Research Article

Research on Evaluation of Sustainable Development of New Urbanization from the Perspective of Urban Agglomeration under the Pythagorean Fuzzy Sets

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In this study, considering the traditional geometric operation laws and Pythagorean fuzzy information, we propose a variety of new distance measures of Pythagorean fuzzy sets such as generalized Pythagorean fuzzy geometric distance (GPF GD) measures and generalized Pythagorean fuzzy weighted geometric distance (GPF WGD) measures. Besides, some special issues including Hamming distance, Euclidean distance, and Hausdorff distance of these raised geometric distance measures are investigated. To testify the valid of these new presented distance measures, we build a decision-making model illustrated by a mathematical calculation example to evaluate the sustainable development of new urbanization from the perspective of urban agglomeration using Pythagorean fuzzy information.

1. Introduction

The concept of the intuitionistic fuzzy set (IFS) is presented by Atanassov [1], which stretches the fuzzy set (FS) [2]. In the IFS, each number is represented by an ordered pair, which consists of two parts, membership μ and nonmembership ν . The summation of the two does not exceeds 1, which can be signified as $\mu + \nu \leq 1$ [3–7]. On the basis of the unipolar bivariate model, Chen [8] proposed an effective correlation model between optimism and pessimism of MCDM under the background of IFSs [9–13]. Chen [14] conducted a comparative study on the MCDM scoring function based on IFSs. By connecting anchor dependency and precision functions, Chen [15] conducted a beneficial research on MADM problems in IFSs. Xiao et al. [16] developed the intuitionistic fuzzy taxonomy method. In addition, the Pythagorean fuzzy set (PFS) [17] has come out as a valid MADM appliance to measure the indeterminacy and complexity of evaluation information. Zhang and Xu [18] constructed an extended model, called Pythagorean-

TOPSIS, to figure out the MADM problems. To better understand the PFS, Pythagorean fuzzy division operations and Pythagorean fuzzy subtraction operations came up first by Peng and Yang [19]. Some meritorious features of continuous Pythagorean fuzzy information are studied by Gou et al. [20]. Garg [21] presented a few novel Pythagorean fuzzy aggregation operators including the PFEWA operator, PFEOWA operator, GPFEWA operator, and GPFEOWA operator. Zeng et al. [22] took advantages of the PFO-WAWAD operator to figure out MADM issues with Pythagorean fuzzy. Chen [23] defined a new PF-VIKOR method for MADM analysis. Bolturk [24] linked the CODAS method with Pythagorean fuzzy environment and built a new evaluation model. Liang et al. [25] came up with the fuzzy Bonferroni mean aggregation operator of Pythagorean theorem based on geometric mean (GM) operation. On the basis of PFSs, Garg [26] came up with a neutral operation of the MAGDM process based on the Pythagorean fuzzy set. Garg [27] defined a Pythagorean fuzzy geometric operator based on neutral operation for MAGDM issues. Molla

et al. [28] defined the Pythagorean fuzzy PROMETHEE method. Deb and Roy [29] proposed the software defined network information security risk assessment based on PFSs. Verma and Merigo [30] defined the generalized similarity measures for PFSs. Chinram et al. [31] defined the new similarity and distance measures of PFSs. Zhao et al. [32] defined the TODIM method for interval-valued Pythagorean fuzzy MAGDM based on cumulative prospect theory. He et al. [33] defined the Pythagorean interval 2-tuple linguistic VIKOR method.

In previous works, some traditional distance measures such as the WHD measure, WED measure, and the WHHD measure have been investigated in the past decades [34–36]. Burillo and Bustince [37] determined the Hamming distance and the Euclidean distance between two IFNs. Then, to consider the uncertainty of membership, Szmidt and Kacprzyk [36] put forward some new distance measures of IFNs. By considering four parameters, the fuzzy distance measure of some Pythagorean theorems in MADM problem is proposed by Li and Zeng [38]. In addition, Zeng et al. [39] further defined some novel distance measures by taking five parameters into account under Pythagorean fuzzy environment. However, these developed distance measurements can only take into account the importance of each deviation value. In order to consider the ordered positions of computed distance measures, Xu and Chen [40] defined the OWD measure based on the OWA operator developed by Yager [41]. The most obvious feature of OWD measures is that they can be used to mitigate (or enhance) the impact of inappropriately large (or small) deviations on aggregate results by giving low (or high) weights. By expanding Xu and Chen's distance formula, Yager [42] put forward a few ordered weighted averaging norms and several similarity measures. Zeng [43] presented some OWD measures with intuitionistic fuzzy information including IFOWD measure and IFHWD measure. Afterwards, motivated by the OWG operator [44], Peng et al. [45] gave out some geometric distance measures based on IFNs. Then, Liu and Peng [46] extended the WGD measure, the OWGD measure, and the HWGD measure to interval-valued intuitionistic fuzzy sets (IVIFSs).

As far as the author knows, there is no research conducted based on geometric distance (GD) measures and Pythagorean fuzzy information [47–50] to apply in MADM problems, and so, it is meaningful to study this problem. Therefore, according to the Pythagorean fuzzy distance (PFD) measure and Pythagorean fuzzy Hausdorff distance (PFHD) measure, the objective of this study is to compute the distance between the alternatives and the optimal scheme by taking advantages of geometric algorithms. To that end, the rest of our article is as follows. Next part introduces a few traditional geometric distance measurements and the basic concepts of PFSs. In Section 3, GPFGD and GPFWD are introduced, and a few special circumstances are studied. In Section 4, we will use the defined geometric distance measure to build the MADM problem model. In Section 5, we use Pythagorean fuzzy information to give a mathematical calculation example for evaluating the sustainable development of new urbanization from the

perspective of urban agglomeration. Section 6 summarizes and comments the whole study.

2. Preliminaries

2.1. Some Geometric Distance Measures. In this section, consider both weighted distance (WD) and geometric operator; we briefly review some geometric distance (GD) measures defined by Peng et al. [45], which are listed as follows.

Definition 1. Given $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ are two groups of real numbers, the generalized geometric distance (GGD) between A and B can be represented as

$$\text{GGD} = \left(\prod_{i=1}^n ((d(a_i, b_i))^\beta)^{1/n} \right)^{1/\beta}, \quad (1)$$

where $\beta > 0$, and $d(a_i, b_i) = |a_i - b_i|$ denotes the distance measure of a_i and b_i .

- (i) If $\beta = 1$, the generalized geometric distance (GGD) will reduce to the Hamming geometric distance (HGD) which are represented as

$$\text{HGD} = \prod_{i=1}^n (d(a_i, b_i))^{1/n}. \quad (2)$$

- (ii) If $\beta = 2$, the generalized geometric distance (GGD) will reduce to the Euclidean geometric distance (EGD) which are represented as

$$\text{EGD} = \sqrt[n]{\prod_{i=1}^n ((d(a_i, b_i))^2)^{1/n}}. \quad (3)$$

Take the weighting vector of each element into account; some weighted geometric distance can be introduced as follows.

Definition 2 (see [45]). Given $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ are two groups of real numbers, their weighting vector is $w = (w_1, w_2, \dots, w_n)$, which satisfies $0 \leq w_i \leq 1$, $\sum_{i=1}^n w_i = 1$; then, the generalized weighted geometric distance (GWGD) between A and B can be defined as

$$\text{GWGD} = \left(\prod_{i=1}^n ((d(a_i, b_i))^\beta)^{w_i} \right)^{1/\beta}, \quad (4)$$

where $\beta > 0$, and $d(a_i, b_i) = |a_i - b_i|$ denotes the distance measure of a_i and b_i .

- (i) If $\beta = 1$, the generalized weighed geometric distance (GWGD) will reduce to the weighted Hamming geometric distance (WHGD) presented as

$$\text{WHGD} = \prod_{i=1}^n (d(a_i, b_i))^{w_i}. \quad (5)$$

- (ii) If $\beta = 2$, the generalized weighed geometric distance (GWGD) will reduce to the weighed Euclidean geometric distance (WEGD) presented as

$$\text{WEGD} = \sqrt[n]{\prod_{i=1}^n ((d(a_i, b_i))^2)^{w_i}}. \quad (6)$$

2.2. Pythagorean Fuzzy Set. Some concepts of PFSs [17] are briefly reviewed in this section. On this basis, we come up with a new PFNs score, accuracy functions, and comparison method.

Definition 3 (see [17]). Assume that X be a fixed set. A PFS has the following expression form.

$$P = \{ \langle x, (\mu_p(x), \nu_p(x)) \rangle | x \in X \}, \quad (7)$$

where $\mu_p: X \rightarrow [0, 1]$ is the degree of membership and $\nu_p: X \rightarrow [0, 1]$ is the degree of nonmembership of the element $x \in X$ to P ; meanwhile, $\forall x \in X$, and the following conditions shall be met:

$$(\mu_p(x))^2 + (\nu_p(x))^2 \leq 1. \quad (8)$$

Definition 4 (see [51]). Given $\tilde{a} = (\mu, \nu)$ is a PFN, a PFN' score function SF can be expressed as follows:

$$\text{SF}(\tilde{a}) = \frac{1}{2}(1 + \mu^2 - \nu^2), \quad \text{S}(\tilde{a}) \in [0, 1]. \quad (9)$$

Definition 5 (see [20]). Given $\tilde{a} = (\mu, \nu)$ is a PFN, a PFN' accuracy function AH of a PFN can be expressed as follows:

$$\text{AH}(\tilde{a}) = \mu^2 + \nu^2, \quad \text{H}(\tilde{a}) \in [0, 1]. \quad (10)$$

It is applied to evaluate the accuracy degree of the PFN $\tilde{a} = (\mu, \nu)$, where $\text{AH}(\tilde{a}) \in [0, 1]$. The larger the value of $\text{AH}(\tilde{a})$, the more the degree of accuracy of the PFN $\tilde{a}$ is.

An order relation between two PFNs was given by Wei and Lu [51] on the basis of the score function SF and the accuracy function AH. It is expressed as follows.

Definition 6 (see [51]). Assume $\tilde{a}_1 = (\mu_1, \nu_1)$ and $\tilde{a}_2 = (\mu_2, \nu_2)$ be two PFNs. For $\tilde{a}_1$, its scores function and accuracy function are, respectively, $\text{SF}(\tilde{a}_1) = 1/2(1 + (\mu_1)^2 - (\nu_1)^2)$ and $\text{AH}(\tilde{a}_1) = (\mu_1)^2 + (\nu_1)^2$. For $\tilde{a}_2$, its scores function and accuracy function are, respectively, $\text{SF}(\tilde{a}_2) = 1/2(1 + (\mu_2)^2 - (\nu_2)^2)$ and $\text{AH}(\tilde{a}_2) = (\mu_2)^2 + (\nu_2)^2$; then, if $\text{SF}(\tilde{a}_1) < \text{SF}(\tilde{a}_2)$, $\tilde{a}_1$ is smaller than $\tilde{a}_2$, denoted by $\tilde{a} < \tilde{b}$; $\text{SF}(\tilde{a}) = \text{SF}(\tilde{b})$.

- (1) If $\text{AH}(\tilde{a}) = \text{AH}(\tilde{b})$, then $\tilde{a}$ is equal to $\tilde{b}$, denoted by $\tilde{a} = \tilde{b}$;

- (2) If $\text{AH}(\tilde{a}) < \text{AH}(\tilde{b})$, then $\tilde{a}$ is smaller than $\tilde{b}$, denoted by $\tilde{a} < \tilde{b}$.

Definition 7 (see [52]). Given $\tilde{a}_1 = (\mu_1, \nu_1)$, $\tilde{a}_2 = (\mu_2, \nu_2)$, and $\tilde{a} = (\mu, \nu)$ are three PFNS, some basic operations on them are defined as follows:

- (1) $\tilde{a}_1 \oplus \tilde{a}_2 = (\sqrt{(\mu_1)^2 + (\mu_2)^2 - (\mu_1)^2(\mu_2)^2}, \nu_1 \nu_2)$
- (2) $\tilde{a}_1 \otimes \tilde{a}_2 = (\mu_1 \mu_2, \sqrt{(\nu_1)^2 + (\nu_2)^2 - (\nu_1)^2(\nu_2)^2})$
- (3) $\lambda \tilde{a} = (\sqrt{1 - (1 - \mu^2)^\lambda}, \nu^\lambda), \lambda > 0$
- (4) $(\tilde{a})^\lambda = (\mu^\lambda, \sqrt{1 - (1 - \nu^2)^\lambda}), \lambda > 0$
- (5) $\tilde{a}^c = (\nu, \mu)$

3. Some Pythagorean Fuzzy Geometric Distance Measures

Based on the GD measures and PFSs, we shall propose the GPFGD measures, the GPFHGD measures, and the GHPFGD in this section.

3.1. Pythagorean Fuzzy Geometric Distance Measures

Definition 8. Suppose that $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ be two groups of PFNs, the generalized Pythagorean fuzzy geometric distance (GPFGD) between A and B can be defined as

$$d_{\text{GPFGD}}(A, B) = \left(\prod_{i=1}^n ((d_{\text{PFD}}(a_i, b_i))^\beta)^{1/n} \right)^{1/\beta}, \quad (11)$$

where $\beta > 0$, and $d_{\text{PFD}}(a_i, b_i)$ denotes the distance measure of two PFNs a_i and b_i which can be expressed as

$$d_{\text{PFD}}(a_i, b_i) = \frac{1}{2}(|\mu_i^2 - \mu_i'^2| + |\nu_i^2 - \nu_i'^2|). \quad (12)$$

- (i) If $\beta = 1$, the generalized Pythagorean fuzzy geometric distance (GPFGD) will reduce to Pythagorean fuzzy Hamming geometric distance (PFHGD):

$$d_{\text{PFHGD}}(A, B) = \prod_{i=1}^n (d_{\text{PFD}}(a_i, b_i))^{1/n}. \quad (13)$$

- (ii) If $\beta = 2$, the generalized Pythagorean fuzzy geometric distance (GPFGD) will reduce to Pythagorean fuzzy Euclidean geometric distance (PFEGD):

$$d_{\text{PFEGD}}(A, B) = \sqrt[n]{\prod_{i=1}^n ((d_{\text{PFD}}(a_i, b_i))^2)^{1/n}}. \quad (14)$$

Definition 9. Suppose that $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ be two groups of PFNs, the generalized Pythagorean fuzzy Hausdorff geometric distance (GPFHGD) between A and B can be defined as

$$d_{\text{GPFHGD}}(A, B) = \left(\prod_{i=1}^n \left((d_{\text{PFHD}}(a_i, b_i))^\beta \right)^{1/n} \right)^{1/\beta}. \quad (15)$$

where $\lambda > 0$, and $d_{\text{PFHD}}(a_i, b_i)$ denotes the Hausdorff distance measure of two PFNs a_i and b_i which can be expressed as

$$d_{\text{PFHD}}(a_i, b_i) = \max_j (|\mu_i^2 - \mu_i^2|, |v_i^2 - v_i^2|). \quad (16)$$

- (i) If $\beta = 1$, the generalized Pythagorean fuzzy Hausdorff geometric distance (GPFHGD) will reduce to Pythagorean fuzzy Hamming–Hausdorff geometric distance (PFHHGD):

$$d_{\text{PFHHGD}}(A, B) = \prod_{i=1}^n (d_{\text{PFHD}}(a_i, b_i))^{1/n}. \quad (17)$$

- (ii) If $\beta = 2$, the generalized Pythagorean fuzzy Hausdorff geometric distance (GPFHGD) will reduce to Pythagorean fuzzy Euclidean–Hausdorff geometric distance (PFEHGD):

$$d_{\text{PFEHGD}}(A, B) = \sqrt[n]{\prod_{i=1}^n ((d_{\text{PFHD}}(a_i, b_i))^2)^{1/n}}. \quad (18)$$

Definition 10. Suppose that $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ be two groups of Pythagorean fuzzy numbers (PFNs), the generalized hybrid Pythagorean fuzzy geometric distance (GHPFGD) between A and B can be defined as

$$d_{\text{GHPFGD}}(A, B) = \left(\prod_{i=1}^n \left(\frac{1}{2} ((d_{\text{PFD}}(a_i, b_i))^\beta + (d_{\text{PFHD}}(a_i, b_i))^\beta) \right)^{1/n} \right)^{1/\beta}. \quad (19)$$

- (i) If $\beta = 1$, the generalized hybrid Pythagorean fuzzy geometric distance (GHPFGD) will reduce to hybrid Pythagorean fuzzy Hamming geometric distance (HPFHGD)

$$d_{\text{HPFHGD}}(A, B) = \prod_{i=1}^n \left(\frac{1}{2} (d_{\text{PFD}}(a_i, b_i) + d_{\text{PFHD}}(a_i, b_i)) \right)^{1/n}. \quad (20)$$

- (ii) If $\beta = 2$, the generalized hybrid Pythagorean fuzzy geometric distance (GHPFGD) will reduce to hybrid Pythagorean fuzzy Euclidean geometric distance (HPFEGD):

$$d_{\text{HPFEGD}}(A, B) = \sqrt[n]{\prod_{i=1}^n \left(\frac{1}{2} ((d_{\text{PFD}}(a_i, b_i))^2 + (d_{\text{PFHD}}(a_i, b_i))^2) \right)^{1/n}}. \quad (21)$$

In general, the above distance measures have the following properties:

- (1) $0 \leq d(A, B) \leq 1$
- (2) $d(A, B) = d(B, A)$
- (3) $d(A, B) = 0$, if and only if $A = B$

3.2. Pythagorean Fuzzy Weighted Geometric Distance Measures. Usually, $x_i \in X$, and it is important to take each element's weight into consideration; thus, in the following, we recommend the weighted geometric distance measures for Pythagorean fuzzy sets (PFSs) such as the generalized Pythagorean fuzzy weighted geometric distance (GPFWGD)

measures, the generalized Pythagorean fuzzy weighted Hausdorff geometric distance (GPFHWGD) measures, and the generalized hybrid Pythagorean fuzzy weighted geometric distance (GHPFWGD) in this section.

Definition 11. Suppose that $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ be two groups of Pythagorean fuzzy numbers (PFNs) with the weighting vector be $w = (w_1, w_2, \dots, w_n)$, which satisfies $0 \leq w_i \leq 1$, $\sum_{i=1}^n w_i = 1$, then the GPFWGD between A and B can be defined as

$$d_{\text{GPFWGD}}(A, B) = \left(\prod_{i=1}^n ((d_{\text{PFD}}(a_i, b_i))^\beta)^{w_i} \right)^{1/\beta}. \quad (22)$$

- (i) If $\beta = 1$, the generalized Pythagorean fuzzy weighted geometric distance (GPFWD) will reduce to Pythagorean fuzzy weighted Hamming geometric distance (PFWHGD):

$$d_{\text{PFWHGD}}(A, B) = \prod_{i=1}^n (d_{\text{PFD}}(a_i, b_i))^{w_i}. \quad (23)$$

- (ii) If $\beta = 2$, the generalized Pythagorean fuzzy weighted geometric distance (GPFWD) will reduce to Pythagorean fuzzy weighted Euclidean geometric distance (PFEWD):

$$d_{\text{PFEWD}}(A, B) = \sqrt[n]{\prod_{i=1}^n ((d_{\text{PFD}}(a_i, b_i))^2)^{w_i}}. \quad (24)$$

Definition 12. Suppose that $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ be two groups of Pythagorean fuzzy numbers (PFNs) with the weighting vector be $w = (w_1, w_2, \dots, w_n)$, which satisfies $0 \leq w_i \leq 1$, $\sum_{i=1}^n w_i = 1$, then the GPFWD between A and B can be defined as

$$d_{\text{GPFWD}}(A, B) = \left(\prod_{i=1}^n ((d_{\text{PFD}}(a_i, b_i))^\beta)^{w_i} \right)^{1/\beta}. \quad (25)$$

- (i) If $\beta = 1$, the generalized Pythagorean fuzzy weighted Hausdorff geometric distance (GPFWHGD) will reduce to Pythagorean fuzzy weighted Hamming–Hausdorff geometric distance (PFWHHGD):

$$d_{\text{PFWHHGD}}(A, B) = \prod_{i=1}^n (d_{\text{PFHD}}(a_i, b_i))^{w_i}. \quad (26)$$

- (ii) If $\beta = 2$, the generalized Pythagorean fuzzy weighted Hausdorff geometric distance (GPFWHGD) will reduce to Pythagorean fuzzy weighted Euclidean–Hausdorff geometric distance (PFEHGD):

$$d_{\text{PFEHGD}}(A, B) = \sqrt[n]{\prod_{i=1}^n ((d_{\text{PFHD}}(a_i, b_i))^2)^{w_i}}. \quad (27)$$

Definition 13. Suppose that $A = (a_1, a_2, \dots, a_n)$ and $B = (b_1, b_2, \dots, b_n)$ be two groups of Pythagorean fuzzy numbers (PFNs) with the weighting vector be $w = (w_1, w_2, \dots, w_n)$, which satisfies $0 \leq w_i \leq 1$, $\sum_{i=1}^n w_i = 1$, then the GHPFWGD between A and B can be defined as

$$d_{\text{GHPFWGD}}(A, B) = \left(\prod_{i=1}^n \left(\frac{1}{2} ((d_{\text{PFD}}(a_i, b_i))^\beta + (d_{\text{PFHD}}(a_i, b_i))^\beta) \right)^{w_i} \right)^{1/\beta}. \quad (28)$$

- (i) If $\beta = 1$, the generalized hybrid Pythagorean fuzzy weighted geometric distance (GHPFWGD) will reduce to hybrid Pythagorean fuzzy weighted Hamming geometric distance (HPFWHGD):

$$d_{\text{HPFWHGD}}(A, B) = \prod_{i=1}^n \left(\frac{1}{2} (d_1(a_{x_i}, b_{x_i}) + d_2(a_{x_i}, b_{x_i})) \right)^{w_i}. \quad (29)$$

- (ii) If $\beta = 2$, the generalized hybrid Pythagorean fuzzy weighted geometric distance (GHPFWGD) will reduce to hybrid Pythagorean fuzzy weighted Euclidean geometric distance (HPFEWD):

$$d_{\text{HPFEWD}}(A, B) = \sqrt[n]{\prod_{i=1}^n \left(\frac{1}{2} ((d_1(a_{x_i}, b_{x_i}))^2 + (d_2(a_{x_i}, b_{x_i}))^2) \right)^{w_i}}. \quad (30)$$

Generally speaking, the weighted distance measurements have the following characteristics as well:

- (1) $0 \leq d(A, B) \leq 1$
- (2) $d(A, B) = d(B, A)$
- (3) $d(A, B) = 0$, if and only if $A = B$

4. Model of MADM Problems Based on PFGD Measures

Based the abovementioned Pythagorean fuzzy geometric distance measures, we shall present the MADM model with Pythagorean fuzzy information. Suppose that $A = \{A_1, A_2, \dots, A_m\}$ be an alternatives group, $G = \{G_1, G_2, \dots, G_n\}$ be an attributes group, their weighting vector is $w = (w_1, w_2, \dots, w_n)$, $w_j \in [0, 1]$, $\sum_{j=1}^n w_j = 1$, and $d = \{d_1, d_2, \dots, d_\lambda\}$ is an expert list, their weighting vector is $\varepsilon = (\varepsilon_1, \varepsilon_2, \dots, \varepsilon_\lambda)$ which satisfies $\varepsilon_j \in [0, 1]$, $\sum_{j=1}^\lambda \varepsilon_j = 1$. Construct the Pythagorean fuzzy evaluation matrix $R^\lambda = (r_{ij}^\lambda)_{m \times n} = (\mu_{ij}^\lambda, \nu_{ij}^\lambda)_{m \times n}$, where $\mu_{ij}^\lambda \in [0, 1]$ indicates the extent to which the alternative A_i satisfies the attributes G_j given by the decision maker d_λ , and $\nu_{ij}^\lambda \in [0, 1]$ indicates the extent that the alternative A_i does not satisfy the attribute G_j given by the decision maker d_λ , $(\mu_{ij}^\lambda)^2 + (\nu_{ij}^\lambda)^2 \leq 1$, $i = 1, 2, \dots, m$, $j = 1, 2, \dots, n$.

Step 1: we utilize the Pythagorean fuzzy weighted geometric (PFWG) operator to fuse information given

in matrix R^λ , and the fused matrix $R = (r_{ij})_{m \times n}$ can be denoted as follows.

$$r_{ij} = \prod_{d=1}^{\lambda} (r_{ij}^d)^{\varepsilon_d} = (r_{ij}^1)^{\varepsilon_1} \otimes (r_{ij}^2)^{\varepsilon_2} \otimes \dots \otimes (r_{ij}^{\lambda})^{\varepsilon_{\lambda}}$$

$$= \left\langle \prod_{d=1}^{\lambda} (\mu_{ij}^d)^{\varepsilon_d}, 1 - \sqrt{1 - \prod_{d=1}^{\lambda} (1 - (\mu_{ij}^d)^2)^{\varepsilon_d}} \right\rangle, \quad i = 1, 2, \dots, m, j = 1, 2, \dots, n. \quad (31)$$

Step 2: determine the best alternative A^+ based on the fused results in equation (11) and get the Pythagorean

fuzzy distance (PFD) and Pythagorean fuzzy Hausdorff distance (PFHD) by using equation (11)

$$A_{1 \times n}^+ = \left\{ \left(\max_i (\mu_{i1}), \min_i (v_{i1}) \right), \left(\max_i (\mu_{i2}), \min_i (v_{i2}) \right), \dots, \left(\max_i (\mu_{in}), \min_i (v_{in}) \right) \right\}. \quad (32)$$

Step 3: utilize above defined Pythagorean fuzzy weighted geometric distance (PFWGD) to compute the distance between A^+ and A_i

Step 4: sort all the alternatives $A_i (i = 1, 2, \dots, m)$ and choose the best one based on the distance value. Obviously, the greater the distance value, the worse the alternative.

Step 5: end

5. Illustrative Example

Urbanization is the only way to develop social modernization and an important channel to accomplish the economic development of undeveloped countries or regions. Currently, the urbanization level in our country is in a stage of rapid development; however, in the past ten years, China's urbanization has followed such an extensive and denotative path as to cause its unsustainability during the development. To better and quicken China's urbanization, the notion of new-type urbanization is put forward in December 2015 at the City Work Meeting of the 18th CPC National Congress, which explicitly shows that this kind of urbanization goes for the natural development rule. In detail, without any damage to the local natural surroundings, local urbanization is allowed to carry on. Only the preprotection of ecological environment can the local development turn to a sustainable path. In other words, the key point is to guarantee the constant natural protection of a local area throughout the whole urbanization. Therefore, the urbanization of different cities should be fulfilled on the premise of having nature protected all the way to accomplish its sustainable and healthy development. Urbanization is the current economic and social development situation and a sign of world development. New urbanization has developed

rapidly in China in recent years. The national new urbanization plan proposes to take people's urbanization as the core and urban agglomeration as the main form and then to improve the level of urban sustainable development. The development model dominated by urban agglomerations is the dominant mode that China's urbanization must follow at this stage, and it is also an inevitable trend of urbanization development. In view of this, this study discusses the evaluation of sustainable development of new urbanization based on the theory associated with research. Therefore, to illustrate the method presented in this study, we will give a numeric-based example for evaluating the sustainable development of new urbanization from the perspective of urban agglomeration using the Pythagorean fuzzy information in this part. Five applicable new urban centers $A_i (i = 1, 2, 3, 4, 5)$ are considered. To evaluate the five applicable new urban centers by three experts $d_\lambda (\lambda = 1, 2, 3)$, four attributes are given: (1) G_1 is the infrastructure; (2) G_2 is the urban-rural integration; (3) G_3 is the economic development; (4) G_4 is the resources and environment. The decision makers evaluate the five possible new urban centers $A_i (i = 1, 2, 3, 4, 5)$ with the above four attributes anonymously in order to avoid mutual influence. The decision matrix $R^\lambda = (r_{ij}^\lambda)_{5 \times 4}$ is presented in Tables 1–3, where $r_{ij}^\lambda (i = 1, 2, 3, 4, 5, j = 1, 2, 3, 4)$ are in the form of PFNs. The attributes' weight vector is $w = (0.16, 0.28, 0.36, 0.20)^T$ and the experts' weighting vector is $\varepsilon = (0.35, 0.40, 0.25)$.

According to equation (31), we can obtain the fused matrix $R = (r_{ij})_{5 \times 4}$ on the basis of the expert's weighting vector and information given in Tables 1–3. The fused results are listed in Table 4.

Then, we can calculate the best alternative $A^+ = (r_j^+)_{1 \times n}$ based on the fused results in Table 4 and equation (32). The computing results are listed as follows.

TABLE 1: Pythagorean fuzzy information matrix R^1 .

	G_1	G_2	G_3	G_4
A_1	(0.6, 0.7)	(0.5, 0.4)	(0.3, 0.6)	(0.8, 0.2)
A_2	(0.1, 0.3)	(0.4, 0.5)	(0.6, 0.2)	(0.5, 0.1)
A_3	(0.7, 0.4)	(0.6, 0.2)	(0.8, 0.5)	(0.4, 0.6)
A_4	(0.3, 0.2)	(0.5, 0.1)	(0.4, 0.6)	(0.2, 0.5)
A_5	(0.3, 0.1)	(0.2, 0.5)	(0.4, 0.2)	(0.6, 0.3)

TABLE 2: Pythagorean fuzzy information matrix R^2 .

	G_1	G_2	G_3	G_4
A_1	(0.3, 0.2)	(0.2, 0.7)	(0.8, 0.4)	(0.5, 0.3)
A_2	(0.4, 0.2)	(0.1, 0.4)	(0.5, 0.4)	(0.6, 0.2)
A_3	(0.8, 0.2)	(0.4, 0.7)	(0.6, 0.1)	(0.5, 0.2)
A_4	(0.4, 0.3)	(0.3, 0.2)	(0.5, 0.1)	(0.6, 0.7)
A_5	(0.2, 0.4)	(0.5, 0.3)	(0.2, 0.6)	(0.7, 0.4)

TABLE 3: Pythagorean fuzzy information matrix R^3 .

	G_1	G_2	G_3	G_4
A_1	(0.3, 0.6)	(0.5, 0.3)	(0.1, 0.5)	(0.4, 0.3)
A_2	(0.2, 0.5)	(0.5, 0.4)	(0.6, 0.2)	(0.4, 0.6)
A_3	(0.6, 0.5)	(0.7, 0.2)	(0.5, 0.2)	(0.1, 0.3)
A_4	(0.4, 0.3)	(0.5, 0.2)	(0.3, 0.7)	(0.4, 0.6)
A_5	(0.6, 0.2)	(0.1, 0.6)	(0.3, 0.6)	(0.5, 0.2)

TABLE 4: Pythagorean fuzzy fusing information matrix R .

	G_1	G_2	G_3	G_4
A_1	(0.3824, 0.4479)	(0.3466, 0.4540)	(0.3375, 0.4925)	(0.5574, 0.7302)
A_2	(0.2071, 0.6621)	(0.2429, 0.5611)	(0.5578, 0.7001)	(0.5086, 0.6491)
A_3	(0.7105, 0.6276)	(0.5302, 0.4954)	(0.6340, 0.6705)	(0.3092, 0.5780)
A_4	(0.3617, 0.7302)	(0.4076, 0.8279)	(0.4070, 0.4708)	(0.3691, 0.3818)
A_5	(0.3033, 0.7170)	(0.2426, 0.5297)	(0.2821, 0.4877)	(0.6097, 0.6732)

$$A^+ = \{(0.7105, 0.4479), (0.5302, 0.4504), (0.6340, 0.4708), (0.6097, 0.3818)\}. \quad (33)$$

Next, we compute the Pythagorean fuzzy distance (PFD) and Pythagorean fuzzy Hausdorff distance (PFHD) by using

equation (12) and equation (16). The computing results are listed as follows.

$$\begin{aligned}
d_{\text{PFD}}(r_{11}, r_1^+) &= 0.1793, d_{\text{PFD}}(r_{12}, r_2^+) = 0.0805, d_{\text{PFD}}(r_{13}, r_3^+) = 0.1545, \\
d_{\text{PFD}}(r_{14}, r_4^+) &= 0.2242, d_{\text{PFD}}(r_{21}, r_1^+) = 0.3498, d_{\text{PFD}}(r_{22}, r_2^+) = 0.1654, \\
d_{\text{PFD}}(r_{23}, r_3^+) &= 0.1797, d_{\text{PFD}}(r_{24}, r_4^+) = 0.1943, d_{\text{PFD}}(r_{31}, r_1^+) = 0.0966, \\
d_{\text{PFD}}(r_{32}, r_2^+) &= 0.0197, d_{\text{PFD}}(r_{33}, r_3^+) = 0.1140, d_{\text{PFD}}(r_{34}, r_4^+) = 0.2322, \\
d_{\text{PFD}}(r_{41}, r_1^+) &= 0.3533, d_{\text{PFD}}(r_{42}, r_2^+) = 0.2972, d_{\text{PFD}}(r_{43}, r_3^+) = 0.1182, \\
d_{\text{PFD}}(r_{44}, r_4^+) &= 0.1178, d_{\text{PFD}}(r_{51}, r_1^+) = 0.3631, d_{\text{PFD}}(r_{52}, r_2^+) = 0.1483, \\
d_{\text{PFD}}(r_{53}, r_3^+) &= 0.1693, d_{\text{PFD}}(r_{54}, r_4^+) = 0.1537.
\end{aligned}$$

(34)

$$\begin{aligned}
d_{\text{PFHD}}(r_{11}, r_1^+) &= 0.3586, d_{\text{PFHD}}(r_{12}, r_2^+) = 0.1610, d_{\text{PFHD}}(r_{13}, r_3^+) = 0.2881, \\
d_{\text{PFHD}}(r_{14}, r_4^+) &= 0.3874, d_{\text{PFHD}}(r_{21}, r_1^+) = 0.4619, d_{\text{PFHD}}(r_{22}, r_2^+) = 0.2221, \\
d_{\text{PFHD}}(r_{23}, r_3^+) &= 0.2685, d_{\text{PFHD}}(r_{24}, r_4^+) = 0.2755, d_{\text{PFHD}}(r_{31}, r_1^+) = 0.1933, \\
d_{\text{PFHD}}(r_{32}, r_2^+) &= 0.0393, d_{\text{PFHD}}(r_{33}, r_3^+) = 0.2279, d_{\text{PFHD}}(r_{34}, r_4^+) = 0.2761, \\
d_{\text{PFHD}}(r_{41}, r_1^+) &= 0.3740, d_{\text{PFHD}}(r_{42}, r_2^+) = 0.4793, d_{\text{PFHD}}(r_{43}, r_3^+) = 0.2363, \\
d_{\text{PFHD}}(r_{44}, r_4^+) &= 0.2355, d_{\text{PFHD}}(r_{51}, r_1^+) = 0.4128, d_{\text{PFHD}}(r_{52}, r_2^+) = 0.2223, \\
d_{\text{PFHD}}(r_{53}, r_3^+) &= 0.3224, d_{\text{PFHD}}(r_{54}, r_4^+) = 0.3074.
\end{aligned} \tag{35}$$

Case 1. Pythagorean fuzzy weighted Hamming geometric distance: suppose $\beta = 1$, we use the PFWHGD measure, the PFWHHGD measure, and the HPFWHGD measure to compute the distances

between each alternative and the ideal alternative and then the rank the alternatives as follows.

(1) Results obtained by PFWHGD measure are

$$\begin{aligned}
d_{\text{PFWHGD}}(A_1, A^+) &= 0.1420, d_{\text{PFWHGD}}(A_2, A^+) = 0.1984, d_{\text{PFWHGD}}(A_3, A^+) = 0.0782, \\
d_{\text{PFWHGD}}(A_4, A^+) &= 0.1821, d_{\text{PFWHGD}}(A_5, A^+) = 0.1808.
\end{aligned} \tag{36}$$

The rank of all the alternatives is $A_3 > A_1 > A_5 > A_4 > A_2$, and the best alternative is A_3 .

(2) Results obtained by PFWHHGD measure are

$$\begin{aligned}
d_{\text{PFWHHGD}}(A_1, A^+) &= 0.2690, d_{\text{PFWHHGD}}(A_2, A^+) = 0.2791, d_{\text{PFWHHGD}}(A_3, A^+) = 0.1410, \\
d_{\text{PFWHHGD}}(A_4, A^+) &= 0.3098, d_{\text{PFWHHGD}}(A_5, A^+) = 0.2994.
\end{aligned} \tag{37}$$

The rank of all the alternatives is $A_3 > A_1 > A_2 > A_5 > A_4$, and the best alternative is A_3 .

(3) Results obtained by HPFWHGD measure are

$$\begin{aligned}
d_{\text{HPFWHGD}}(A_1, A^+) &= 0.2056, d_{\text{HPFWHGD}}(A_2, A^+) = 0.2388, d_{\text{HPFWHGD}}(A_3, A^+) = 0.1102, \\
d_{\text{HPFWHGD}}(A_4, A^+) &= 0.2475, d_{\text{HPFWHGD}}(A_5, A^+) = 0.2412.
\end{aligned} \tag{38}$$

The rank of all the alternatives is $A_3 > A_1 > A_2 > A_5 > A_4$, and the best alternative is A_3 .

the information in Table 4, and then, all the alternatives are sorted according to the PFNs' score and precision function, and the analysis results were as follows.

Case 2. Pythagorean fuzzy weighted geometric operator: according to the PFWG operator, we can aggregate

(4) Results obtained by the PFWG operator are

$$\begin{aligned}
r_1 &= (0.3835, 0.5452), r_2 = (0.3703, 0.6061), r_3 = (0.532, 0.6579), \\
r_4 &= (0.3918, 0.719), r_5 = (0.3192, 0.7077).
\end{aligned} \tag{39}$$

Then, by score function, we can get

TABLE 5: Evaluation results of these methods.

Methods	Ranking order	The best alternative	The worst alternative
SPFWA operator [53]	$A_3 > A_1 > A_2 > A_4 > A_5$	A_3	A_5
SPFWG operator [53]	$A_3 > A_1 > A_2 > A_4 > A_5$	A_3	A_5
PF-projection model [25]	$A_3 > A_1 > A_2 > A_4 > A_5$	A_3	A_5
PF-TOPSIS method [18]	$A_3 > A_1 > A_2 > A_4 > A_5$	A_3	A_5
PF-TODIM method [54]	$A_3 > A_1 > A_2 > A_4 > A_5$	A_3	A_5
The developed method	$A_3 > A_1 > A_2 > A_4 > A_5$	A_3	A_5

$$s(A_1) = 0.4249, s(A_2) = 0.3849, s(A_3) = 0.4251, s(A_4) = 0.3183, s(A_5) = 0.3006. \quad (40)$$

The rank of all the alternatives is $A_3 > A_1 > A_2 > A_4 > A_5$, and the optimal alternative is A_3 .

6. Compare Analysis

In this section, our defined method is made comparison with some other methods to show its superiority.

Eventually, the results of these methods are in Table 5.

From Table 5, it is evident that the best alternative is F_3 , while the worst alternative is F_1 in most situations. In other words, these methods' order is slightly different. Different methods can tackle MAGDM from different angles.

7. Conclusion

The sum of squares of membership and nonmembership less than or equal to 1 is a valuable property of the PFSs, and it can be used as a meaningful decision-making tool to deal with uncertainty of information. On the basis of the traditional Hamming distance, Euclidean distance, Hausdorff distance, and geometric distance, a variety of Pythagorean fuzzy geometric distance measurement methods are proposed. Then, taking the weighting vector of input arguments into account, we further investigate some PFWGD measures and illustrate some special cases. To address the MADM problems with PFSs more effectively, a decision model is established. Finally, we demonstrate the potential application through a numeric-based example about evaluating the sustainable development of new urbanization from the perspective of urban agglomeration to explain the approach presented in this study. In our future directions, we shall go on to apply the defined models and algorithms to other uncertain and fuzzy fields in the future [55–61] and apply these distance measures to interval-valued PFSs [62–68].

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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