculated by

$$P_{ij} = \frac{\max(0, (\alpha(x_{ij}) - \alpha(\Gamma_j)))}{\alpha(\Gamma_j))}, \quad (22)$$

where $\alpha(x_{ij})$ and $\alpha(\Gamma_j)$ are respectively the score function values of $x_{ij}$ and $\Gamma_j$ based on (7).

The negative distance $N_{ij}$ from average is calculated by

$$N_{ij} = \frac{\max(0, (\alpha(\Gamma_j) - \alpha(x_{ij})))}{\alpha(\Gamma_j))} \quad (23)$$

Step 3: Build the difference matrices.

On the basis of (22)-(23), the difference matrix $Q = (q_{ij})_{nm}$ is denoted as

$$q_{ij} = \begin{cases} \frac{1}{2}(P_{ij} + N_{ij}) & \text{when } x_{ij} \succ \Gamma_j \text{ or } x_{ij} \sim \Gamma_j \\ \frac{1}{2}(P_{ij} + N_{ij}) & \text{when } x_{ij} \prec \Gamma_j \end{cases} \quad (24)$$

D. Phase IV: Obtain the ranking orders employing ELECTRE III approach

In this phase, the ELECTRE III approach is suggested to get the final ranking orders of alternatives. The details are shown in the reminder of this subsection.

Step 1: Compute the concordance index.

The concordance index between alternative $\varphi_i$ and $\varphi_j$ is determined with

$$CI(\varphi_i, \varphi_j) = \sum_{j=1}^{m} (\alpha_{ij} \cdot \eta(q_{ij}, q_{ij})), \quad (25)$$

where $\eta(q_{ij}, q_{ij}) = \begin{cases} 0, & q_{ij} \sim q_{ij} \\ \frac{\Delta_j + q_{ij} - q_{ij}}{\Delta_j - \Delta_j}, & \Delta_j < q_{ij} \sim q_{ij} < \Delta_j \\ 1, & q_{ij} \sim q_{ij} \leq \Delta_j \end{cases}$

$\Delta_j$ and $\Delta_j$ are the indifference and preference thresholds against criterion $\pi_j$, respectively, and $0 \leq \Delta_j \leq \Delta_j$.

Step 2: Calculate the credibility index.

The discordance degree between $q_{ij}$ and $q_{ij}$ is obtained with

$$DI(q_{ij}, q_{ij}) = \begin{cases} 0, & q_{ij} \sim q_{ij} \leq \Delta_j \\ \frac{q_{ij} - q_{ij}}{\Delta_j}, & \Delta_j < q_{ij} \sim q_{ij} < \Delta_j \\ 1, & q_{ij} \sim q_{ij} \geq \Delta_j \end{cases} \quad (26)$$

where $0 \leq \Delta_j \leq \Delta_j$.

Then, the credibility index of alternative $\varphi_i$ over $\varphi_j$ is computed by

$$CR(\varphi_i, \varphi_j) = CI(\varphi_i, \varphi_j) \cdot \prod_{j=1}^{m} BI_i(\varphi_i, \varphi_j), \quad (27)$$

where $BI_i(\varphi_i, \varphi_j)$ is defined as

$$BI_i(\varphi_i, \varphi_j) = \begin{cases} 1 - DI(q_{ij}, q_{ij}), & \text{when } DI(q_{ij}, q_{ij}) > CI(\varphi_i, \varphi_j) \\ 1, & \text{when } DI(q_{ij}, q_{ij}) \leq CI(\varphi_i, \varphi_j) \end{cases}$$

Step 3: Get the rankings based on the ranking index.

The ranking index of alternative $\varphi_i$ ($i = 1, 2, \ldots, n$) is calculated with

$$RI(\varphi_i) = \sum_{i=1}^{n} CR(\varphi_i, \varphi_i) - \sum_{i=1}^{n} CR(\varphi_i, \varphi_j) \quad (28)$$

Finally, the rank of each alternative can be obtained in line with the value of the corresponding ranking index value. That is to say, a larger value of $RI(\varphi_i)$ indicates a better alternative $\varphi_i$.

IV. CASE STUDY

In this section, a case is researched by employing the proposed method to assess the cleaner production for gold mines.

A. Evaluation criteria system

In this subsection, an evaluation criteria system of cleaner production including seven criteria is established according to the specific characteristics of gold mines and some literature [9,37,43] about cleaner production. More details are demonstrated in Table 2.

B. Evaluation procedures and results

In this subsection, the proposed method is applied to make evaluations of cleaner production for four gold mines after the influence indicators are identified.

In Phase I, DMs are invited to make judgments for alternatives under criteria according to Table 3. Thereafter, their evaluation information can be transformed into PFNs. The original evaluation matrix $Z$ is shown in Table 4. Since the criteria $\pi_i$ and $\pi_i$ belong to cost type whereas other criteria are benefit type, based on (13), a normalized decision making matrix $X$ is obtained in Table 5.

In Phase II, the extended SWARA model is utilized to obtain the subjective criteria weights. After discussions, DMs provide the rankings of criteria according to their significance as: $\pi_1 \succ \pi_2 \sim \pi_3 \succ \pi_4 \succ \pi_5 \succ \pi_6 \succ \pi_7 \succ \pi_8$. Then, the relative importance degrees between adjacent criteria are also given with linguistic evaluation values in the second column of Table 6. Based on Table 1 and (15)-(16), the subjective weight values are calculated, as shown in Table 6.

Subsequently, the mean-squared deviation model is advised to compute the objective criteria weights. By using (17), the mean value of each alternative is calculated as: $x_1 = (0.471, 0.221, 0.252)$, $x_2 = (0.542, 0.200, 0.229)$,
Within different ranking orders; two similar ranks can be

is another statistic to demonstrate the

Suppose \( \lambda = 0.5 \), the combined criteria weights are computed with (20) as:

\( \alpha_1 = 0.190 \), \( \alpha_2 = 0.161 \), \( \alpha_3 = 0.137 \), \( \alpha_4 = 0.129 \),

\( \alpha_5 = 0.138 \), \( \alpha_6 = 0.109 \) and \( \alpha_7 = 0.136 \).

In Phase III, a difference matrix is built with the EDAS approach. At first, the average solution against each criterion is calculated by using (21) as: \( \Gamma_1 = (0.452,0.221,0.274) \), \( \Gamma_2 = (0.539,0.200,0.236) \), \( \Gamma_3 = (0.654,0.141,0.150) \), \( \Gamma_4 = (0.482,0.132,0.304) \), \( \Gamma_5 = (0.560,0.119,0.212) \), \( \Gamma_6 = (0.624,0.157,0.174) \) and \( \Gamma_7 = (0.640,0.157,0.126) \).

Then, based on (22) and (23), the positive distance from average matrix \( \bar{P} \) and negative distance from average matrix \( \bar{N} \) are obtained in Table 7 and Table 8, respectively. At last, on the basis of (24), the difference matrix \( Q \) is determined, as shown in Table 9.

In Phase IV, the ranking orders are acquired by using the ELECTRE III approach. Firstly, let \( \Delta_1 = 0.1 \) and \( \nabla_j = 0.2 \) for all criteria, based on (25), the concordance indexes between two different alternatives are computed, as shown in Table 10. Meanwhile, assume \( \Upsilon_j = 0.5 \) for all criteria, the credibility indexes of a certain alternative over another one are calculated by using (26)-(27), as shown in Table 11. Finally, on the basis of (28), the ranking index of each alternative is determined as:

\( RI(\varphi_1) = -0.755 \), \( RI(\varphi_2) = 1.617 \), \( RI(\varphi_3) = -0.058 \) and \( RI(\varphi_4) = -0.805 \).

Since \( RI(\varphi_2) > RI(\varphi_3) > RI(\varphi_1) > RI(\varphi_4) \), then the ranking order of alternatives is \( \varphi_2 > \varphi_3 > \varphi_1 > \varphi_4 \) and the best alternative is \( \varphi_2 \).

### V. COMPARATIVE ANALYSIS and DISCUSSIONS

In this section, a comparative analysis with distinct decision making methods is conducted to reveal the validity and highlights of the integrated EDAS-ELECTRE method. The ranking results by using diverse methods are displayed in Table 12.

In the following, the aggregation means proposed by Jahan et al. [44] is adopted to select the optimal ranking order.

At first, the numbers of times a mine is assigned to diverse ranking orders are accounted (See Table 13). Take \( \varphi_1 \) as an example, the times of the ranking of 2 is one, that of 3 is two and that of 4 is two. Thereafter, the smoothing of mines distribution over ranks is calculated, as exhibited in Table 14.

At last, the best ranking result \( \varphi_2 \succ \varphi_3 \succ \varphi_1 \succ \varphi_4 \) is attained through resolving the following model:

\[
\begin{align*}
\text{Max } & K = \sum_{i=1}^{4} \sum_{f=1}^{4} (S_{i,f} \cdot f^{-1/2} \cdot W_{i,f}) \\
\text{s.t. } & \sum_{i=1}^{4} W_{i,f} = 1, \quad f = 1, 2, 3, 4 \\
& \sum_{i=1}^{4} W_{i,f} = 1, \quad i = 1, 2, 3, 4 \\
& W_{i,f} = 0 \text{ or } 1 
\end{align*}
\]

(29)

For visibility, this optimal order and the ranking orders listed in Table 12 are all described in Fig. 2. It is clear that the ranking orders by using Model (29), the PFWGA operator and our method are the same. That is to say, our method is more favorable than other techniques (i.e., the PFWGA operator, extended MABAC and traditional EDAS) for addressing cleaner production problems for gold mines.

To further justify the strength of the proposed method, the Spearman’s rank-correlation test [45] is suggested to indicate the discrepancy among the best order and other rankings in Table 12.

In the Spearman’s rank-correlation test, two significant equations are used as [44]:

\[
\Xi = 1 - \frac{6 \cdot \sum_{i=1}^{n} (\text{dis}(\varphi_i))^2}{n(n^2-1)},
\]

(30)

\[
\zeta = 3 \cdot \sqrt{n-1},
\]

(31)

where \( \Xi \in [-1,1] \) is a statistic to reveal the relations among various ranking orders, and a closer value between \( \Xi \) and 1 (or -1) represents a higher correlation between two ranking results (In particular, if \( \Xi = 1 \) or \( -1 \), an entirely direct or inverse relation between different ranking orders can be recognized); \( \text{dis}(\varphi_i) \) is the difference degree for the gold mine \( \varphi_i \) within different ranking orders; \( n \) is the number of gold mines; \( \zeta \) is another statistic to demonstrate the relationships, and if \( \zeta \geq 1.645 \), two similar ranks can be identified even using two different methods.

Then, based on (30) and (31), the values of \( \Xi \) and \( \zeta \) are calculated in the fourth and fifth columns of Table 12. It can be seen that the extended MABAC and classical EDAS approaches have the largest deviation values, followed by the PFWGA operator. At the same time, completely positive relationships among the rankings in the PFWGA operator, the proposed method and Model (29) are demonstrated. It indicates that our method is more applicable than majority of picture fuzzy methods for evaluating cleaner production performance in gold mines. The probable reason for this conclusion may be that the ideas and application conditions of different decision making methods are dissimilar. The EDAS-ELECTRE method displays unique ability in the situation where non-complementary criteria exist, whereas other methods are all based on the assumption of the compensation trait of evaluation criteria. Within the
evaluation issue of cleaner production for gold mines, assessment criteria are non-compensatory, so that our method performed well in this case. Besides, the same ranking orders of the PFWAA operators and the proposed method may be caused by the original evaluation information.

In summary, the highlights of the proposed method are listed as follows:

1. The PFNs are used for DMs to express evaluation information under complex decision making circumstances, so that more types of assessment answers can be contained in the original decision making matrix.

2. In the process of determining criteria weights, not only the objective facts but also the preference and attitudes of DMs are taken into consideration. As a result, a more comprehensive weight vector can be obtained.

3. The traditional EDAS approach is modified with the idea of ELECTRE III to efficiently handle the situation when some evaluation criteria cannot be compensated for each other.

VI. CONCLUSIONS
Considering the negative effects of the traditional production pattern on environment, more and more mining companies prefer to choose cleaner production as the means of achieving sustainable development. This study focused on establishing appropriate frameworks to assess the cleaner production capability for gold mines. Seven primary evaluation criteria were identified and PFNs were introduced for DMs to adequately describe their opinions under these criteria. Then, the traditional EDAS and ELECTRE III approaches were integrated to select the optimal mine among four gold mines in the terms of cleaner production. The key motivations of recommending the combined EDAS-ELECTRE method are two-fold. First, the EDAS is a convenient and efficient approach for DMs to make evaluations even under picture fuzzy environment. Second, the idea of ELECTRE III was blended into the classical EDAS model for addressing the non-compensatory issues of cleaner production evaluation criteria. Furthermore, a comprehensive weight determination technique based on SWARA and mean-squared deviation approach was presented to get the combined criteria weights. The case study and comparative analysis justified that the proposed method performed great practicability and efficiency in the process of assessing cleaner production for gold mines.

Even though the non-compensation feature of criteria was considered in this study, other interrelationships among criteria are not taken into account. On the basis of the preceding investigations, finding eligible decision making methods to solve practical problems under different conditions is necessary in the future. Moreover, further exploration of cleaner production assessment criteria is significant as well.

APPENDIX
Table 1. Relative importance index [39].

<table>
<thead>
<tr>
<th>Linguistic variables</th>
<th>Relative importance index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equally important (EI)</td>
<td>0</td>
</tr>
<tr>
<td>A little more important (ALMI)</td>
<td>0.25</td>
</tr>
<tr>
<td>Much more important (MMM)</td>
<td>0.5</td>
</tr>
<tr>
<td>Far more important (FMI)</td>
<td>0.75</td>
</tr>
<tr>
<td>A lot more important (ALMIM)</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Evaluation criteria of cleaner production for gold mines.

<table>
<thead>
<tr>
<th>Primary criteria</th>
<th>Benefit/Cost</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production process and equipment $\pi_1$</td>
<td>Benefit</td>
<td>It indicates the level of production process and equipment, which contains the mining technology and production equipment.</td>
</tr>
<tr>
<td>Resource and energy consumption $\pi_2$</td>
<td>Cost</td>
<td>It indicates the consumption of resource and energy, which contains the water consumption of unit product and comprehensive energy consumption of unit product.</td>
</tr>
<tr>
<td>Waste utilization $\pi_3$</td>
<td>Benefit</td>
<td>It indicates the comprehensive utilization of waste, which contains the utilization rate of solid waste, utilization rate of waste water and utilization rate of associated resources.</td>
</tr>
<tr>
<td>Pollutants emission $\pi_4$</td>
<td>Cost</td>
<td>It indicates the emission of various pollutants, which contains the solid waste disposal rate, standard discharge rate of wastewater and standard discharge rate of exhaust gas.</td>
</tr>
<tr>
<td>Ecological environment $\pi_5$</td>
<td>Benefit</td>
<td>It indicates the governance of ecological environment, which contains the land reclamation rate and greening rate of industrial sites.</td>
</tr>
<tr>
<td>Product characteristics $\pi_6$</td>
<td>Benefit</td>
<td>It indicates the green characteristics of product, which contains the loss rate of gold ore and dilution rate of gold ore.</td>
</tr>
<tr>
<td>Management level $\pi_7$</td>
<td>Benefit</td>
<td>It indicates the management level of cleaner production, which contains the integrality of cleaner production regulations and execution of cleaner production.</td>
</tr>
</tbody>
</table>
Table 3. Evaluation table of cleaner production in gold mines.

<table>
<thead>
<tr>
<th>Primary criteria</th>
<th>Opinions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production process and equipment</td>
<td>High performance</td>
</tr>
<tr>
<td></td>
<td>Medium performance</td>
</tr>
<tr>
<td></td>
<td>Low performance</td>
</tr>
<tr>
<td>Resource and energy consumption</td>
<td>High consumption</td>
</tr>
<tr>
<td></td>
<td>Medium consumption</td>
</tr>
<tr>
<td></td>
<td>Low consumption</td>
</tr>
<tr>
<td>Waste utilization</td>
<td>High utilization</td>
</tr>
<tr>
<td></td>
<td>Medium utilization</td>
</tr>
<tr>
<td></td>
<td>Low utilization</td>
</tr>
<tr>
<td>Pollutants emission</td>
<td>High emission</td>
</tr>
<tr>
<td></td>
<td>Medium emission</td>
</tr>
<tr>
<td></td>
<td>Low emission</td>
</tr>
<tr>
<td>Ecological environment</td>
<td>High performance</td>
</tr>
<tr>
<td></td>
<td>Medium performance</td>
</tr>
<tr>
<td></td>
<td>Low performance</td>
</tr>
<tr>
<td>Product characteristics</td>
<td>High quality</td>
</tr>
<tr>
<td></td>
<td>Medium quality</td>
</tr>
<tr>
<td></td>
<td>Low quality</td>
</tr>
<tr>
<td>Management level</td>
<td>High level</td>
</tr>
<tr>
<td></td>
<td>Medium level</td>
</tr>
<tr>
<td></td>
<td>Low level</td>
</tr>
</tbody>
</table>

Table 4. Initial decision making matrix \( Z \).

<table>
<thead>
<tr>
<th>( Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_1 )</td>
</tr>
<tr>
<td>( \pi_2 )</td>
</tr>
<tr>
<td>( \pi_3 )</td>
</tr>
<tr>
<td>( \pi_4 )</td>
</tr>
<tr>
<td>( \pi_5 )</td>
</tr>
<tr>
<td>( \pi_6 )</td>
</tr>
<tr>
<td>( \pi_7 )</td>
</tr>
</tbody>
</table>

Table 5. Normalized assessment matrix \( X \).

<table>
<thead>
<tr>
<th>( X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_1 )</td>
</tr>
<tr>
<td>( \pi_2 )</td>
</tr>
<tr>
<td>( \pi_3 )</td>
</tr>
<tr>
<td>( \pi_4 )</td>
</tr>
<tr>
<td>( \pi_5 )</td>
</tr>
<tr>
<td>( \pi_6 )</td>
</tr>
<tr>
<td>( \pi_7 )</td>
</tr>
</tbody>
</table>

Table 6. Subjective criteria weights.

<table>
<thead>
<tr>
<th>Linguistic values</th>
<th>Relative importance index ( p_{(j)} )</th>
<th>Importance degree ( c_{(j)} )</th>
<th>Subjective weights ( \omega_{(j)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi_1 )</td>
<td>1</td>
<td>0.667</td>
<td>0.175</td>
</tr>
<tr>
<td>( \pi_2 )</td>
<td>MMM</td>
<td>0.667</td>
<td>0.175</td>
</tr>
<tr>
<td>( \pi_3 )</td>
<td>EI</td>
<td>0.533</td>
<td>0.140</td>
</tr>
<tr>
<td>( \pi_4 )</td>
<td>ALMI</td>
<td>0.427</td>
<td>0.112</td>
</tr>
<tr>
<td>( \pi_5 )</td>
<td>ALMI</td>
<td>0.285</td>
<td>0.075</td>
</tr>
<tr>
<td>( \pi_6 )</td>
<td>ALMI</td>
<td>0.228</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Table 7. Positive distance from average matrix \( P \).

<table>
<thead>
<tr>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi_1 )</td>
</tr>
<tr>
<td>( \pi_1 )</td>
</tr>
<tr>
<td>( \pi_2 )</td>
</tr>
<tr>
<td>( \pi_3 )</td>
</tr>
<tr>
<td>( \pi_4 )</td>
</tr>
<tr>
<td>( \pi_5 )</td>
</tr>
<tr>
<td>( \pi_6 )</td>
</tr>
<tr>
<td>( \pi_7 )</td>
</tr>
</tbody>
</table>

Table 8. Negative distance from average matrix \( N \).

| \( \phi_1 \) | \( \phi_2 \) | \( \phi_3 \) | \( \phi_4 \) |
| \( \pi_1 \) | -0.220 | 0.060 | 0.339 | 0.060 |
| \( \pi_2 \) | -0.171 | 0.487 | -0.171 | -0.171 |
| \( \pi_3 \) | 0.096 | -0.004 | -0.103 | -0.004 |
| \( \pi_4 \) | 0.062 | 0.623 | -0.500 | -0.219 |
| \( \pi_5 \) | -0.356 | 0.075 | -0.213 | 0.362 |
| \( \pi_6 \) | 0.279 | -0.055 | -0.055 | -0.278 |
| \( \pi_7 \) | 0.084 | -0.305 | 0.279 | -0.208 |

Table 9. Difference matrix \( Q \).

| \( \phi_1 \) | \( \phi_2 \) | \( \phi_3 \) | \( \phi_4 \) |
| \( \phi_1 \) | 1.000 | 0.382 | 0.621 | 0.672 |
| \( \phi_2 \) | 0.755 | 1.000 | 0.674 | 0.862 |
| \( \phi_3 \) | 0.627 | 0.572 | 1.000 | 0.733 |
| \( \phi_4 \) | 0.626 | 0.601 | 0.565 | 1.000 |

Table 10. Concordance index between two different alternatives.

| \( \phi_1 \) | \( \phi_2 \) | \( \phi_3 \) | \( \phi_4 \) |
| \( \phi_1 \) | 1.000 | 0.000 | 0.000 | 0.000 |
| \( \phi_2 \) | 0.755 | 1.000 | 0.000 | 0.862 |
| \( \phi_3 \) | 0.000 | 0.000 | 1.000 | 0.000 |
| \( \phi_4 \) | 0.000 | 0.000 | 0.058 | 1.000 |

Table 11. Credibility index between two different alternatives.

<p>| ( \phi_1 ) | ( \phi_2 ) | ( \phi_3 ) | ( \phi_4 ) |
| ( \phi_1 ) | 1.000 | 0.000 | 0.000 | 1.732 |</p>
<table>
<thead>
<tr>
<th>Method</th>
<th>Rank 1</th>
<th>Rank 2</th>
<th>Rank 3</th>
<th>Rank 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFWAA operator [17]</td>
<td>( \varphi_2 \succ \varphi_3 \succ \varphi_4 )</td>
<td>( \varphi_2 )</td>
<td>0.2</td>
<td>0.346</td>
</tr>
<tr>
<td>Extended MABAC [19]</td>
<td>( \varphi_2 \succ \varphi_3 \succ \varphi_1 )</td>
<td>( \varphi_2 )</td>
<td>-0.8</td>
<td>-1.386</td>
</tr>
<tr>
<td>Traditional EDAS</td>
<td>( \varphi_2 \succ \varphi_3 \succ \varphi_1 )</td>
<td>( \varphi_2 )</td>
<td>-0.8</td>
<td>-1.386</td>
</tr>
<tr>
<td>The proposed method</td>
<td>( \varphi_2 \succ \varphi_3 \succ \varphi_1 )</td>
<td>( \varphi_3 )</td>
<td>1</td>
<td>1.732</td>
</tr>
</tbody>
</table>

Table 13. Numbers of times of a mine is assigned to dissimilar ranks.

<table>
<thead>
<tr>
<th>Gold mines</th>
<th>Rank 1</th>
<th>Rank 2</th>
<th>Rank 3</th>
<th>Rank 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi_1 )</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( \varphi_2 )</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varphi_3 )</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varphi_4 )</td>
<td></td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Table 14. Smoothing of mines distribution over ranks (\( S_{ij} \)).

<table>
<thead>
<tr>
<th>Gold mines</th>
<th>Rank 1</th>
<th>Rank 2</th>
<th>Rank 3</th>
<th>Rank 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varphi_1 )</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>( \varphi_2 )</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( \varphi_3 )</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( \varphi_4 )</td>
<td>0</td>
<td>0</td>
<td>21</td>
<td>5</td>
</tr>
</tbody>
</table>
Phase I: Construct the decision making matrix

Construct an initial decision making matrix

- Evaluation criteria
- Experts decision group

Normalize the assessment matrix

- Benefit criteria
- Cost criteria

Phase II: Determine the comprehensive criteria weights

Extended SWARA model

- Rank the assessment criteria
- Get the relative importance index
- Compute the importance degree
- Calculate the subjective criteria weights

Mean-squared deviation model

- Select the aggregation operator
- Calculate the mean value
- Obtain the mean-squared deviation value
- Compute the objective criteria weights

Obtain the combined criteria weights

- Linear combinations
- Comprehensive criteria weights

Phase III: Establish the difference matrix

EDAS approach

- Attain the average solutions under criteria
- Compute the positive distance from average matrix
- Compute the negative distance from average matrix
- Build the difference matrix

Phase IV: Obtain the ranking orders

ELECTRE III approach

- Compute the concordance index
- Calculate the credibility index
- Compute the disconcordance index
- Calculate the ranking index
- Get the rankings

**FIGURE 1.** Framework of the EDAS-ELECTRE method.
**REFERENCES**


