



# Enhancing Multi-Attribute Decision Making with Pythagorean Fuzzy Hamacher Aggregation Operators

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**Abstract:** The attention of many researchers has been drawn to Pythagorean fuzzy information, which involves Pythagorean fuzzy numbers and their aggregation operators. In this study, the concept of the Pythagorean fuzzy set is discussed, along with the Hamacher t-norm and t-conorm operators. Furthermore, novel aggregation operators are developed using the operational rules of the Hamacher t-norm and t-conorm. The primary objective of this article is to develop a multi-attribute decision-making method in a Pythagorean fuzzy environment using Pythagorean fuzzy Hamacher aggregation operators. It is noted that the Hamacher operator, which is a generalization of the algebraic Einstein operator and contains a parameter, is more potent than some existing operators. Finally, an example of an enterprise application software selection problem is presented to demonstrate the proposed method.

**Keywords:** Pythagorean fuzzy set; Pythagorean fuzzy number; Hamacher operation; Pythagorean fuzzy Hamacher aggregation operator; Multi-attribute decision making

## 1 Introduction

The important and efficient role of the MADM problem in various decision-making domains, such as engineering and social science, has been widely recognized. MADM approaches are utilized to process and attribute information to compute a suitable alternative or rank alternatives for decision support. These approaches are exercised in different domains, including engineering technology, operation research, and management science.

**Table 1.** List of abbreviations

Abbreviation	Full form
AO	Aggregation Operator
DEM	Decision Matrix
DE	Decision Expert
FS	Fuzzy Set
IFS	Intuitionistic Fuzzy Set
MADM	Multi-Attribute Decision Making
MCDM	Multi-Criteria Decision Making
MF	Membership Function
NMF	Non-Membership Function
OR	Operational Rule
PyFE	Pythagorean Fuzzy Environment
PyFI	Pythagorean Fuzzy Information
PyFN	Pythagorean Fuzzy Number
PyFS	Pythagorean Fuzzy Set

In the Pythagorean Fuzzy Environment (PyFE), various types of traditional decision-making approaches are available. For instance, Liang et al. [1] developed a new extension of the TOPSIS (The Technique for Order of

Preference by Similarity to Ideal Solution) approach with the hesitant PyFE, Zhang [2] proposed decision-making based on similarity measur, Garg [3] proposed strategic decision making with immediate probabilities along with the Pythagorean Fuzzy Numbers (PyFNs), Yu et al. [4] proposed the TOPSIS method in the interval-valued Pythagorean fuzzy environment, Zhang [5] proposed the hierarchical QUALIFLEX (The qualitative flexible multiple criteria ) approach in the PyFE, Ren et al. [6] proposed the Pythagorean fuzzy TODIM approach, and Khan et al. [7] proposed the extension of TOPSIS based on the Choquet integral (See Table 1).

The MCDM approach has also been used in some research papers. Fodor and Roubens [8] elaborated on axiomatic concepts and procedures of MCDM in a book, while Greco et al. [9] proposed an MCDM approach that is interpreted in rough set theory. Ho et al. [10] proposed a review article based on supplier evaluation and selection using the MCDM technique, and Kahraman et al. [11] proposed supplier selection using the Analytic Hierarchy Process. Malczewski [12] conducted a GIS based MCDM survey from 1990 to 2004, and Mardani et al. [13] reviewed the literature on studies on energy management problems from 1995 to 2015. Myint et al. [14] proposed the idea of land use and land cover change using the MCDM approach with the help of Markov chain and cellular automata analysis. Pohekar and Ramachandran [15] reviewed works of literature on sustainable energy planning using MCDM, while Rey-Valette et al. [16] proposed an MCDM with a participation-based methodology for selecting sustainable development indicators. Silvestri [17] proposed a multi-criteria risk analysis technique to improve safety in manufacturing systems.

In this present article, the Pythagorean Fuzzy Information (PyFI) is used to solve the MADM problem. Atanassov [18] introduced the notion of Interval Fuzzy Sets (IFS) in 1983, which consist of Membership Function (MF) and Non-Membership Function (NMF) to deal with the uncertainty of an element's belongingness to an FS. The concept of Zadeh's Fuzzy Sets (FS) [19], which was introduced in 1965 and consisted only of MF, was generalized by IFS. Yager [20] introduced the notion of Pythagorean Fuzzy Sets (PyFS), which include more fuzzy information than that of FS and IFS [18]. In other words, PyFS is superior to both FS and IFS in terms of possessing information. For example, while an IFS does not include the fuzzy information  $\langle 0.7, 0.5 \rangle$  as  $0.7 + 0.5 \not\leq 1$ , it can be included in the PyFS as  $0.7^2 + 0.5^2 \leq 1$ . It is important to note that a member of an IFS belongs to a PyFS, but the converse may not be valid (see Figure 1).

The Aggregation Operator (AO) is crucial in combining fuzzy information into a single datum and solving a MADM issue. Various research works have been conducted on the MADM approach in the Pythagorean Fuzzy Environment (PyFE) based on Dombi averaging and geometric operators. Jana et al. [21] and Khan et al. [22] proposed Pythagorean fuzzy Dombi AOs. Similarly, Jana et al. [23] introduced Dombi AOs in a bipolar fuzzy environment [24–26], while Rahman et al. [27] developed Pythagorean fuzzy Einstein weighted geometric AOs to solve MCDM problems.

Many research works have utilized Hamacher AOs. Gao [28] proposed Pythagorean fuzzy Hamacher prioritized aggregation operators in MCDM, and Gao et al. [29] introduced dual hesitant bipolar fuzzy Hamacher prioritized aggregation operator in MCDM. Other studies developed intuitionistic fuzzy Hamacher aggregation operators [30], single-valued neutrosophic trapezoidal Hamacher aggregation operators [31], picture fuzzy Hamacher aggregation operators [32], dual hesitant Hamacher aggregation operators [33], Hamacher aggregation operators in the interval-valued intuitionistic fuzzy environment [34], Hamacher aggregation operators using generalized neutrosophic numbers [35], hesitant Pythagorean fuzzy Hamacher aggregation operators [36], hesitant fuzzy Hamacher aggregation operators [37], linguistic intuitionistic fuzzy Hamacher aggregation operators [38], analytical articles regarding the Hamacher AOs in uncertain MCDM problems [39], m-polar fuzzy Hamacher AOs [40], picture fuzzy Hamacher AOs [41], bipolar fuzzy Hamacher AOs [42], and dual hesitant Pythagorean fuzzy Hamacher AOs [43]. Additionally, Wei [44] proposed Hamacher AO in the PyFE, while Wu et al. [45] developed single-valued neutrosophic 2-tuple linguistic Hamacher AOs in MCDM, and Zhou et al. [46] proposed hesitant fuzzy Hamacher AOs in MCDM.

However, the use of Hamacher AOs with the Pythagorean Fuzzy Information (PyFI) is a novel work in the MADM approach, which is discussed in this present article. The authors introduced various Pythagorean fuzzy Hamacher operators, such as Pythagorean fuzzy Hamacher weighted averaging (PyFHWA) operator, Pythagorean fuzzy Hamacher ordered weighted averaging (PyFHOWA) operator, Pythagorean fuzzy Hamacher hybrid averaging (PyFHHA) operator, Pythagorean fuzzy Hamacher weighted geometric (PyFHWG) operator, Pythagorean fuzzy Hamacher ordered weighted geometric (PyFHOWG) operator, and Pythagorean fuzzy Hamacher hybrid geometric (PyFHHG) operator.

In this research article, the PyFI is used in the aggregation process based on Pythagorean fuzzy Hamacher averaging and geometric operators to choose the best alternative of enterprise application software, considering the predefined attributes proposed by the Decision Experts (DEs).

This paper is organized as follows: In section 2, we review some fundamental concepts of Pythagorean Fuzzy Sets (PyFS), including t-norm and t-conorm operators, as well as Pythagorean fuzzy weighted averaging operator, Pythagorean fuzzy ordered weighted averaging operator, Pythagorean fuzzy hybrid averaging operator, Pythagorean

fuzzy weighted geometric operator, Pythagorean fuzzy ordered weighted geometric operator, and Pythagorean fuzzy hybrid geometric operator.

In section 3, Hamacher t-norm and t-conorm operators are defined. Section 4 discusses three types of Pythagorean fuzzy averaging operators and their properties, including some theorems. Similarly, section 5 discusses three types of Pythagorean fuzzy geometric operators and their properties, including some theorems.

In section 6, an algorithm is presented for solving a MADM problem based on the Pythagorean fuzzy Hamacher weighted averaging (PyFHWA) operator and Pythagorean fuzzy Hamacher weighted geometric (PyFHWG) operator. A numerical example of selecting the best enterprise application software is provided in the same section. Finally, in section 7, we draw a conclusion.

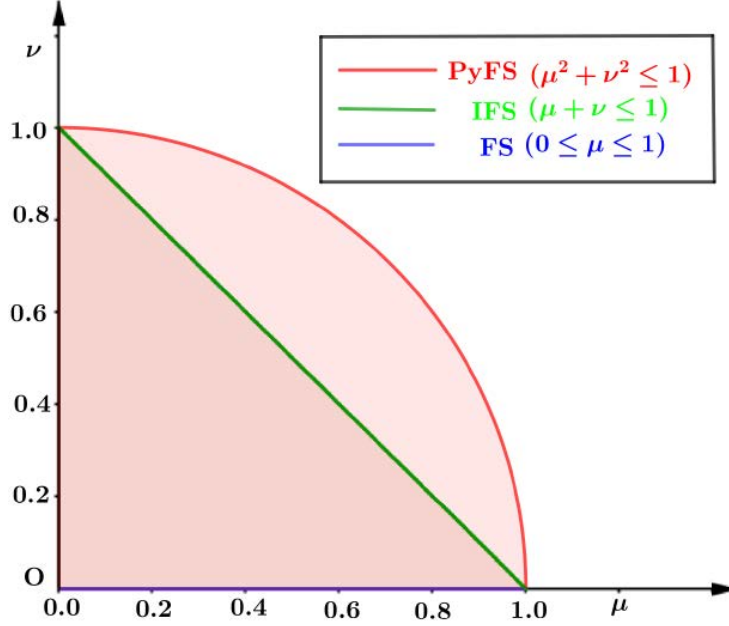


Figure 1. Graphical presentation of PyFS, IFS and FS.

## 2 Preliminaries

A concise review has been done along with triangular norm (t-norm) and triangular connorm (t-conorm) operators [47, 48].

**Definition 2.1** [20, 49, 50] (PyFS)

PyFS on the universe of discourse  $\mathcal{U}$  is defined by  $\tilde{\mathfrak{P}} = \left\{ \langle \varrho, \mathfrak{T}_{\tilde{\mathfrak{P}}}(\varrho), \aleph_{\tilde{\mathfrak{P}}}(\varrho) \rangle : \varrho \in \mathcal{U} \right\}$ , where the  $MF\mathfrak{T}_{\tilde{\mathfrak{P}}} : \mathcal{U} \rightarrow [0, 1]$ ,  $NMF\aleph_{\tilde{\mathfrak{P}}} : \mathcal{U} \rightarrow [0, 1]$  are constrained as  $0 \leq \mathfrak{T}_{\tilde{\mathfrak{P}}}^2(\varrho) + \aleph_{\tilde{\mathfrak{P}}}^2(\varrho) \leq 1$ . Another function  $\pi_{\tilde{\mathfrak{P}}} : \mathcal{U} \rightarrow [0, 1]$  is arisen which is related to the MF and NMF functions by the relation  $\mathfrak{T}_{\tilde{\mathfrak{P}}}^2(\varrho) + \aleph_{\tilde{\mathfrak{P}}}^2(\varrho) + \pi_{\tilde{\mathfrak{P}}}^2(\varrho) = 1$  for all  $\varrho \in \mathcal{U}$  i.e.,

$\pi_{\tilde{\mathfrak{P}}}(\varrho) = \sqrt{1 - \left( \mathfrak{T}_{\tilde{\mathfrak{P}}}^2(\varrho) + \aleph_{\tilde{\mathfrak{P}}}^2(\varrho) \right)}$ , which is called the degree of hesitation margin or indeterminacy function. For

given  $\varrho \in \mathcal{U}$ ,  $\langle \mathfrak{T}_{\tilde{\mathfrak{P}}}(\varrho), \aleph_{\tilde{\mathfrak{P}}}(\varrho) \rangle$  is called the Pythagorean fuzzy value corresponding to the PyFS,  $\tilde{\mathfrak{P}}$  and it is denoted as  $\tilde{\mathfrak{P}} = \langle \mathfrak{T}_{\tilde{\mathfrak{P}}}, \aleph_{\tilde{\mathfrak{P}}} \rangle$  in short and named as PyFN.

**Definition 2.2** [51] (t-norm and t-conorm operators)

t-norm or triangular norm operator is a binary, conjunctive type operator which maps unit square to the unit interval, i.e.,  $t : [0, 1]^2 \rightarrow [0, 1]$  and satisfies the properties as follows:

- (i)  $t(0, \varrho_1) = 0$ ,  $t(1, \varrho_1) = \varrho_1$ , for all  $\varrho_1 \in [0, 1]$ .
- (ii)  $t(\varrho_1, \varrho_2) = t(\varrho_2, \varrho_1)$ , for all  $\varrho_1, \varrho_2 \in [0, 1]$ .
- (iii)  $t(\varrho_1, t(\varrho_2, \varrho_3)) = t(t(\varrho_1, \varrho_2), \varrho_3)$ , for all  $\varrho_1, \varrho_2, \varrho_3 \in [0, 1]$ .
- (iv)  $t(\varrho_1, \varrho_2) \leq t(\varrho'_1, \varrho'_2)$ , for all  $\varrho_1 \leq \varrho'_1$ ,  $\varrho_2 \leq \varrho'_2$  and  $\varrho_1, \varrho_2, \varrho'_1, \varrho'_2 \in [0, 1]$ .

t-conorm or s-norm or triangular conorm operator is a binary, disjunctive type operator which maps unit square to the unit interval, i.e.,  $s : [0, 1]^2 \rightarrow [0, 1]$  and satisfies the following properties as follows:

- (i)  $s(0, \varrho_1) = \varrho_1$ ,  $s(1, \varrho_1) = 1$ .
- (ii)  $s(\varrho_1, \varrho_2) = s(\varrho_2, \varrho_1)$ , for all  $\varrho_1, \varrho_2 \in [0, 1]$ .
- (iii)  $s(\varrho_1, s(\varrho_2, \varrho_3)) = s(s(\varrho_1, \varrho_2), \varrho_3)$ , for all  $\varrho_1, \varrho_2, \varrho_3 \in [0, 1]$ .

(iv)  $s(\varrho_1, \varrho_2) \leq s(\varrho'_1, \varrho'_2)$ , for all  $\varrho_1 \leq \varrho'_1, \varrho_2 \leq \varrho'_2$  and for all  $\varrho_1, \varrho_2, \varrho'_1, \varrho'_2 \in [0, 1]$ .

Both the operators are related by the relation  $s(a, b) = 1 - t(1 - a, 1 - b)$  i.e., they satisfy the De'Morgan's duality for all  $(a, b) \in [0, 1]^2$ .

**Definition 2.3** [52] (Score function): Let  $\text{PyFS}(\mathcal{U})$  denotes all PyFSs on the universe of discourse  $\mathcal{U}$ . The score function  $\tilde{\varphi} = \langle \mathfrak{T}_{\tilde{\varphi}}, \mathfrak{N}_{\tilde{\varphi}} \rangle \in \text{PyFS}(\mathcal{U})$  is denoted as  $Sc(\tilde{\varphi})$  and defined as  $Sc(\tilde{\varphi}) = \mathfrak{T}_{\tilde{\varphi}}^2 - \mathfrak{N}_{\tilde{\varphi}}^2$ . Clearly,  $Sc(\tilde{\varphi}) \in [-1, 1]$ . For any two PyFNs  $\tilde{\varphi}_1$  and  $\tilde{\varphi}_2$ , if  $Sc(\tilde{\varphi}_1) > Sc(\tilde{\varphi}_2)$  then  $\tilde{\varphi}_1 > \tilde{\varphi}_2$  and if  $Sc(\tilde{\varphi}_1) = Sc(\tilde{\varphi}_2)$  then  $\tilde{\varphi}_1 = \tilde{\varphi}_2$ .

Sometimes, the score function in definition-2.3 may give an unreasonable result. For example, the score values of two PyFNs,  $\langle 0.5, 0.5 \rangle$  and  $\langle 0.6, 0.6 \rangle$ , remain the same and which implies that the two PyFNs are equal. However, clearly, it is seen that they never are equal. It was pointed out by Peng and Yang [53] and defined the accuracy function of PyFNs.

**Definition 2.4** [53] (Accuracy function): Let  $\text{PyFS}(\mathcal{U})$  denotes all PyFSs on the universe of discourse  $\mathcal{U}$ . The accuracy function of  $\tilde{\varphi} = \langle \mathfrak{T}_{\tilde{\varphi}}, \mathfrak{N}_{\tilde{\varphi}} \rangle \in \text{PyFS}(\mathcal{U})$  is denoted as  $Ac(\tilde{\varphi})$  and defined as  $Ac(\tilde{\varphi}) = \mathfrak{T}_{\tilde{\varphi}}^2 + \mathfrak{N}_{\tilde{\varphi}}^2$ . Clearly,  $Ac(\tilde{\varphi}) \in [0, 1]$ .

The score function and accuracy function are useful tools to determine the order of a given set of PyFNs. Hence  $\text{PyFS}(\mathcal{U})$ , with the score function and accuracy function, forms a totally ordered set, and the order of two PyFNs are proposed by Peng and Yang [53] as follows:

(i) If  $Sc(\tilde{\varphi}_1) < Sc(\tilde{\varphi}_2)$ , then  $\tilde{\varphi}_1 < \tilde{\varphi}_2$ .

(ii) If  $Sc(\tilde{\varphi}_1) > Sc(\tilde{\varphi}_2)$ , then  $\tilde{\varphi}_1 > \tilde{\varphi}_2$ ,

(iii) If  $Sc(\tilde{\varphi}_1) = Sc(\tilde{\varphi}_2)$ , then

(a) If  $Ac(\tilde{\varphi}_1) < Ac(\tilde{\varphi}_2)$ , then  $\tilde{\varphi}_1 < \tilde{\varphi}_2$ ,

(b) If  $Ac(\tilde{\varphi}_1) > Ac(\tilde{\varphi}_2)$ , then  $\tilde{\varphi}_1 > \tilde{\varphi}_2$ ,

(c) If  $Ac(\tilde{\varphi}_1) = Ac(\tilde{\varphi}_2)$ , then  $\tilde{\varphi}_1 \simeq \tilde{\varphi}_2$ ,

where  $\tilde{\varphi}_1 = \langle \tilde{T}_{\tilde{\varphi}_1}, \mathfrak{N}_{\tilde{\varphi}_1} \rangle \in \text{PyFS}(\mathcal{U})$  and  $\tilde{\varphi}_2 = \langle \tilde{T}_{\tilde{\varphi}_2}, \mathfrak{N}_{\tilde{\varphi}_2} \rangle \in \text{PyFS}(\mathcal{U})$ .

**Definition 2.5** [54–56] (Lattice structure of PyFNs):

Let  $\text{PyFN}(\mathcal{U})$  be the set of Pythagorean fuzzy numbers on  $\mathcal{U}$  and  $\leq_L$  be a partial order relation defined on  $\text{PyFN}(\mathcal{U})$ .  $\tilde{\varphi}_1 = \langle \mathfrak{T}_{\tilde{\varphi}_1}, \mathfrak{N}_{\tilde{\varphi}_1} \rangle, \tilde{\varphi}_2 = \langle \mathfrak{T}_{\tilde{\varphi}_2}, \mathfrak{N}_{\tilde{\varphi}_2} \rangle$  be two Pythagorean fuzzy numbers on  $\text{PyFN}(\mathcal{U})$ . Now  $\tilde{\varphi}_1 \leq_L \tilde{\varphi}_2 \implies \mathfrak{T}_{\tilde{\varphi}_1} \leq \mathfrak{T}_{\tilde{\varphi}_2}$  and  $\mathfrak{N}_{\tilde{\varphi}_1} \geq \mathfrak{N}_{\tilde{\varphi}_2}$ . Thus  $(\text{PyFN}(\mathcal{U}), \leq_L)$  forms a lattice with the partial order relation defined above containing  $\langle 0, 1 \rangle$  as bottom element and  $\langle 1, 0 \rangle$  as top element of the Lattice.

**Lemma 2.1** Let  $\tilde{a} = \langle a_1, a_2 \rangle, \tilde{b} = \langle b_1, b_2 \rangle$  be two PyFNs. If  $\tilde{a} \leq_L \tilde{b}$  then  $\tilde{a} \leq \tilde{b}$  but the converse may not be true.

**proof:** Here,  $\tilde{a} = \langle a_1, a_2 \rangle, \tilde{b} = \langle b_1, b_2 \rangle$ . We know  $\tilde{a} \leq_L \tilde{b}$  implies  $a_1 \leq b_1$  and  $a_2 \geq b_2$ .

Now,  $Sc(\tilde{a}) = a_1^2 - a_2^2 \leq b_1^2 - b_2^2 = Sc(\tilde{b})$  i.e.,  $Sc(\tilde{a}) \leq Sc(\tilde{b})$ .

**Case-1:** If  $Sc(\tilde{a}) < Sc(\tilde{b})$ , then  $\tilde{a} < \tilde{b}$ .

**Case-2:** If  $Sc(\tilde{a}) = Sc(\tilde{b})$ , then we have to check corresponding accuracy values.

Since,  $a_1 \leq b_1$  and  $a_2 \geq b_2$  we suppose that  $b_1 = a_1 + p$  and  $a_2 = b_2 + q$ , where the scalars  $p, q \geq 0$ .

Then  $\tilde{a} = \langle a_1, b_2 + q \rangle$  and  $\tilde{b} = \langle a_1 + p, b_2 \rangle$ .

Therefore  $Sc(\tilde{a}) = Sc(\tilde{b})$  implies that  $a_1^2 - (b_2 + q)^2 = (a_1 + p)^2 - b_2^2$ .

i.e.,  $2pa_1 + 2qb_2 + p^2 + q^2 = 0$ , which is possible for any  $a_1, b_2$  only when  $p = 0$  and  $q = 0$  simultaneously.

Then,  $Ac(\tilde{a}) = a_1^2 + (b_2 + q)^2 = a_1^2 + b_2^2$ , as  $q = 0$ .

$Ac(\tilde{b}) = (a_1 + p)^2 + b_2^2 = a_1^2 + b_2^2$ , as  $p = 0$ .

Thus, in this case  $Sc(\tilde{a}) = Sc(\tilde{b})$  and  $Ac(\tilde{a}) = Ac(\tilde{b})$ .

Hence,  $\tilde{a} = \tilde{b}$ .

Hence, from Case-1 and Case-2 we can write that if  $\tilde{a} \leq_L \tilde{b}$  then  $\tilde{a} \leq \tilde{b}$ .

To prove the converse part, we take  $\tilde{a} = \langle 0.7, 0.6 \rangle$  and  $\tilde{b} = \langle 0.5, 0.2 \rangle$ .

Now  $Sc(\tilde{a}) = 0.49 - 0.36 = 0.13$  and  $Sc(\tilde{b}) = 0.25 - 0.04 = 0.21$ .

Thus,  $\tilde{a} \leq \tilde{b}$ . But it does not imply  $\tilde{a} \leq_L \tilde{b}$  because, although it satisfies  $a_2 \geq b_2$ , it does not satisfy the condition  $a_1 \leq b_1$ .

**Properties 1** [53] For any two PyFNs,  $\tilde{\varphi}_1 = \langle \mathfrak{T}_{\tilde{\varphi}_1}, \mathfrak{N}_{\tilde{\varphi}_1} \rangle, \tilde{\varphi}_2 = \langle \mathfrak{T}_{\tilde{\varphi}_2}, \mathfrak{N}_{\tilde{\varphi}_2} \rangle$  defined on the universe of discourse  $\mathcal{U}$ , the containment, equality, union, intersection and complement operational laws respectively are as follows:

(i)  $\tilde{\varphi}_1 \subseteq \tilde{\varphi}_2$  iff  $\mathfrak{T}_{\tilde{\varphi}_1}(\varrho) \leq \mathfrak{T}_{\tilde{\varphi}_2}(\varrho), \mathfrak{N}_{\tilde{\varphi}_1}(\varrho) \geq \mathfrak{N}_{\tilde{\varphi}_2}(\varrho)$ , for all  $\varrho \in \mathcal{U}$ .

(ii)  $\tilde{\varphi}_1 = \tilde{\varphi}_2$  iff  $\tilde{\varphi}_1 \subseteq \tilde{\varphi}_2$  and  $\tilde{\varphi}_1 \supseteq \tilde{\varphi}_2$ .

(iii)  $\tilde{\varphi}_1 \cup \tilde{\varphi}_2 = \langle \max\{\mathfrak{T}_{\tilde{\varphi}_1}, \mathfrak{T}_{\tilde{\varphi}_2}\}, \min\{\mathfrak{N}_{\tilde{\varphi}_1}, \mathfrak{N}_{\tilde{\varphi}_2}\} \rangle$ .

(iv)  $\tilde{\varphi}_1 \cap \tilde{\varphi}_2 = \langle \min\{\mathfrak{T}_{\tilde{\varphi}_1}, \mathfrak{T}_{\tilde{\varphi}_2}\}, \max\{\mathfrak{N}_{\tilde{\varphi}_1}, \mathfrak{N}_{\tilde{\varphi}_2}\} \rangle$ .

(v)  $\tilde{\varphi}_1^c = \langle \mathfrak{N}_{\tilde{\varphi}_1}, \mathfrak{T}_{\tilde{\varphi}_1} \rangle$ .

**Definition 2.6** [49, 52] (Operations on PyFNs):

For any three PyFNs,  $\tilde{\varphi} = \langle \mathfrak{T}_{\tilde{\varphi}}, \mathfrak{N}_{\tilde{\varphi}} \rangle, \tilde{\varphi}_1 = \langle \mathfrak{T}_{\tilde{\varphi}_1}, \mathfrak{N}_{\tilde{\varphi}_1} \rangle, \tilde{\varphi}_2 = \langle \mathfrak{T}_{\tilde{\varphi}_2}, \mathfrak{N}_{\tilde{\varphi}_2} \rangle$  in  $\text{PyNS}(\mathcal{U})$  and for scalar  $\tau > 0$  the basic operational rules on PyFNs are as follows:

$$(i) \tilde{\wp}_1 \oplus \tilde{\wp}_2 = \langle \sqrt{\mathfrak{T}_{\tilde{\wp}_1}^2 + \mathfrak{T}_{\tilde{\wp}_2}^2 - \mathfrak{T}_{\tilde{\wp}_1}^2 \mathfrak{T}_{\tilde{\wp}_2}^2}, \aleph_{\tilde{\wp}_1} \aleph_{\tilde{\wp}_2} \rangle.$$

$$(ii) \tilde{\wp}_1 \otimes \tilde{\wp}_2 = \langle \mathfrak{T}_{\tilde{\wp}_1} \mathfrak{T}_{\tilde{\wp}_2}, \sqrt{\aleph_{\tilde{\wp}_1}^2 + \aleph_{\tilde{\wp}_2}^2 - \aleph_{\tilde{\wp}_1}^2 \aleph_{\tilde{\wp}_2}^2} \rangle.$$

$$(iii) \tau \tilde{\wp} = \langle \sqrt{1 - (1 - \mathfrak{T}_{\tilde{\wp}}^2)^\tau}, \aleph_{\tilde{\wp}}^\tau \rangle.$$

$$(iv) \tilde{\wp}^\tau = \langle \mathfrak{T}_{\tilde{\wp}}^\tau, \sqrt{1 - (1 - \aleph_{\tilde{\wp}}^2)^\tau} \rangle.$$

Yager [57] introduced some properties on the operational laws of PyFNs, which are given below:

**Theorem 2.1** For any three PyFNs,  $\tilde{\wp}_1 = \langle \mathfrak{T}_{\tilde{\wp}_1}, \aleph_{\tilde{\wp}_1} \rangle$ ,  $\tilde{\wp}_2 = \langle \mathfrak{T}_{\tilde{\wp}_2}, \aleph_{\tilde{\wp}_2} \rangle$ ,  $\tilde{\wp}_3 = \langle \mathfrak{T}_{\tilde{\wp}_3}, \aleph_{\tilde{\wp}_3} \rangle$  in  $\text{PyFN}(\mathfrak{U})$  and for any scalar  $\tau_1 > 0$ ,  $\tau_2 > 0$ .

$$(i) \tilde{\wp}_1 \oplus \tilde{\wp}_2 = \tilde{\wp}_2 \oplus \tilde{\wp}_1.$$

$$(ii) \tilde{\wp}_1 \otimes \tilde{\wp}_2 = \tilde{\wp}_2 \otimes \tilde{\wp}_1.$$

$$(iii) \tau_1(\tilde{\wp}_1 \oplus \tilde{\wp}_2) = \tau_1 \tilde{\wp}_1 \oplus \tau_1 \tilde{\wp}_2.$$

$$(iv) (\tilde{\wp}_1 \otimes \tilde{\wp}_2)^{\tau_1} = \tilde{\wp}_1^{\tau_1} \otimes \tilde{\wp}_2^{\tau_1}.$$

$$(v) \tau_1 \tilde{\wp}_1 \oplus \tau_2 \tilde{\wp}_1 = (\tau_1 + \tau_2) \tilde{\wp}_1.$$

$$(vi) \tilde{\wp}_1^{\tau_1} \otimes \tilde{\wp}_1^{\tau_2} = \tilde{\wp}_1^{\tau_1 + \tau_2}.$$

$$(vii) \tilde{\wp}_1 \oplus (\tilde{\wp}_2 \oplus \tilde{\wp}_3) = (\tilde{\wp}_1 \oplus \tilde{\wp}_2) \oplus \tilde{\wp}_3.$$

$$(viii) \tilde{\wp}_1 \otimes (\tilde{\wp}_2 \otimes \tilde{\wp}_3) = (\tilde{\wp}_1 \otimes \tilde{\wp}_2) \otimes \tilde{\wp}_3.$$

To aggregate a given set of PyFNs, some Pythagorean averaging and geometric type AOs are used. The basic Pythagorean fuzzy AOs which are constructed on the basis of binary operators  $\oplus$ ,  $\otimes$  defined earlier on  $\text{PyFNs}(\mathfrak{U})$  are defined below.

**Definition 2.7** [58, 59] (Pythagorean fuzzy weighted averaging (PyFWA) operator)

Let  $\mathfrak{P} = \{\tilde{\wp}_j = \langle \mathfrak{T}_{\tilde{\wp}_j}, \aleph_{\tilde{\wp}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . PyFWA operator is a mapping  $PyFWA_\ell : \mathfrak{P}^h \rightarrow \mathfrak{P}$  which is defined below.

$$PyFWA_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_h) = \bigoplus_{j=1}^h (\ell_j \tilde{\wp}_j),$$

where,  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  be a weight vector such that  $\ell_j \in [0, 1]$ ,  $j = 1, 2, \dots, h$  and  $\sum_{j=1}^h \ell_j = 1$ .

$$\text{Hence, } PyFWA_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_h) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \dots \oplus \ell_h \tilde{\wp}_h = \left\langle \sqrt{1 - \prod_{j=1}^h (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}, \prod_{j=1}^h \aleph_{\tilde{\wp}_j}^{\ell_j} \right\rangle.$$

**Definition 2.8** [60] (Pythagorean fuzzy ordered weighted averaging (PyFOWA) operator)

Let  $\mathfrak{P} = \{\tilde{\wp}_j = \langle \mathfrak{T}_{\tilde{\wp}_j}, \aleph_{\tilde{\wp}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . PyFOWA operator is a mapping  $PyFOWA_\ell : \mathfrak{P}^h \rightarrow \mathfrak{P}$  which is defined below.

$$PyFOWA_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_h) = \bigoplus_{j=1}^h (\ell_j \tilde{\wp}_{\sigma(j)}),$$

where,  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  is a weight vector such that  $\ell_j \in [0, 1]$ ,  $j = 1, 2, \dots, h$  and  $\sum_{j=1}^h \ell_j = 1$  and  $(\sigma(1), \sigma(2), \dots, \sigma(h))$

is a permutation of  $(1, 2, \dots, h)$  such that  $\tilde{\wp}_{\sigma(j-1)} \geq \tilde{\wp}_{\sigma(j)}$  for all  $j = 2, 3, \dots, h$ .

$$\text{Hence, } PyFOWA_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_h) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \dots \oplus \ell_h \tilde{\wp}_h = \left\langle \sqrt{1 - \prod_{j=1}^h (1 - \mathfrak{T}_{\tilde{\wp}_{\sigma(j)}}^2)^{\ell_j}}, \prod_{j=1}^h \aleph_{\tilde{\wp}_{\sigma(j)}}^{\ell_j} \right\rangle.$$

**Definition 2.9** [58, 61] (Pythagorean fuzzy hybrid averaging (PyFHA) operator)

Let  $\mathfrak{P} = \{\tilde{\phi}_j = \langle \mathfrak{T}_{\tilde{\phi}_j}, \mathfrak{N}_{\tilde{\phi}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathcal{U})$ . PyFHA operator is a mapping  $\text{PyFHA}_{\ell, \Omega} : \mathfrak{P}^h \rightarrow \mathfrak{P}$  which is defined below.

$$\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \dots, \tilde{\phi}_h) = \bigoplus_{j=1}^h (\ell_j \tilde{\phi}_{\sigma(j)}^*),$$

where,  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, h$  and  $\sum_{j=1}^h \ell_j = 1$  and  $\tilde{\phi}_j^* = h\Omega_j \tilde{\phi}_j$  and  $(\sigma(1), \sigma(2), \dots, \sigma(h))$  is a permutation of  $(1, 2, \dots, h)$  such that  $\tilde{\phi}_{\sigma(j-1)}^* \geq \tilde{\phi}_{\sigma(j)}^*$  for all  $j = 2, 3, \dots, h$  and  $\Omega = (\Omega_1, \Omega_2, \dots, \Omega_h)^T$  is a associated weight vector such that  $\Omega_j \in [0, 1]$  for all  $j = 1, 2, 3, \dots, h$  and  $\sum_{j=1}^h \Omega_j = 1$ .

Hence,  $\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \dots, \tilde{\phi}_h) = \ell_1 \tilde{\phi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\phi}_{\sigma(2)}^* \oplus \dots \oplus \ell_h \tilde{\phi}_{\sigma(h)}^* = \left\langle \sqrt{1 - \prod_{j=1}^h (1 - \mathfrak{T}_{\tilde{\phi}_{\sigma(j)}^*}^2)^{\ell_j}}, \prod_{j=1}^h \mathfrak{N}_{\tilde{\phi}_{\sigma(j)}^*}^{\ell_j} \right\rangle$ .

**Lemma 2.2** If  $\ell = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})^T$  then  $\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4) = \text{PyFWA}_{\Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4)$ .

**proof:** It is given that  $\ell = (\ell_1, \ell_2, \ell_3, \ell_4) = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})$  and  $\Omega = (\Omega_1, \Omega_2, \Omega_3, \Omega_4)$  be an associated weight vector.

Now we have  $\tilde{\phi}_j^* = 4\Omega_j \tilde{\phi}_j$  for  $j = 1, 2, 3, 4$ .

Suppose, without loss of generality that,  $\tilde{\phi}_2^* \geq \tilde{\phi}_1^* \geq \tilde{\phi}_4^* \geq \tilde{\phi}_3^*$  i.e.,  $\tilde{\phi}_{\sigma(1)}^* \geq \tilde{\phi}_{\sigma(2)}^* \geq \tilde{\phi}_{\sigma(3)}^* \geq \tilde{\phi}_{\sigma(4)}^*$ .

Hence,  $\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4) = \bigoplus_{j=1}^4 (\ell_j \tilde{\phi}_{\sigma(j)}^*)$

$$\begin{aligned} &= \ell_1 \tilde{\phi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\phi}_{\sigma(2)}^* \oplus \ell_3 \tilde{\phi}_{\sigma(3)}^* \oplus \ell_4 \tilde{\phi}_{\sigma(4)}^* \\ &= \frac{1}{4} [\tilde{\phi}_{\sigma(1)}^* \oplus \tilde{\phi}_{\sigma(2)}^* \oplus \tilde{\phi}_{\sigma(3)}^* \oplus \tilde{\phi}_{\sigma(4)}^*] = \frac{1}{4} [\tilde{\phi}_2^* \oplus \tilde{\phi}_1^* \oplus \tilde{\phi}_4^* \oplus \tilde{\phi}_3^*] = \frac{1}{4} [4\Omega_2 \tilde{\phi}_2 \oplus 4\Omega_1 \tilde{\phi}_1 \oplus 4\Omega_4 \tilde{\phi}_4 \oplus 4\Omega_3 \tilde{\phi}_3] = \\ &\bigoplus_{j=1}^4 (\Omega_j \tilde{\phi}_j) = \text{PyFWA}_{\Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4). \end{aligned}$$

**Theorem 2.2** If  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T = (\frac{1}{h}, \frac{1}{h}, \dots, \frac{1}{h})^T$  then  $\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \dots, \tilde{\phi}_h) = \text{PyFWA}_{\Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \dots, \tilde{\phi}_h)$ .

**proof:** The proof is similar to the proof of Theorem 4.11.

**Lemma 2.3**

If  $\Omega = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})^T$  then  $\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4) = \text{PyFOWA}_{\ell}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4)$ .

**proof:** Now we have  $\Omega = (\Omega_1, \Omega_2, \Omega_3, \Omega_4) = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})^T$  and  $\ell = (\ell_1, \ell_2, \ell_3, \ell_4)^T$  as weight vectors.

Now, we have  $\tilde{\phi}_j^* = 4\Omega_j \tilde{\phi}_j$ , which becomes  $\tilde{\phi}_j^* = \tilde{\phi}_j \forall j = 1, 2, 3, 4$ .

Suppose, without loss of generality,  $\tilde{\phi}_2^* \geq \tilde{\phi}_1^* \geq \tilde{\phi}_4^* \geq \tilde{\phi}_3^*$  i.e.,

$$\tilde{\phi}_{\sigma(1)}^* \geq \tilde{\phi}_{\sigma(2)}^* \geq \tilde{\phi}_{\sigma(3)}^* \geq \tilde{\phi}_{\sigma(4)}^*$$

$$\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4) = \bigoplus_{j=1}^4 (\ell_j \tilde{\phi}_{\sigma(j)}^*) = \ell_1 \tilde{\phi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\phi}_{\sigma(2)}^* \oplus \ell_3 \tilde{\phi}_{\sigma(3)}^* \oplus \ell_4 \tilde{\phi}_{\sigma(4)}^*$$

$$= \bigoplus_{j=1}^4 (\ell_j \tilde{\phi}_{\sigma(j)}) = \text{PyFOWA}_{\ell}(\tilde{\phi}_1, \tilde{\phi}_2, \tilde{\phi}_3, \tilde{\phi}_4).$$

**Theorem 2.3** If  $\Omega = (\Omega_1, \Omega_2, \dots, \Omega_h)^T = (\frac{1}{h}, \frac{1}{h}, \dots, \frac{1}{h})^T$  then  $\text{PyFHA}_{\ell, \Omega}(\tilde{\phi}_1, \tilde{\phi}_2, \dots, \tilde{\phi}_h) = \text{PyFOWA}_{\ell}(\tilde{\phi}_1, \tilde{\phi}_2, \dots, \tilde{\phi}_h)$ .

**proof:** The proof is similar to the proof of Theorem 4.12.

It is clear from Theorem 2.2, and Theorem 2.3 that PyFWA, PyFOWA operators are the particular cases of PyFHA operator or PyFHA operator is the generalization of PyFWA and PyFOWA operators.

**Definition 2.10** [27, 41] (Pythagorean fuzzy weighted geometric (PyFWG) operator)

Let  $\mathfrak{P} = \{\tilde{\phi}_j = \langle \mathfrak{T}_{\tilde{\phi}_j}, \mathfrak{N}_{\tilde{\phi}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of Pythagorean fuzzy numbers in  $\text{PyFN}(\mathcal{U})$ . PyFWG operator is a mapping  $\text{PyFWG}_{\ell} : \mathfrak{P}^h \rightarrow \mathfrak{P}$  which is defined below.

$$\text{PyFWG}_{\ell}(\tilde{\phi}_1, \tilde{\phi}_2, \dots, \tilde{\phi}_h) = \bigotimes_{j=1}^h (\tilde{\phi}_j)^{\ell_j},$$

where  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, h$  and  $\sum_{j=1}^h \ell_j = 1$ .



228 That is  $PyFWG_{\ell}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}}) = \tilde{\wp}_1^{\ell_1} \otimes \tilde{\wp}_2^{\ell_2} \otimes \dots \otimes \tilde{\wp}_{\tilde{h}}^{\ell_{\tilde{h}}} = \left\langle \prod_{j=1}^{\tilde{h}} \mathfrak{T}_{\tilde{\wp}_j}^{\ell_j}, \sqrt{1 - \prod_{j=1}^{\tilde{h}} (1 - \aleph_{\tilde{\wp}_j}^2)^{\ell_j}} \right\rangle$ .

229 **Definition 2.11** [62] (Pythagorean fuzzy ordered weighted geometric (PyFOWG) operator)

230 Let  $\mathfrak{P} = \{\tilde{\wp}_j = \langle \mathfrak{T}_{\tilde{\wp}_j}, \aleph_{\tilde{\wp}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . PyFOWG operator is a mapping  
231  $PyFOWG_{\ell} : \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  which is defined below.

$$232 \quad PyFOWG_{\ell}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}}) = \bigotimes_{j=1}^{\tilde{h}} (\tilde{\wp}_{\sigma(j)}^{\ell_j}),$$

233 where,  $\ell = (\ell_1, \ell_2, \dots, \ell_{\tilde{h}})^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \ell_j = 1$  and  $(\sigma(1), \sigma(2), \dots, \sigma(\tilde{h}))$   
234 is a permutation of  $(1, 2, \dots, \tilde{h})$  such that  $\tilde{\wp}_{\sigma(j-1)} \geq \tilde{\wp}_{\sigma(j)}$  for all  $j = 2, 3, \dots, \tilde{h}$ .

235 That is  $PyFOWG_{\ell}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}})$

$$236 = \tilde{\wp}_{\sigma(1)}^{\ell_1} \otimes \tilde{\wp}_{\sigma(2)}^{\ell_2} \otimes \dots \otimes \tilde{\wp}_{\sigma(\tilde{h})}^{\ell_{\tilde{h}}} = \left\langle \prod_{j=1}^{\tilde{h}} \mathfrak{T}_{\tilde{\wp}_{\sigma(j)}}^{\ell_j}, \sqrt{1 - \prod_{j=1}^{\tilde{h}} (1 - \aleph_{\tilde{\wp}_{\sigma(j)}}^2)^{\ell_j}} \right\rangle.$$

237 **Definition 2.12** [63] (Pythagorean fuzzy hybrid geometric (PyFHG) operator)

238 Let  $\mathfrak{P} = \{\tilde{\wp}_j = \langle \mathfrak{T}_{\tilde{\wp}_j}, \aleph_{\tilde{\wp}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . PyFHG operator is a mapping  
239  $PyFHG_{\ell, \Omega} : \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  which is defined below.

$$240 \quad PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}}) = \bigotimes_{j=1}^{\tilde{h}} (\tilde{\wp}_{\sigma(j)}^*)^{\ell_j},$$

241 where,  $\ell = (\ell_1, \ell_2, \dots, \ell_{\tilde{h}})^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \ell_j = 1$  and  $\tilde{\wp}_j^* = (\tilde{\wp}_j)^{\tilde{h}\Omega_j}$   
242 and  $(\sigma(1), \sigma(2), \dots, \sigma(\tilde{h}))$  is a permutation of  $(1, 2, \dots, \tilde{h})$  such that  $\tilde{\wp}_{\sigma(j-1)}^* \geq \tilde{\wp}_{\sigma(j)}^*$  for all  $j = 2, 3, \dots, \tilde{h}$  and  
243  $\Omega = (\Omega_1, \Omega_2, \dots, \Omega_{\tilde{h}})^T$  is a associated weight vector such that  $\Omega_j \in [0, 1]$  for all  $j = 1, 2, 3, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \Omega_j = 1$ .

244 That is  $PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}})$

$$245 = (\tilde{\wp}_{\sigma(1)}^*)^{\ell_1} \otimes (\tilde{\wp}_{\sigma(2)}^*)^{\ell_2} \otimes \dots \otimes (\tilde{\wp}_{\sigma(\tilde{h})}^*)^{\ell_{\tilde{h}}} = \left\langle \prod_{j=1}^{\tilde{h}} \mathfrak{T}_{\tilde{\wp}_{\sigma(j)}^*}^{\ell_j}, \sqrt{1 - \prod_{j=1}^{\tilde{h}} (1 - \aleph_{\tilde{\wp}_{\sigma(j)}^*}^2)^{\ell_j}} \right\rangle.$$

246 **Lemma 2.4** If  $\ell = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})^T$  then  $PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4) = PyFWG_{\Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4)$ .

247 **Proof:** We have  $\ell = (\ell_1, \ell_2, \ell_3, \ell_4) = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})$  and  $\Omega = (\Omega_1, \Omega_2, \Omega_3, \Omega_4)$  as weight vectors.

248 Now,  $\tilde{\wp}_j^* = (\tilde{\wp}_j)^{4\Omega_j}$  for  $j = 1, 2, 3, 4$ .

249 Suppose, without loss of generality, that  $\tilde{\wp}_2^* \geq \tilde{\wp}_1^* \geq \tilde{\wp}_4^* \geq \tilde{\wp}_3^*$

250 i.e.,  $\tilde{\wp}_{\sigma(1)}^* \geq \tilde{\wp}_{\sigma(2)}^* \geq \tilde{\wp}_{\sigma(3)}^* \geq \tilde{\wp}_{\sigma(4)}^*$

251 Hence,  $PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4) = \bigotimes_{j=1}^4 (\tilde{\wp}_{\sigma(j)}^*)^{\ell_j}$

$$252 = (\tilde{\wp}_{\sigma(1)}^*)^{\ell_1} \otimes (\tilde{\wp}_{\sigma(2)}^*)^{\ell_2} \otimes (\tilde{\wp}_{\sigma(3)}^*)^{\ell_3} \otimes (\tilde{\wp}_{\sigma(4)}^*)^{\ell_4}$$

$$253 = \bigotimes_{j=1}^4 (\Omega_j \tilde{\wp}_j) = PyFWG_{\Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4).$$

254 **Theorem 2.4** If  $\ell = (\ell_1, \ell_2, \dots, \ell_{\tilde{h}})^T = (\frac{1}{\tilde{h}}, \frac{1}{\tilde{h}}, \dots, \frac{1}{\tilde{h}})^T$  then  $PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}}) = PyFWG_{\Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}})$ .

255 **proof:** The proof is similar as Theorem 5.11.

256 **Lemma 2.5** If  $\Omega = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})^T$  then  $PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4) = PyFOWG_{\ell}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4)$ .

257 **Proof:** We have  $\Omega = (\Omega_1, \Omega_2, \Omega_3, \Omega_4) = (\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})^T$  and  $\ell = (\ell_1, \ell_2, \ell_3, \ell_4)^T$  as weight vectors.

258 Now,  $\tilde{\wp}_j^* = (\tilde{\wp}_j)^{4\Omega_j}$ , which becomes  $\tilde{\wp}_j^* = \tilde{\wp}_j \forall j = 1, 2, 3, 4$

259 Without loss of generality, we assume that  $\tilde{\wp}_2^* \geq \tilde{\wp}_1^* \geq \tilde{\wp}_4^* \geq \tilde{\wp}_3^*$

260 i.e.,  $\tilde{\wp}_{\sigma(1)}^* \geq \tilde{\wp}_{\sigma(2)}^* \geq \tilde{\wp}_{\sigma(3)}^* \geq \tilde{\wp}_{\sigma(4)}^*$ .

261 Therefore,  $PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4) = \bigotimes_{j=1}^4 (\tilde{\wp}_{\sigma(j)}^*)^{\ell_j} = (\tilde{\wp}_{\sigma(1)}^*)^{\ell_1} \otimes (\tilde{\wp}_{\sigma(2)}^*)^{\ell_2} \otimes (\tilde{\wp}_{\sigma(3)}^*)^{\ell_3} \otimes (\tilde{\wp}_{\sigma(4)}^*)^{\ell_4}$

$$262 = \bigotimes_{j=1}^4 (\tilde{\wp}_{\sigma(j)})^{\ell_j} = PyFOWG_{\ell}(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4).$$

263 **Theorem 2.5** If  $\Omega = (\Omega_1, \Omega_2, \dots, \Omega_{\tilde{h}})^T = (\frac{1}{\tilde{h}}, \frac{1}{\tilde{h}}, \dots, \frac{1}{\tilde{h}})^T$  then  $PyFHG_{\ell, \Omega}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\tilde{h}})$

264  $= PyFOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h).$

265 **Proof:** The proof is similar as Theorem 5.12.

266 It is clear from the Theorem 2.4 and Theorem 2.5 that PyFWG and PyFOWG operators are the particular cases  
267 of the PyFHG operator, or it can be said that the PyFHG operator is the generalization of PyFWG and PyFOWG  
268 operators.

### 269 3 Hamacher t-norm and Hamacher t-conorm

270 Hamacher introduced the Hamacher t-norm and Hamacher t-conorm operators. Liu and Peide [34] proposed the  
271 de

272 nitions of the same, Lu et al. [64] as follows:

273 **Definition 3.1** (Hamacher t-norm operator and Hamacher t-conorm operator)

274 Hamacher t-norm is a function  $\otimes^H : [0, 1]^2 \rightarrow [0, 1]$  which is defined below.

275  $a \otimes^H b = \frac{ab}{\kappa + (1-\kappa)(a+b-ab)}$  for all  $(a, b) \in [0, 1]^2$  and scalar parameter  $\kappa > 0$ .

276 Hamacher t-conorm operator is a function  $\oplus^H : [0, 1]^2 \rightarrow [0, 1]$  which is defined below.

277  $a \oplus^H b = \frac{a+b-ab-(1-\kappa)ab}{1-(1-\kappa)ab} \forall (a, b) \in [0, 1]^2$  and scalar parameter  $\kappa > 0$ .

278 **Case-1:** If  $\kappa = 1$  then  $a \otimes^H b = ab$ , which is basic algebraic t-norm operator and  $a \oplus^H b = a + b - ab$ , which is  
279 basic algebraic t-conorm operator.

280 **Case-2:** If  $\kappa = 2$  then  $a \otimes^H b = \frac{ab}{1+(1-a)(1-b)}$ , which is called Einstein t-norm operator and  $a \oplus^H b = \frac{a+b}{1+ab}$ , which  
281 is called Einstein t-conorm operator.

**Example 1** Let  $a = 0.7, b = 0.4$  and  $\kappa = 2$  then

$$a \otimes^H b = \frac{0.7 \times 0.4}{2 + (1-2)(0.7 + 0.4 - 0.28)} = 0.237 \in [0, 1]$$

$$a \oplus^H b = \frac{0.7 + 0.4 - 0.4 \times 0.7 - (1-2) \times 0.7 \times 0.4}{1 - (1-2) \times 0.7 \times 0.4} = 0.781 \in [0, 1]$$

282 We have applied Hamacher t-norm and Hamacher t-conorm on real numbers on  $[0, 1]$ , but now we are going to  
283 apply those operators on PyFNs and with the help of Hamacher t-norm and t-conorm operations [34, 36] and basic  
284 Pythagorean fuzzy ORs [49, 52] we get the following ORs which are defined as follows:

#### 285 3.1 ORs on Pythagorean Fuzzy Numbers Based on Hamacher t-norm and Hamacher t-conorm Operators

286 Let  $\tilde{\varphi} = \langle \mathfrak{T}_{\tilde{\varphi}}, \mathfrak{N}_{\tilde{\varphi}} \rangle$ ,  $\tilde{\varphi}_1 = \langle \mathfrak{T}_{\tilde{\varphi}_1}, \mathfrak{N}_{\tilde{\varphi}_1} \rangle$  and  $\tilde{\varphi}_2 = \langle \mathfrak{T}_{\tilde{\varphi}_2}, \mathfrak{N}_{\tilde{\varphi}_2} \rangle$  be three PyFNs in  $PyFN(\mathfrak{U})$  and  $\tau > 0$  be an any  
287 scalar. The basic ORs [55] are as follows:

288 (i)  $\tilde{\varphi}_1 \oplus^H \tilde{\varphi}_2 = \left\langle \sqrt{\frac{\mathfrak{T}_{\tilde{\varphi}_1}^2 + \mathfrak{T}_{\tilde{\varphi}_2}^2 - \mathfrak{T}_{\tilde{\varphi}_1}^2 \mathfrak{T}_{\tilde{\varphi}_2}^2 - (1-\kappa)\mathfrak{T}_{\tilde{\varphi}_1}^2 \mathfrak{T}_{\tilde{\varphi}_2}^2}{1-(1-\kappa)\mathfrak{T}_{\tilde{\varphi}_1}^2 \mathfrak{T}_{\tilde{\varphi}_2}^2}}, \sqrt{\frac{\mathfrak{N}_{\tilde{\varphi}_1} \mathfrak{N}_{\tilde{\varphi}_2}}{\kappa + (1-\kappa)(\mathfrak{N}_{\tilde{\varphi}_1}^2 + \mathfrak{N}_{\tilde{\varphi}_2}^2 - \mathfrak{N}_{\tilde{\varphi}_1}^2 \mathfrak{N}_{\tilde{\varphi}_2}^2)}} \right\rangle.$

289 (ii)  $\tilde{\varphi}_1 \otimes^H \tilde{\varphi}_2 = \left\langle \frac{\mathfrak{T}_{\tilde{\varphi}_1} \mathfrak{T}_{\tilde{\varphi}_2}}{\sqrt{\kappa + (1-\kappa)(\mathfrak{T}_{\tilde{\varphi}_1}^2 + \mathfrak{T}_{\tilde{\varphi}_2}^2 - \mathfrak{T}_{\tilde{\varphi}_1}^2 \mathfrak{T}_{\tilde{\varphi}_2}^2)}}, \sqrt{\frac{\mathfrak{N}_{\tilde{\varphi}_1}^2 + \mathfrak{N}_{\tilde{\varphi}_2}^2 - \mathfrak{N}_{\tilde{\varphi}_1}^2 \mathfrak{N}_{\tilde{\varphi}_2}^2 - (1-\kappa)\mathfrak{N}_{\tilde{\varphi}_1}^2 \mathfrak{N}_{\tilde{\varphi}_2}^2}{1-(1-\kappa)\mathfrak{N}_{\tilde{\varphi}_1}^2 \mathfrak{N}_{\tilde{\varphi}_2}^2}} \right\rangle.$

290 (iii)  $\tau \tilde{\varphi} = \left\langle \sqrt{\frac{\{1+(\kappa-1)\mathfrak{T}_{\tilde{\varphi}}^2\}^\tau - (1-\mathfrak{T}_{\tilde{\varphi}}^2)^\tau}{\{1+(\kappa-1)\mathfrak{T}_{\tilde{\varphi}}^2\}^\tau + (\kappa-1)(1-\mathfrak{T}_{\tilde{\varphi}}^2)^\tau}}, \frac{\sqrt{\kappa(\mathfrak{N}_{\tilde{\varphi}}^\tau)}}{\sqrt{\{1+(\kappa-1)(1-\mathfrak{N}_{\tilde{\varphi}}^2)\}^\tau + (\kappa-1)\mathfrak{N}_{\tilde{\varphi}}^2}^\tau}} \right\rangle.$

291 (iv)  $\tilde{\varphi}^\tau = \left\langle \frac{\sqrt{\kappa(\mathfrak{T}_{\tilde{\varphi}}^\tau)}}{\sqrt{\{1+(\kappa-1)(1-\mathfrak{T}_{\tilde{\varphi}}^2)\}^\tau + (\kappa-1)\mathfrak{T}_{\tilde{\varphi}}^2}^\tau}}, \sqrt{\frac{\{1+(\kappa-1)\mathfrak{N}_{\tilde{\varphi}}^2\}^\tau - (1-\mathfrak{N}_{\tilde{\varphi}}^2)^\tau}{\{1+(\kappa-1)\mathfrak{N}_{\tilde{\varphi}}^2\}^\tau + (\kappa-1)(1-\mathfrak{N}_{\tilde{\varphi}}^2)^\tau}} \right\rangle.$

### 295 4 Pythagorean Fuzzy Hamacher Averaging Operators

296 In this section, three types of Pythagorean fuzzy Hamacher averaging operators have been discussed, which are  
297 the Pythagorean fuzzy Hamacher weighted averaging (PyFHWa) operator, Pythagorean fuzzy Hamacher ordered  
298 weighted averaging (PyFHOWa) operator and Pythagorean fuzzy Hamacher hybrid averaging (PyFHHa) operator.  
299 Now  $\oplus^H$  and  $\otimes^H$  are denoted as  $\oplus$  and  $\otimes$ , respectively, and the definitions of those operators are as follows:

#### 300 4.1 Pythagorean Fuzzy Hamacher Weighted Averaging Operator

301 **Definition 4.1** (Pythagorean fuzzy Hamacher weighted averaging (PyFHWa) operator)

302 Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $PyFN(\mathfrak{U})$ . PyFHWa operator is a mapping  
303  $PyFHWa_{\ell} : \mathfrak{P}^h \rightarrow \mathfrak{P}$ , defined below.

304  $PyFHWa_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) = \bigoplus_{j=1}^h (\ell_j \tilde{\varphi}_j),$



where,  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, h$  and  $\sum_{j=1}^h \ell_j = 1$ .

**Theorem 4.1** Let  $\mathfrak{P} = \{\tilde{\wp}_j = \langle \mathfrak{T}_{\tilde{\wp}_j}, \aleph_{\tilde{\wp}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . Then prove that  $\text{PyFHW}A_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_h) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \dots \oplus \ell_h \tilde{\wp}_h$

$$\begin{aligned}
&= \left\langle \sqrt{\frac{\prod_{j=1}^h \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} - \prod_{j=1}^h (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}{\prod_{j=1}^h \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^h (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}}, \right. \\
&\quad \left. \sqrt{\kappa} \prod_{j=1}^h \aleph_{\tilde{\wp}_j}^{\ell_j} \right\rangle \\
&\quad \sqrt{\prod_{j=1}^h \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\wp}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^h \aleph_{\tilde{\wp}_j}^{2\ell_j}} \\
&\quad \textbf{Proof:} \text{ For } h = 2, \text{ we have } \text{PyFHW}A_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_h) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2. \\
&\text{Now, } \ell_1 \tilde{\wp}_1 = \\
&\quad \left\langle \sqrt{\frac{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_1}^2\}^{\ell_1} - (1 - \mathfrak{T}_{\tilde{\wp}_1}^2)^{\ell_1}}{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_1}^2\}^{\ell_1} + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\wp}_1}^2)^{\ell_1}}}, \frac{\sqrt{\kappa} \aleph_{\tilde{\wp}_1}^{\ell_1}}{\sqrt{\{1 + (\kappa - 1)(1 - \aleph_{\tilde{\wp}_1}^2)\}^{\ell_1} + (\kappa - 1) \aleph_{\tilde{\wp}_1}^{2\ell_1}}} \right\rangle \\
&\text{and } \ell_2 \tilde{\wp}_2 = \\
&\quad \left\langle \sqrt{\frac{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_2}^2\}^{\ell_2} - (1 - \mathfrak{T}_{\tilde{\wp}_2}^2)^{\ell_2}}{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_2}^2\}^{\ell_2} + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\wp}_2}^2)^{\ell_2}}}, \frac{\sqrt{\kappa} \aleph_{\tilde{\wp}_2}^{\ell_2}}{\sqrt{\{1 + (\kappa - 1)(1 - \aleph_{\tilde{\wp}_2}^2)\}^{\ell_2} + (\kappa - 1) \aleph_{\tilde{\wp}_2}^{2\ell_2}}} \right\rangle \\
&\therefore \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 = \left\langle \sqrt{\frac{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_1}^2\}^{\ell_1} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_2}^2\}^{\ell_2} - (1 - \mathfrak{T}_{\tilde{\wp}_1}^2)^{\ell_1} (1 - \mathfrak{T}_{\tilde{\wp}_2}^2)^{\ell_2}}{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_1}^2\}^{\ell_1} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_2}^2\}^{\ell_2} + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\wp}_1}^2)^{\ell_1} (1 - \mathfrak{T}_{\tilde{\wp}_2}^2)^{\ell_2}}}, \right. \\
&\quad \left. \frac{\sqrt{\kappa} \aleph_{\tilde{\wp}_1}^{\ell_1} \aleph_{\tilde{\wp}_2}^{\ell_2}}{\sqrt{\{1 + (\kappa - 1)(1 - \aleph_{\tilde{\wp}_1}^2)\}^{\ell_1} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\wp}_2}^2)\}^{\ell_2} + (\kappa - 1) \aleph_{\tilde{\wp}_1}^{2\ell_1} \aleph_{\tilde{\wp}_2}^{2\ell_2}}} \right\rangle. \\
&\text{i.e., } \text{PyFHW}A_\ell(\tilde{\wp}_1, \tilde{\wp}_2) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 =
\end{aligned}$$

$$\begin{aligned}
&\left\langle \sqrt{\frac{\prod_{j=1}^2 \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} - \prod_{j=1}^2 (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}{\prod_{j=1}^2 \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^2 (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}}, \right. \\
&\quad \left. \sqrt{\kappa} \prod_{j=1}^2 \aleph_{\tilde{\wp}_j}^{\ell_j} \right\rangle. \\
&\quad \sqrt{\prod_{j=1}^2 \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\wp}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^2 \aleph_{\tilde{\wp}_j}^{2\ell_j}}
\end{aligned}$$

That is, the theorem is valid for  $h = 2$ .

We assume that the theorem is true for  $h = \varsigma \in \mathbf{N}$  i.e.,

$$\text{PyFHW}A_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_\varsigma) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \dots \oplus \ell_\varsigma \tilde{\wp}_\varsigma =$$

$$\begin{aligned}
&\left\langle \sqrt{\frac{\prod_{j=1}^\varsigma \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} - \prod_{j=1}^\varsigma (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}{\prod_{j=1}^\varsigma \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^\varsigma (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}}, \right. \\
&\quad \left. \sqrt{\kappa} \prod_{j=1}^\varsigma \aleph_{\tilde{\wp}_j}^{\ell_j} \right\rangle \\
&\quad \sqrt{\prod_{j=1}^\varsigma \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\wp}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^\varsigma \aleph_{\tilde{\wp}_j}^{2\ell_j}}
\end{aligned}$$

$$\begin{aligned}
& \therefore PyFHW A_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_\varsigma, \tilde{\wp}_{\varsigma+1}) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \dots \oplus \ell_\varsigma \tilde{\wp}_\varsigma \oplus \ell_{\varsigma+1} \tilde{\wp}_{\varsigma+1} \\
& = PyFHW A(\ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \dots \oplus \ell_\varsigma \tilde{\wp}_\varsigma) \oplus \ell_{\varsigma+1} \tilde{\wp}_{\varsigma+1} \\
& = \left\langle \sqrt{\frac{\prod_{j=1}^{\varsigma} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} - \prod_{j=1}^{\varsigma} (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}{\prod_{j=1}^{\varsigma} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\varsigma} (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}}, \right. \\
& \quad \left. \frac{\sqrt{\kappa} \prod_{j=1}^{\varsigma} \aleph_{\tilde{\wp}_j}^{\ell_j}}{\sqrt{\prod_{j=1}^{\varsigma} \{1 + (\kappa - 1) (1 - \aleph_{\tilde{\wp}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\varsigma} \aleph_{\tilde{\wp}_j}^{2\ell_j}}} \right\rangle \oplus \left\langle \sqrt{\frac{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_{\varsigma+1}}^2\}^{\ell_{\varsigma+1}} - (1 - \mathfrak{T}_{\tilde{\wp}_{\varsigma+1}}^2)^{\ell_{\varsigma+1}}}{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_{\varsigma+1}}^2\}^{\ell_{\varsigma+1}} + (\kappa - 1) (1 - \mathfrak{T}_{\tilde{\wp}_{\varsigma+1}}^2)^{\ell_{\varsigma+1}}}}, \right. \\
& \quad \left. \frac{\sqrt{\kappa} \cdot \aleph_{\tilde{\wp}_{\varsigma+1}}^{\ell_{\varsigma+1}}}{\sqrt{\{1 + (\kappa - 1) (1 - \aleph_{\tilde{\wp}_{\varsigma+1}}^2)\}^{\ell_{\varsigma+1}} + (\kappa - 1) \aleph_{\tilde{\wp}_{\varsigma+1}}^{2\ell_{\varsigma+1}}}}} \right\rangle = \\
& \left\langle \sqrt{\frac{\prod_{j=1}^{\varsigma+1} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} - \prod_{j=1}^{\varsigma+1} (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}{\prod_{j=1}^{\varsigma+1} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\varsigma+1} (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}}, \right. \\
& \quad \left. \frac{\sqrt{\kappa} \prod_{j=1}^{\varsigma+1} \aleph_{\tilde{\wp}_j}^{\ell_j}}{\sqrt{\prod_{j=1}^{\varsigma+1} \{1 + (\kappa - 1) (1 - \aleph_{\tilde{\wp}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\varsigma+1} \aleph_{\tilde{\wp}_j}^{2\ell_j}}} \right\rangle.
\end{aligned}$$

Hence the theorem is true for  $\hbar = \varsigma + 1$  when it is assumed to be true for  $\hbar = \varsigma$ . It is also proved that the theorem is true for  $\hbar = 2$ . Then by Mathematical induction, we can say that the theorem is true for all  $\hbar \in \mathbb{N}$ .

Therefore,  $PyFHW A_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_\hbar) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \dots \oplus \ell_\hbar \tilde{\wp}_\hbar$

$$\begin{aligned}
& = \left\langle \sqrt{\frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} - \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}}, \right. \\
& \quad \left. \frac{\sqrt{\kappa} \prod_{j=1}^{\hbar} \aleph_{\tilde{\wp}_j}^{\ell_j}}{\sqrt{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) (1 - \aleph_{\tilde{\wp}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\hbar} \aleph_{\tilde{\wp}_j}^{2\ell_j}}} \right\rangle \text{ for all } \hbar \in \mathbb{N}. \text{ It can also be proved that the resultant number} \\
& \text{is also a PyFN.}
\end{aligned}$$

The value of this operator concerning some PyFNs is shown in Example 2.

**Example 2** Let  $\tilde{\wp}_1 = \langle 0.7, 0.6 \rangle$ ,  $\tilde{\wp}_2 = \langle 0.5, 0.4 \rangle$ ,  $\tilde{\wp}_3 = \langle 0.7, 0.3 \rangle$ ,  $\tilde{\wp}_4 = \langle 0.3, 0.4 \rangle$ ,  $\tilde{\wp}_4 = \langle 0.3, 0.4 \rangle$  be the four PyFNs with the weight vector  $\ell = (0.2, 0.1, 0.3, 0.4)^T$  and for  $\kappa = 3$ ,  
 $PyFHW A_\ell(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4) = \ell_1 \tilde{\wp}_1 \oplus \ell_2 \tilde{\wp}_2 \oplus \ell_3 \tilde{\wp}_3 \oplus \ell_4 \tilde{\wp}_4$

$$= \left\langle \sqrt{\frac{\prod_{j=1}^4 \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} - \prod_{j=1}^4 (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}{\prod_{j=1}^4 \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\wp}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^4 (1 - \mathfrak{T}_{\tilde{\wp}_j}^2)^{\ell_j}}}, \right.$$

$$\sqrt{\kappa} \prod_{j=1}^4 \aleph_{\tilde{\varphi}_j}^{\ell_j} \left\langle \frac{\prod_{j=1}^4 \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^4 \aleph_{\tilde{\varphi}_j}^{2\ell_j}}{\sqrt{\prod_{j=1}^4 \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^4 \aleph_{\tilde{\varphi}_j}^{2\ell_j}}} \right\rangle = \langle 0.497, 0.422 \rangle.$$

**Theorem 4.2** (Idempotency Property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \hbar\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . If  $\tilde{\varphi}_j = \tilde{\varphi}$  for all  $j = 1, 2, \dots, \hbar$  then  $\text{PyFHW}A_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_\hbar) = \tilde{\varphi}$ .

**Proof:** We have  $\text{PyFHW}A_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_\hbar) = \ell_1 \tilde{\varphi}_1 \oplus \ell_2 \tilde{\varphi}_2 \oplus \dots \oplus \ell_\hbar \tilde{\varphi}_\hbar$

$$= \left\langle \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j} - \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}}{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}}, \sqrt{\kappa} \prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}_j}^{\ell_j} \right\rangle$$

As  $\tilde{\varphi}_j = \tilde{\varphi}$  for all  $j=1,2,\dots,\hbar$  i.e.  $\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle = \langle \mathfrak{T}_{\tilde{\varphi}}, \aleph_{\tilde{\varphi}} \rangle$  for all  $j = 1, 2, \dots, \hbar$  then

$\text{PyFHW}A_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_\hbar) =$

$$\left\langle \frac{\sum_{j=1}^{\hbar} \ell_j}{\sum_{j=1}^{\hbar} \ell_j}, \frac{\sum_{j=1}^{\hbar} \ell_j}{\sum_{j=1}^{\hbar} \ell_j} \right\rangle, \left\langle \frac{\sqrt{\kappa} \cdot (\aleph_{\tilde{\varphi}})^{\sum_{j=1}^{\hbar} \ell_j}}{\sqrt{\{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}}^2)\}^{\sum_{j=1}^{\hbar} \ell_j} + (\kappa - 1)(\aleph_{\tilde{\varphi}})^{\sum_{j=1}^{\hbar} \ell_j}}} \right\rangle$$

As we have  $\text{PyFHW}A_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_\hbar) =$

$$\left\langle \sqrt{\frac{\{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}}^2\} - (1 - \mathfrak{T}_{\tilde{\varphi}}^2)}{\{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}}^2\} + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\varphi}}^2)}}, \frac{\sqrt{\kappa} \cdot (\aleph_{\tilde{\varphi}})}{\sqrt{\{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}}^2)\} + (\kappa - 1)(\aleph_{\tilde{\varphi}})^2}} \right\rangle = \langle \mathfrak{T}_{\tilde{\varphi}}, \aleph_{\tilde{\varphi}} \rangle = \tilde{\varphi}.$$

**Theorem 4.3** (Boundness Property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \hbar\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$  with the total order relation  $\leq$  defined on it. If  $\tilde{\varphi}^+ = \langle \mathfrak{T}_{\tilde{\varphi}^+}, \aleph_{\tilde{\varphi}^+} \rangle = \max_j \{\tilde{\varphi}_j\} = \max_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$  and  $\tilde{\varphi}^- = \langle \mathfrak{T}_{\tilde{\varphi}^-}, \aleph_{\tilde{\varphi}^-} \rangle = \min_j \{\tilde{\varphi}_j\} = \min_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$  then  $\text{PyFHW}A_\ell : \mathfrak{P}^\hbar \rightarrow \mathfrak{P}$  is bounded as below.

$\tilde{\varphi}^- \leq \text{PyFHW}A_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_\hbar) \leq \tilde{\varphi}^+.$

**Proof:** As  $\text{PyFHW}A_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_\hbar)$  is also a PyFN then we assume that it is  $\langle \mathfrak{T}_{\tilde{\varphi}}, \aleph_{\tilde{\varphi}} \rangle$ . It is given that  $\tilde{\varphi}^+ = \langle \mathfrak{T}_{\tilde{\varphi}^+}, \aleph_{\tilde{\varphi}^+} \rangle = \max_j \{\tilde{\varphi}_j\} = \max_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$  and  $\tilde{\varphi}^- = \langle \mathfrak{T}_{\tilde{\varphi}^-}, \aleph_{\tilde{\varphi}^-} \rangle = \min_j \{\tilde{\varphi}_j\} = \min_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$  then

$\mathfrak{T}_{\tilde{\varphi}_j} \leq \mathfrak{T}_{\tilde{\varphi}^+}$  and  $\aleph_{\tilde{\varphi}_j} \geq \aleph_{\tilde{\varphi}^+}$  for all  $j = 1, 2, \dots, \hbar$ .

And  $\mathfrak{T}_{\tilde{\varphi}_j} \geq \mathfrak{T}_{\tilde{\varphi}^-}$  and  $\aleph_{\tilde{\varphi}_j} \leq \aleph_{\tilde{\varphi}^-}$  for all  $j = 1, 2, \dots, \hbar$ .

Let  $f(\varrho) = \frac{1 + (\kappa - 1)\varrho^2}{1 - \varrho^2}$

$\therefore f'(\varrho) = \frac{2x\kappa}{(1 - \varrho^2)^2} > 0$ , for all  $\varrho \in (0, 1]$  and  $\kappa > 0$ , which shows that  $f(\varrho)$  is increasing function.

Therefore,  $\mathfrak{T}_{\tilde{\varphi}_j} \leq \mathfrak{T}_{\tilde{\varphi}^+}$  we can write  $f(\mathfrak{T}_{\tilde{\varphi}_j}) \leq f(\mathfrak{T}_{\tilde{\varphi}^+})$  i.e.,  $\frac{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}_j}^2}{1 - \mathfrak{T}_{\tilde{\varphi}_j}^2} \leq \frac{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}^+}^2}{1 - \mathfrak{T}_{\tilde{\varphi}^+}^2}$  or,  $\frac{\{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j}}{(1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}} \leq$

$\frac{\{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}^+}^2\}^{\ell_j}}{(1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{\ell_j}}$  or,  $\prod_{j=1}^{\hbar} \frac{\{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j}}{(1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}} \leq \prod_{j=1}^{\hbar} \frac{\{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\varphi}^+}^2\}^{\ell_j}}{(1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{\ell_j}}$  then

$$\begin{aligned}
& \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j}}{\prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}} \leq \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\}^{\ell_j}}{\prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{\ell_j}} \text{ therefore,} \\
& \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j} - \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}}{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j} + \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}} \leq \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\}^{\ell_j} - \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{\ell_j}}{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\}^{\ell_j} + \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{\ell_j}} \text{ or,} \\
& \sqrt{\frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j} - \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}}{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)^{\ell_j}}} \\
& \leq \sqrt{\frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\}^{\ell_j} - \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{\ell_j}}{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\hbar} (1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{\ell_j}}} \\
& \therefore \mathfrak{T}_{\tilde{\varphi}} \leq \sqrt{\frac{\frac{\sum_{j=1}^{\hbar} \ell_j}{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\}^{J=1}} - \frac{\sum_{j=1}^{\hbar} \ell_j}{(1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{J=1}}}{\frac{\sum_{j=1}^{\hbar} \ell_j}{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\}^{J=1}} + \frac{\sum_{j=1}^{\hbar} \ell_j}{(\kappa - 1)(1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)^{J=1}}}} \text{ i.e., } \mathfrak{T}_{\tilde{\varphi}} \leq \sqrt{\frac{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\} - (1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)}{\{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}^+}^2\} + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\varphi}^+}^2)}}} \\
& \therefore \mathfrak{T}_{\tilde{\varphi}} \leq \mathfrak{T}_{\tilde{\varphi}^+}, \text{ Similarly, we can prove that } \mathfrak{T}_{\tilde{\varphi}} \geq \mathfrak{T}_{\tilde{\varphi}^-}. \\
& \text{Let } g(\varrho) = \frac{1 + (\kappa - 1)(1 - \varrho^2)}{\varrho^2} \\
& \text{therefore } g'(\varrho) = -\frac{2\kappa}{\varrho^3} < 0 \text{ for all } \varrho \in (0, 1] \text{ and } \kappa > 0, \text{ which shows that } g(\varrho) \text{ is decreasing function. Hence for} \\
& \aleph_{\tilde{\varphi}_j} \geq \aleph_{\tilde{\varphi}^+} \text{ we have } g(\aleph_{\tilde{\varphi}_j}) \leq g(\aleph_{\tilde{\varphi}^+}). \\
& \text{i.e., } \frac{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)}{\aleph_{\tilde{\varphi}_j}^2} \leq \frac{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}^+}^2)}{\aleph_{\tilde{\varphi}^+}^2} \text{ then} \\
& \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)\}^{\ell_j}}{\prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}_j}^{2\ell_j}} \leq \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}^+}^2)\}^{\ell_j}}{\prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}^+}^{2\ell_j}} \text{ or,} \\
& \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)\}^{\ell_j}}{\prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}_j}^{2\ell_j}} + (\kappa - 1) \leq \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}^+}^2)\}^{\ell_j}}{\prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}^+}^{2\ell_j}} + (\kappa - 1) \text{ or,} \\
& \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)\}^{\ell_j}}{\prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}_j}^{2\ell_j}} + (\kappa - 1) \leq \frac{\sum_{j=1}^{\hbar} \ell_j}{\sum_{\substack{j=1 \\ \aleph_{\tilde{\varphi}^+}}}^{\hbar} \ell_j} + (\kappa - 1) \\
& \text{or,}
\end{aligned}$$

$$\begin{aligned}
& \frac{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)\}^{\ell_j}}{\prod_{j=1}^{\tilde{h}} \aleph_{\tilde{\varphi}_j}^{2\ell_j}} + (\kappa - 1) \leq \frac{\{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}^+}^2)\}}{\aleph_{\tilde{\varphi}^+}^2} + (\kappa - 1) \text{ or,} \\
& \sqrt{\frac{\kappa \cdot \prod_{j=1}^{\tilde{h}} \aleph_{\tilde{\varphi}_j}^{2\ell_j}}{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} (\aleph_{\tilde{\varphi}_j}^{2\ell_j})}} \geq \aleph_{\tilde{\varphi}^+} \text{ i.e.,} \\
& \sqrt{\frac{\sqrt{\kappa} \cdot \prod_{j=1}^{\tilde{h}} \aleph_{\tilde{\varphi}_j}^{\ell_j}}{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} (\aleph_{\tilde{\varphi}_j}^{2\ell_j})}} \geq \aleph_{\tilde{\varphi}^+} \text{ then } \aleph_{\tilde{\varphi}} \geq \aleph_{\tilde{\varphi}^+} \text{ and similarly we can show that} \\
& \aleph_{\tilde{\varphi}} \leq \aleph_{\tilde{\varphi}^-}.
\end{aligned}$$

Thus we have proved that  $\mathfrak{T}_{\tilde{\varphi}^-} \leq \mathfrak{T}_{\tilde{\varphi}} \leq \mathfrak{T}_{\tilde{\varphi}^+}$  and  $\aleph_{\tilde{\varphi}^-} \geq \aleph_{\tilde{\varphi}} \geq \aleph_{\tilde{\varphi}^+}$ .  
Now  $Sc(\tilde{\varphi}) = \mathfrak{T}_{\tilde{\varphi}}^2 - \aleph_{\tilde{\varphi}}^2 \leq \mathfrak{T}_{\tilde{\varphi}^+}^2 - \aleph_{\tilde{\varphi}^+}^2 = Sc(\tilde{\varphi}^+)$  and if  $Sc(\tilde{\varphi}) < Sc(\tilde{\varphi}^+)$  then  $\tilde{\varphi} < \tilde{\varphi}^+$  and if equality occurs then with the help of Lemma 2.1, we can write that  $Ac(\tilde{\varphi}) = Ac(\tilde{\varphi}^+)$  and then  $\tilde{\varphi} = \tilde{\varphi}^+$ . Hence after calculating score values and accuracy values, we can write that  $\tilde{\varphi} \leq \tilde{\varphi}^+$ .  
Again  $Sc(\tilde{\varphi}) = \mathfrak{T}_{\tilde{\varphi}}^2 - \aleph_{\tilde{\varphi}}^2 \geq \mathfrak{T}_{\tilde{\varphi}^-}^2 - \aleph_{\tilde{\varphi}^-}^2 = Sc(\tilde{\varphi}^-)$  and if  $Sc(\tilde{\varphi}) > Sc(\tilde{\varphi}^-)$  then  $\tilde{\varphi} > \tilde{\varphi}^-$ . If equality occurs then with the help of Lemma 2.1, we can write that  $Ac(\tilde{\varphi}) = Ac(\tilde{\varphi}^-)$  and then  $\tilde{\varphi} = \tilde{\varphi}^-$ . Hence calculating score and accuracy values we can write that  $\tilde{\varphi}^- \leq \tilde{\varphi}$ .  
Then we can write that  $\tilde{\varphi}^- \leq \tilde{\varphi} \leq \tilde{\varphi}^+$ .  
Hence,  $\tilde{\varphi}^- \leq PyFHW A(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) \leq \tilde{\varphi}^+$ .

**Theorem 4.4** (Monotonicity Property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j : j = 1, 2, \dots, \tilde{h}\}$  and  $\mathfrak{P}' = \{\tilde{\varphi}_j' : j = 1, 2, \dots, \tilde{h}\}$  be the two sets of PyFNs. If  $\tilde{\varphi}_j \leq \tilde{\varphi}_j'$  then  $PyFHW A_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) \leq PyFHW A_{\ell}(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_{\tilde{h}}')$ .  
The Monotonicity property of the PyFHOWA operator is verified by Example 3.

**Example 3**

Let  $\tilde{\varphi}_1 = \langle 0.2, 0.7 \rangle, \tilde{\varphi}_2 = \langle 0.3, 0.9 \rangle, \tilde{\varphi}_3 = \langle 0.5, 0.8 \rangle$  and  $\tilde{\varphi}_1' = \langle 0.3, 0.6 \rangle, \tilde{\varphi}_2' = \langle 0.4, 0.3 \rangle, \tilde{\varphi}_3' = \langle 0.6, 0.7 \rangle$ . Let the weight vector be  $\ell = (0.2, 0.3, 0.5)^T$  and parameter value  $\kappa = 3$  then  
in this case  $\tilde{\varphi}_1 \leq_L \tilde{\varphi}_1', \tilde{\varphi}_2 \leq_L \tilde{\varphi}_2', \tilde{\varphi}_3 \leq_L \tilde{\varphi}_3'$ . Hence  $\tilde{\varphi}_1 \leq \tilde{\varphi}_1', \tilde{\varphi}_2 \leq \tilde{\varphi}_2', \tilde{\varphi}_3 \leq \tilde{\varphi}_3'$ . It is given that  $\kappa = 3$  and  $\ell = (0.2, 0.3, 0.5)^T$ . Now  $PyFHW A(\tilde{\varphi}_1, \tilde{\varphi}_2, \tilde{\varphi}_3) = \langle 0.3614, 0.8221 \rangle$  and  $PyFHW A(\tilde{\varphi}_1', \tilde{\varphi}_2', \tilde{\varphi}_3') = \langle 0.4684, 0.7172 \rangle$   
Now  $Sc(PyFHW A(\tilde{\varphi}_1, \tilde{\varphi}_2, \tilde{\varphi}_3)) = -0.5451$  and  $Sc(PyFHW A(\tilde{\varphi}_1', \tilde{\varphi}_2', \tilde{\varphi}_3')) = -0.2950$ .  
 $\therefore PyFHW A(\tilde{\varphi}_1, \tilde{\varphi}_2, \tilde{\varphi}_3) \leq PyFHW A(\tilde{\varphi}_1', \tilde{\varphi}_2', \tilde{\varphi}_3')$ .

**4.2 Pythagorean Fuzzy Hamacher Ordered Weighted Averaging Operator**

**Definition 4.2** (Pythagorean fuzzy Hamacher ordered weighted averaging (PyFHOWA) operator)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $PyFN(\mathfrak{U})$ . PyFHOWA operator is a mapping  $PyFHOWA_{\ell} : \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  which is defined below.

$$PyFHOWA_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \bigoplus_{j=1}^{\tilde{h}} (\ell_j \tilde{\varphi}_{\sigma(j)}),$$

where  $\ell = (\ell_1, \ell_2, \dots, \ell_{\tilde{h}})^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \ell_j = 1$  and  $(\sigma(1), \sigma(2), \dots, \sigma(\tilde{h}))$  is a permutation of  $(1, 2, \dots, \tilde{h})$  such that  $\tilde{\varphi}_{\sigma(j-1)} \geq \tilde{\varphi}_{\sigma(j)} \forall j = 2, 3, \dots, \tilde{h}$ .

**Theorem 4.5** Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $PyFN(\mathfrak{U})$ . Then

$$PyFHOWA_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \bigoplus_{j=1}^{\tilde{h}} (\ell_j \tilde{\varphi}_{\sigma(j)}) = \ell_1 \tilde{\varphi}_{\sigma(1)} \oplus \ell_2 \tilde{\varphi}_{\sigma(2)} \oplus \dots \oplus \ell_{\tilde{h}} \tilde{\varphi}_{\sigma(\tilde{h})} =$$

$$\left\langle \sqrt{\frac{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}}^2\}^{\ell_j} - \prod_{j=1}^{\tilde{h}} (1 - \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}}^2)^{\ell_j}}{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} (1 - \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}}^2)^{\ell_j}}}, \right. \\ \left. \sqrt{\kappa \prod_{j=1}^{\tilde{h}} \aleph_{\tilde{\varphi}_{\sigma(j)}}^{\ell_j}} \right\rangle \\ \sqrt{\frac{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1) (1 - \aleph_{\tilde{\varphi}_{\sigma(j)}}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} \aleph_{\tilde{\varphi}_{\sigma(j)}}^{2\ell_j}}{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1) (1 - \aleph_{\tilde{\varphi}_{\sigma(j)}}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} \aleph_{\tilde{\varphi}_{\sigma(j)}}^{2\ell_j}}}} \right\rangle.$$

**Theorem 4.6** (Idempotency property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j: j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs on  $\text{PyFN}(\mathfrak{U})$ . If  $\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle = \tilde{\varphi} = \langle \mathfrak{T}_{\tilde{\varphi}}, \aleph_{\tilde{\varphi}} \rangle$  for all  $j = 1, 2, \dots, \tilde{h}$  then  $\text{PyFHOWA}_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \tilde{\varphi}$ .

**Theorem 4.7** (Boundness property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle: j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$  with the total order relation  $\leq$  defined on it. If  $\tilde{\varphi}^+ = \langle \mathfrak{T}_{\tilde{\varphi}^+}, \aleph_{\tilde{\varphi}^+} \rangle = \max_j \{\tilde{\varphi}_j\} = \max_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$  and  $\tilde{\varphi}^- = \langle \mathfrak{T}_{\tilde{\varphi}^-}, \aleph_{\tilde{\varphi}^-} \rangle = \min_j \{\tilde{\varphi}_j\} = \min_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$  then  $\text{PyFHOWA}_{\ell}: \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  is bounded as below.

$$\tilde{\varphi}^- \leq \text{PyFHOWA}_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) \leq \tilde{\varphi}^+.$$

**Theorem 4.8** (Monotonicity property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j: j = 1, 2, \dots, \tilde{h}\}$  and  $\mathfrak{P}' = \{\tilde{\varphi}_j': j = 1, 2, \dots, \tilde{h}\}$  be the two sets PyFNs. If  $\tilde{\varphi}_j \leq \tilde{\varphi}_j'$  then  $\text{PyFHOWA}_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) \leq \text{PyFHOWA}_{\ell}(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_{\tilde{h}}')$ .

**Theorem 4.9** (Commutativity property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j: j = 1, 2, \dots, \tilde{h}\}$  and  $\mathfrak{P}' = \{\tilde{\varphi}_j': j = 1, 2, \dots, \tilde{h}\}$  be the two sets of PyFNs. If  $(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_{\tilde{h}}')$  be any permutation of  $(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}})$  then  $\text{PyFHOWA}_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \text{PyFHOWA}_{\ell}(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_{\tilde{h}}')$ .

Pythagorean fuzzy Hamacher hybrid averaging (PyFHHA) operator is a combination of PyFHOWA and PyFHOWA operators, and it is defined below.

### 4.3 Pythagorean Fuzzy Hamacher Hybrid Averaging Operator

**Definition 4.3** (Pythagorean fuzzy Hamacher hybrid averaging (PyFHHA) operator)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle: j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . PyFHHA operator is a mapping  $\text{PyFHHA}_{\ell, \Omega}: \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  which is defined below.

$$\text{PyFHHA}_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \bigoplus_{j=1}^{\tilde{h}} (\ell_j \tilde{\varphi}_{\sigma(j)}^*),$$

where  $\ell = (\ell_1, \ell_2, \dots, \ell_{\tilde{h}})^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \ell_j = 1$  and  $\tilde{\varphi}_j^* = \tilde{h} \Omega_j \tilde{\varphi}_j$

and  $(\sigma(1), \sigma(2), \dots, \sigma(\tilde{h}))$  is a permutation of  $(1, 2, \dots, \tilde{h})$  such that  $\tilde{\varphi}_{\sigma(j-1)}^* \geq \tilde{\varphi}_{\sigma(j)}^* \forall j = 2, 3, \dots, \tilde{h}$  and

$\Omega = (\Omega_1, \Omega_2, \dots, \Omega_{\tilde{h}})^T$  is a associated weight vector such that  $\Omega_j \in [0, 1] \forall j = 1, 2, 3, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \Omega_j = 1$ .

i.e.,  $\text{PyFHHA}_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \ell_1 \tilde{\varphi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\varphi}_{\sigma(2)}^* \oplus \dots \oplus \ell_{\tilde{h}} \tilde{\varphi}_{\sigma(\tilde{h})}^*$ .

**Theorem 4.10** Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle: j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$  then

$$\text{PyFHHA}_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \ell_1 \tilde{\varphi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\varphi}_{\sigma(2)}^* \oplus \dots \oplus \ell_{\tilde{h}} \tilde{\varphi}_{\sigma(\tilde{h})}^* =$$

$$\left\langle \sqrt{\frac{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_{\sigma^*(j)}}^2\}^{\ell_j} - \prod_{j=1}^{\tilde{h}} (1 - \mathfrak{T}_{\tilde{\varphi}_{\sigma^*(j)}}^2)^{\ell_j}}{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1) \mathfrak{T}_{\tilde{\varphi}_{\sigma^*(j)}}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} (1 - \mathfrak{T}_{\tilde{\varphi}_{\sigma^*(j)}}^2)^{\ell_j}}}, \right. \\ \left. \sqrt{\kappa \prod_{j=1}^{\tilde{h}} \aleph_{\tilde{\varphi}_{\sigma^*(j)}}^{\ell_j}} \right\rangle,$$



$$\sqrt{\kappa} \prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}_{\sigma^*(j)}}^{\ell_j} \left\langle \frac{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_{\sigma^*(j)}}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}_{\sigma^*(j)}}^{2\ell_j}}{\prod_{j=1}^{\hbar} \{1 + (\kappa - 1)(1 - \aleph_{\tilde{\varphi}_{\sigma^*(j)}}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\hbar} \aleph_{\tilde{\varphi}_{\sigma^*(j)}}^{2\ell_j}} \right\rangle.$$

**Theorem 4.11** If  $\ell = (\frac{1}{\hbar}, \frac{1}{\hbar}, \dots, \frac{1}{\hbar})^T$  then  $PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\hbar}) = PyFHW A_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\hbar})$ .

**Proof.** We prove this theorem by Mathematical induction. Suppose  $\ell = (\ell_1, \ell_2) = (\frac{1}{2}, \frac{1}{2})^T$  and  $\Omega = (\Omega_1, \Omega_2)^T$  be an associated weight vector.

In this case we know that  $\tilde{\varphi}_j^* = 2\Omega_j \tilde{\varphi}_j$  for  $j = 1, 2$ .

Without loss of generality, we assume that  $\tilde{\varphi}_2^* \geq \tilde{\varphi}_1^*$  i.e.,  $\tilde{\varphi}_{\sigma(1)}^* \geq \tilde{\varphi}_{\sigma(2)}^*$

$$\text{Now, } PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2) = \bigoplus_{j=1}^2 (\ell_j \tilde{\varphi}_{\sigma(j)}^*) = \ell_1 \tilde{\varphi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\varphi}_{\sigma(2)}^* = \frac{1}{2} [\tilde{\varphi}_{\sigma(1)}^* \oplus \tilde{\varphi}_{\sigma(2)}^*] = \frac{1}{2} [\tilde{\varphi}_2^* \oplus \tilde{\varphi}_1^*] = \frac{1}{2} [2\Omega_2 \tilde{\varphi}_2 \oplus$$

$$2\Omega_1 \tilde{\varphi}_1] = \bigoplus_{j=1}^2 (\Omega_j \tilde{\varphi}_j) = PyFHW A_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2).$$

Hence, the theorem is true for  $\hbar = 2$ .

Suppose, the theorem is true for first  $\varsigma \in \mathbb{N}$  terms.

Then  $PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}) = PyFHW A_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma})$ .

i.e.  $\ell_1 \tilde{\varphi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\varphi}_{\sigma(2)}^* \oplus \dots \oplus \ell_{\varsigma} \tilde{\varphi}_{\sigma(\varsigma)}^* = \Omega_1 \tilde{\varphi}_1 \oplus \Omega_2 \tilde{\varphi}_2 \oplus \dots \oplus \Omega_{\varsigma} \tilde{\varphi}_{\varsigma}$  and in this case  $\ell = (\ell_1, \ell_2, \dots, \ell_{\varsigma})^T = (\frac{1}{\varsigma}, \frac{1}{\varsigma}, \dots, \frac{1}{\varsigma})^T$ .

$$\text{Now, } PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}) = \bigoplus_{j=1}^{\varsigma+1} (\ell_j \tilde{\varphi}_{\sigma(j)}^*)$$

$$= \underbrace{\ell_1 \tilde{\varphi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\varphi}_{\sigma(2)}^* \oplus \dots \oplus \ell_{\varsigma} \tilde{\varphi}_{\sigma(\varsigma)}^*}_{\varsigma \text{ terms}} \oplus \ell_{\varsigma+1} \tilde{\varphi}_{\sigma(\varsigma+1)}^*$$

$$= \Omega_1 \tilde{\varphi}_1 \oplus \Omega_2 \tilde{\varphi}_2 \oplus \dots \oplus \Omega_{\varsigma} \tilde{\varphi}_{\varsigma} \oplus \ell_{\varsigma+1} \tilde{\varphi}_{\sigma(\varsigma+1)}^*$$

Obviously, we can say that  $\tilde{\varphi}_{\sigma(\varsigma+1)}^* = \tilde{\varphi}_{\varsigma+1}^* = (\varsigma + 1)\Omega_{\varsigma+1} \tilde{\varphi}_{\varsigma+1}$  and  $\ell_{\varsigma+1} = \frac{1}{\varsigma+1}$ .

$$\text{Hence, we can write that } PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}) = \bigoplus_{j=1}^{\varsigma+1} (\ell_j \tilde{\varphi}_{\sigma(j)}^*)$$

$$= \ell_1 \tilde{\varphi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\varphi}_{\sigma(2)}^* \oplus \dots \oplus \ell_{\varsigma} \tilde{\varphi}_{\sigma(\varsigma)}^* \oplus \ell_{\varsigma+1} \tilde{\varphi}_{\sigma(\varsigma+1)}^*$$

$$= \Omega_1 \tilde{\varphi}_1 \oplus \Omega_2 \tilde{\varphi}_2 \oplus \dots \oplus \Omega_{\varsigma} \tilde{\varphi}_{\varsigma} \oplus \Omega_{\varsigma+1} \tilde{\varphi}_{\varsigma+1} = PyFHW A_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}).$$

Thus the theorem is true for  $\hbar = \varsigma + 1$  when it is supposed to be true for  $\hbar = \varsigma$ .

Hence the theorem is valid for all  $\hbar \in \mathbb{N}$  by Mathematical induction.

**Theorem 4.12** If  $\Omega = (\frac{1}{\hbar}, \frac{1}{\hbar}, \dots, \frac{1}{\hbar})^T$  then  $PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\hbar}) = PyFHOW A_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\hbar})$ .

**Proof.** Let  $\Omega = (\Omega_1, \Omega_2)^T = (\frac{1}{2}, \frac{1}{2})^T$  and  $\ell = (\ell_1, \ell_2)^T$  be weight vectors.

Now,  $\tilde{\varphi}_j^* = 4\Omega_j \tilde{\varphi}_j$ , which becomes  $\tilde{\varphi}_j^* = \tilde{\varphi}_j$  for  $j = 1, 2$ .

Without loss of generality we suppose  $\tilde{\varphi}_2^* \geq \tilde{\varphi}_1^*$  i.e.  $\tilde{\varphi}_{\sigma(1)}^* \geq \tilde{\varphi}_{\sigma(2)}^*$ .

$$\text{Now, } PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \tilde{\varphi}_3, \tilde{\varphi}_4) = \bigoplus_{j=1}^2 (\ell_j \tilde{\varphi}_{\sigma(j)}^*) = \ell_1 \tilde{\varphi}_{\sigma(1)}^* \oplus \ell_2 \tilde{\varphi}_{\sigma(2)}^*$$

$$= \ell_1 \tilde{\varphi}_{\sigma(1)} \oplus \ell_2 \tilde{\varphi}_{\sigma(2)} = \bigoplus_{j=1}^2 (\ell_j \tilde{\varphi}_{\sigma(j)}) = PyFHOW A_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2).$$

Thus the theorem is true for  $\hbar = 2$ .

We assume that the theorem is true for  $\hbar = \varsigma \in \mathbb{N}$ . Then we can write that

$$PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}) = PyFHOW A_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}) \text{ i.e., } \bigoplus_{j=1}^{\varsigma} (\ell_j \tilde{\varphi}_{\sigma(j)}^*) = \bigoplus_{j=1}^{\varsigma} (\ell_j \tilde{\varphi}_{\sigma(j)}) \text{ and in this case}$$

$$\Omega = (\frac{1}{\varsigma}, \frac{1}{\varsigma}, \dots, \frac{1}{\varsigma})^T.$$

$$\text{Now, } PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}) = \bigoplus_{j=1}^{\varsigma} (\ell_j \tilde{\varphi}_{\sigma(j)}^*) \oplus \ell_{\varsigma+1} \tilde{\varphi}_{\sigma(\varsigma+1)}^*. \text{ It is clear that } \tilde{\varphi}_{\sigma(\varsigma+1)}^* = \tilde{\varphi}_{\sigma(\varsigma+1)} \text{ and}$$

$$\ell_{\varsigma+1} = \frac{1}{\varsigma+1}.$$

Hence, we can write that  $PyFHH A_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1})$

$$= \bigoplus_{j=1}^{\varsigma} (\ell_j \tilde{\wp}_{\sigma(j)}) \oplus \ell_{\varsigma+1} \tilde{\wp}_{\sigma(\varsigma+1)} = \bigoplus_{j=1}^{\varsigma+1} (\ell_j \tilde{\wp}_{\sigma(j)}) = PyFHOWA_{\ell}(\tilde{\wp}_1, \tilde{\wp}_2, \dots, \tilde{\wp}_{\varsigma}, \tilde{\wp}_{\varsigma+1}).$$

Therefore the theorem is true for  $\tilde{h} = \varsigma + 1$  when it is assumed to be true for  $\tilde{h} = \varsigma$ .

Hence by Mathematical induction, we can say that the Lemma is true for all  $\tilde{h} \in \mathbf{N}$ .

It is clear from the Theorem 4.11, Theorem 4.12 that PyFHOWA and PyFHWA operators are the particular cases of PyFHHA operator or, in other words, PyFHHA operator is the generalization of PyFHOWA and PyFHWA operators.

The value of the PyFHHA operator concerning some PyFNs is shown in Example 4.

**Example 4** Let  $\tilde{\wp}_1 = \langle 0.2, 0.9 \rangle$ ,  $\tilde{\wp}_2 = \langle 0.3, 0.7 \rangle$ ,  $\tilde{\wp}_3 = \langle 0.1, 0.9 \rangle$ ,  $\tilde{\wp}_4 = \langle 0.4, 0.6 \rangle$ . Let  $\ell = (0.2, 0.1, 0.3, 0.4)^T$  and  $\Omega = (0.1, 0.3, 0.4, 0.2)^T$  be the corresponding weight vectors and  $\kappa = 3$ . Now  $\tilde{\wp}_1^* = 4\Omega_1\tilde{\wp}_1 = 0.4\tilde{\wp}_1 =$

$$0.4\tilde{\wp}_1 = \left\langle \sqrt{\frac{\{1 + (3-1)0.2^2\}^{0.4} - (1-0.2^2)^{0.4}}{\{1 + (3-1)0.2^2\}^{0.4} + (3-1)(1-0.2^2)^{0.4}}}, \frac{\sqrt{3} \cdot (0.9)^{0.4}}{\sqrt{\{1 + (3-1)(1-0.9^2)\}^{0.4} + (3-1)0.9^{(2 \times 0.4)}}}} \right\rangle$$

$$= \langle 0.126, 0.962 \rangle.$$

Similarly, we can find

$$\tilde{\wp}_2^* = 4\Omega_2\tilde{\wp}_2 = 1.2\tilde{\wp}_2 = \langle 0.330, 0.593 \rangle.$$

$$\tilde{\wp}_3^* = 4\Omega_3\tilde{\wp}_3 = 1.6\tilde{\wp}_3 = \langle 0.590, 0.878 \rangle.$$

$$\tilde{\wp}_4^* = 4\Omega_4\tilde{\wp}_4 = 0.8\tilde{\wp}_4 = \langle 0.356, 0.686 \rangle.$$

$$\text{Now } Sc(\tilde{\wp}_1^*) = -0.910, Sc(\tilde{\wp}_2^*) = -0.243, Sc(\tilde{\wp}_3^*) = -0.423, Sc(\tilde{\wp}_4^*) = -0.344.$$

$$\therefore \tilde{\wp}_2^* > \tilde{\wp}_4^* > \tilde{\wp}_3^* > \tilde{\wp}_1^* \text{ then } \tilde{\wp}_{\sigma(1)}^* = \tilde{\wp}_2^*, \tilde{\wp}_{\sigma(2)}^* = \tilde{\wp}_4^*, \tilde{\wp}_{\sigma(3)}^* = \tilde{\wp}_3^* \text{ and } \tilde{\wp}_{\sigma(4)}^* = \tilde{\wp}_1^*$$

$$\therefore PyFHHA(\tilde{\wp}_1, \tilde{\wp}_2, \tilde{\wp}_3, \tilde{\wp}_4) =$$

$$\left\langle \frac{\prod_{j=1}^4 \{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\wp}_{\sigma^*(j)}}^2\}^{\ell_j} - \prod_{j=1}^4 (1 - \mathfrak{T}_{\tilde{\wp}_{\sigma^*(j)}}^2)^{\ell_j}}{\prod_{j=1}^4 \{1 + (\kappa - 1)\mathfrak{T}_{\tilde{\wp}_{\sigma^*(j)}}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^4 (1 - \mathfrak{T}_{\tilde{\wp}_{\sigma^*(j)}}^2)^{\ell_j}}, \frac{\sqrt{\kappa} \prod_{j=1}^4 \mathfrak{N}_{\tilde{\wp}_{\sigma^*(j)}}^{\ell_j}}{\sqrt{\prod_{j=1}^4 \{1 + (\kappa - 1)(1 - \mathfrak{N}_{\tilde{\wp}_{\sigma^*(j)}}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^4 \mathfrak{N}_{\tilde{\wp}_{\sigma^*(j)}}^{2\ell_j}}} \right\rangle$$

$$= \left\langle \sqrt{\frac{0.419}{2.947}}, \frac{\sqrt{3} \times 0.821}{\sqrt{1.503 + 2 \times 0.674}} \right\rangle = \langle 0.377, 0.842 \rangle.$$

## 5 Pythagorean Fuzzy Hamacher Geometric Operators

In this section we will discuss about three types of Pythagorean fuzzy Hamacher geometric AOs which are Pythagorean fuzzy Hamacher weighted geometric (PyFHWG) operator, Pythagorean fuzzy Hamacher ordered weighted geometric (PyFHOWG) operator and Pythagorean fuzzy Hamacher hybrid geometric (PyFHHG) operator.

### 5.1 Pythagorean Fuzzy Hamacher Weighted Geometric Operator

**Definition 5.1** (Pythagorean fuzzy Hamacher weighted geometric (PyFHWG) operator)

Let  $\mathfrak{P} = \{\tilde{\wp}_j = \langle \mathfrak{T}_{\tilde{\wp}_j}, \mathfrak{N}_{\tilde{\wp}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of Pythagorean fuzzy numbers in  $\text{PyFN}(\mathfrak{U})$ . PyFHWG operator is a mapping  $PyFHWG_{\ell} : \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  which is defined below.

$$PyFHWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \bigotimes_{j=1}^{\tilde{h}} (\tilde{\varphi}_j)^{\ell_j},$$

where  $\ell = (\ell_1, \ell_2, \dots, \ell_{\tilde{h}})^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \ell_j = 1$ .

**Theorem 5.1** Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . Then

$$PyFHWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \bigotimes_{j=1}^{\tilde{h}} (\tilde{\varphi}_j)^{\ell_j} =$$

$$\left\langle \frac{\sqrt{\kappa} \prod_{j=1}^{\tilde{h}} \mathfrak{T}_{\tilde{\varphi}_j}^{\ell_j}}{\sqrt{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\varphi}_j}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} \mathfrak{T}_{\tilde{\varphi}_j}^{2\ell_j}}}, \right. \\ \left. \frac{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1)\mathfrak{N}_{\tilde{\varphi}_j}^2\}^{\ell_j} - \prod_{j=1}^{\tilde{h}} (1 - \mathfrak{N}_{\tilde{\varphi}_j}^2)^{\ell_j}}{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1)\mathfrak{N}_{\tilde{\varphi}_j}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} (1 - \mathfrak{N}_{\tilde{\varphi}_j}^2)^{\ell_j}} \right\rangle.$$

**Theorem 5.2** (Idempotency property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . If  $\tilde{\varphi}_j = \tilde{\varphi}$  for all  $j = 1, 2, \dots, \tilde{h}$  then  $PyFHWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \tilde{\varphi}$ .

**Theorem 5.3** (Boundness property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$  with the total order relation  $\leq$  defined on it. If  $\tilde{\varphi}^+ = \langle \mathfrak{T}_{\tilde{\varphi}^+}, \mathfrak{N}_{\tilde{\varphi}^+} \rangle = \max_j \{\tilde{\varphi}_j\} = \max_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle\}$  and  $\tilde{\varphi}^- = \langle \mathfrak{T}_{\tilde{\varphi}^-}, \mathfrak{N}_{\tilde{\varphi}^-} \rangle = \min_j \{\tilde{\varphi}_j\} = \min_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle\}$  then  $PyFHWG_{\ell} : \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  is bounded as below  $\tilde{\varphi}^- \leq PyFHWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) \leq \tilde{\varphi}^+$ .

**Theorem 5.4** (Monotonicity property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j : j = 1, 2, \dots, \tilde{h}\}$  and  $\mathfrak{P}' = \{\tilde{\varphi}_j' : j = 1, 2, \dots, \tilde{h}\}$  be the two sets of PyFNs. If  $\tilde{\varphi}_j \leq \tilde{\varphi}_j'$  then  $PyFHWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) \leq PyFHWG_{\ell}(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_{\tilde{h}}')$ .

## 5.2 Pythagorean Fuzzy Hamacher Ordered Weighted Geometric Operator

**Definition 5.2** (Pythagorean fuzzy Hamacher ordered weighted geometric (PyFHOWG) operator)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ . PyFOWG operator is a mapping  $PyFHOWG_{\ell} : \mathfrak{P}^{\tilde{h}} \rightarrow \mathfrak{P}$  which is defined below.

$$PyFHOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \bigotimes_{j=1}^{\tilde{h}} (\tilde{\varphi}_{\sigma(j)}^{\ell_j}),$$

where  $\ell = (\ell_1, \ell_2, \dots, \ell_{\tilde{h}})^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, \tilde{h}$  and  $\sum_{j=1}^{\tilde{h}} \ell_j = 1$  and  $(\sigma(1), \sigma(2), \dots, \sigma(\tilde{h}))$

is a permutation of  $(1, 2, \dots, \tilde{h})$  such that  $\tilde{\varphi}_{\sigma(j-1)} \geq \tilde{\varphi}_{\sigma(j)}$  for all  $j = 2, 3, \dots, \tilde{h}$ .

That is  $PyFHOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \tilde{\varphi}_{\sigma(1)}^{\ell_1} \otimes \tilde{\varphi}_{\sigma(2)}^{\ell_2} \otimes \dots \otimes \tilde{\varphi}_{\sigma(\tilde{h})}^{\ell_{\tilde{h}}}$ .

**Theorem 5.5** Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \mathfrak{N}_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, \tilde{h}\}$  be the set of PyFNs in  $\text{PyFN}(\mathfrak{U})$ .

Then

$$PyFHOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\tilde{h}}) = \tilde{\varphi}_{\sigma(1)}^{\ell_1} \otimes \tilde{\varphi}_{\sigma(2)}^{\ell_2} \otimes \dots \otimes \tilde{\varphi}_{\sigma(\tilde{h})}^{\ell_{\tilde{h}}} =$$

$$\left\langle \frac{\sqrt{\kappa} \prod_{j=1}^{\tilde{h}} \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}}^{\ell_j}}{\sqrt{\prod_{j=1}^{\tilde{h}} \{1 + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^{\tilde{h}} \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}}^{2\ell_j}}}, \right.$$

$$\sqrt{\frac{\prod_{j=1}^h \{1 + (\kappa - 1) \aleph_{\tilde{\varphi}_{\sigma(j)}}^2\}^{\ell_j} - \prod_{j=1}^h (1 - \aleph_{\tilde{\varphi}_{\sigma(j)}}^2)^{\ell_j}}{\prod_{j=1}^h \{1 + (\kappa - 1) \aleph_{\tilde{\varphi}_{\sigma(j)}}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^h (1 - \aleph_{\tilde{\varphi}_{\sigma(j)}}^2)^{\ell_j}}} \rangle.$$

**Theorem 5.6** (Idempotency property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathcal{U})$ . If  $\tilde{\varphi}_j = \tilde{\varphi}$  for all  $j = 1, 2, \dots, h$  then  $\text{PyFHOWG}_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) = \tilde{\varphi}$ .

**Theorem 5.7** (Boundness property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathcal{U})$  with the total order relation  $\leq$  defined on it. If  $\tilde{\varphi}^+ = \langle \mathfrak{T}_{\tilde{\varphi}^+}, \aleph_{\tilde{\varphi}^+} \rangle = \max_j \{\tilde{\varphi}_j\} = \max_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$  and  $\tilde{\varphi}^- = \langle \mathfrak{T}_{\tilde{\varphi}^-}, \aleph_{\tilde{\varphi}^-} \rangle = \min_j \{\tilde{\varphi}_j\} = \min_j \{\langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle\}$

then  $\text{PyFHOWG}_\ell : \mathfrak{P}^h \rightarrow \mathfrak{P}$  is bounded as below:

$$\tilde{\varphi}^- \leq \text{PyFHOWG}_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) \leq \tilde{\varphi}^+.$$

**Theorem 5.8** (Monotonicity property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j : j = 1, 2, \dots, h\}$  and  $\mathfrak{P}' = \{\tilde{\varphi}_j' : j = 1, 2, \dots, h\}$  be the two sets of PyFNs. If  $\tilde{\varphi}_j \leq \tilde{\varphi}_j'$  then  $\text{PyFHOWG}_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) \leq \text{PyFHOWG}_\ell(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_h')$ .

**Theorem 5.9** (Commutativity property)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j : j = 1, 2, \dots, h\}$  and  $\mathfrak{P}' = \{\tilde{\varphi}_j' : j = 1, 2, \dots, h\}$  be the two sets of PyFNs. If  $(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_h')$  be any permutation of  $(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h)$  then  $\text{PyFHOWG}_\ell(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) = \text{PyFHOWG}_\ell(\tilde{\varphi}_1', \tilde{\varphi}_2', \dots, \tilde{\varphi}_h')$ .

### 5.3 Pythagorean Fuzzy Hamacher Hybrid Geometric Operator

**Definition 5.3** (Pythagorean fuzzy Hamacher hybrid geometric (PyFHHG) operator)

Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathcal{U})$ . PyFHHG operator is a mapping  $\text{PyFHHG}_{\ell, \Omega} : \mathfrak{P}^h \rightarrow \mathfrak{P}$  which is defined below:

$$\text{PyFHHG}_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) = \bigotimes_{j=1}^h (\tilde{\varphi}_{\sigma(j)}^*)^{\ell_j},$$

where  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  is a weight vector such that  $\ell_j \in [0, 1], j = 1, 2, \dots, h$  and  $\sum_{j=1}^h \ell_j = 1$  and  $\tilde{\varphi}_j^* = (\tilde{\varphi}_j)^{h\Omega_j}$

and  $(\sigma(1), \sigma(2), \dots, \sigma(h))$  is a permutation of  $(1, 2, \dots, h)$  such that  $\tilde{\varphi}_{\sigma(j-1)}^* \geq \tilde{\varphi}_{\sigma(j)}^*$  for all  $j = 2, 3, \dots, h$  and

$\Omega = (\Omega_1, \Omega_2, \dots, \Omega_h)^T$  is an associated weight vector such that  $\Omega_j \in [0, 1]$  for all  $j = 1, 2, 3, \dots, h$  and  $\sum_{j=1}^h \Omega_j = 1$ .

**Theorem 5.10** Let  $\mathfrak{P} = \{\tilde{\varphi}_j = \langle \mathfrak{T}_{\tilde{\varphi}_j}, \aleph_{\tilde{\varphi}_j} \rangle : j = 1, 2, \dots, h\}$  be the set of PyFNs in  $\text{PyFN}(\mathcal{U})$ . Then

$$\text{PyFHHG}_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) =$$

$$\left\langle \frac{\sqrt{\kappa} \prod_{j=1}^h \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}^*}^{\ell_j}}{\sqrt{\prod_{j=1}^h \{1 + (\kappa - 1)(1 - \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}^*}^2)\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^h \mathfrak{T}_{\tilde{\varphi}_{\sigma(j)}^*}^{2\ell_j}}}, \sqrt{\frac{\prod_{j=1}^h \{1 + (\kappa - 1) \aleph_{\tilde{\varphi}_{\sigma(j)}^*}^2\}^{\ell_j} - \prod_{j=1}^h (1 - \aleph_{\tilde{\varphi}_{\sigma(j)}^*}^2)^{\ell_j}}{\prod_{j=1}^h \{1 + (\kappa - 1) \aleph_{\tilde{\varphi}_{\sigma(j)}^*}^2\}^{\ell_j} + (\kappa - 1) \prod_{j=1}^h (1 - \aleph_{\tilde{\varphi}_{\sigma(j)}^*}^2)^{\ell_j}}} \right\rangle.$$

**Theorem 5.11** If  $\ell = (\frac{1}{h}, \frac{1}{h}, \dots, \frac{1}{h})^T$  then  $\text{PyFHHG}_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h) = \text{PyFHWG}_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_h)$ .

**Proof.** We will prove it by Mathematical induction.

Let  $\ell = (\ell_1, \ell_2)^T = (\frac{1}{2}, \frac{1}{2})^T$  and  $\Omega = (\Omega_1, \Omega_2)^T$  be an associated weight vector.

Therefore  $\tilde{\varphi}_j^* = (\tilde{\varphi}_j)^{2\Omega_j}$  for  $j = 1, 2$ .

We suppose, without loss of generality, that  $\tilde{\varphi}_2^* \geq \tilde{\varphi}_1^*$  i.e.  $\tilde{\varphi}_{\sigma(1)}^* \geq \tilde{\varphi}_{\sigma(2)}^*$ .

$$\begin{aligned}
584 \quad & \text{Now, } PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2) = \bigotimes_{j=1}^2 (\tilde{\varphi}_{\sigma(j)}^*)^{\ell_j} = (\tilde{\varphi}_{\sigma(1)}^*)^{\ell_1} \otimes (\tilde{\varphi}_{\sigma(2)}^*)^{\ell_2} \\
585 \quad & = (\tilde{\varphi}_2^*)^{\ell_1} \otimes (\tilde{\varphi}_1^*)^{\ell_2} = \{(\tilde{\varphi}_2)^{2\Omega_2}\}^{\ell_1} \otimes \{(\tilde{\varphi}_1)^{2\Omega_1}\}^{\ell_2} = \bigotimes_{j=1}^2 (\tilde{\varphi}_j)^{\Omega_j} = PyFHWG_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2).
\end{aligned}$$

586 Thus the theorem is true for  $\hbar = 2$ .

587 We assume that the theorem is true for  $\hbar = \varsigma \in \mathbf{N}$  i.e.,  $PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma})$   
588  $= PyFHWG_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma})$  i.e.,  $(\tilde{\varphi}_{\sigma(1)}^*)^{\ell_1} \otimes (\tilde{\varphi}_{\sigma(2)}^*)^{\ell_2} \otimes \dots \otimes (\tilde{\varphi}_{\sigma(\varsigma)}^*)^{\ell_{\varsigma}} = (\tilde{\varphi}_1)^{\Omega_1} \otimes (\tilde{\varphi}_2)^{\Omega_2} \otimes \dots \otimes (\tilde{\varphi}_{\varsigma})^{\Omega_{\varsigma}}$  and  
589 in this case  $\ell = (\ell_1, \ell_2, \dots, \ell_{\varsigma})^T = (\frac{1}{\varsigma}, \frac{1}{\varsigma}, \dots, \frac{1}{\varsigma})^T$  and  $\tilde{\varphi}_j^* = (\tilde{\varphi}_j)^{\varsigma\Omega_j}$ ,  
590  $j = 1, 2, \dots, \varsigma$ .

$$\begin{aligned}
591 \quad & \text{Now, } PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}) = \\
592 \quad & \underbrace{(\tilde{\varphi}_{\sigma(1)}^*)^{\ell_1} \otimes (\tilde{\varphi}_{\sigma(2)}^*)^{\ell_2} \otimes \dots \otimes (\tilde{\varphi}_{\sigma(\varsigma)}^*)^{\ell_{\varsigma}}}_{\varsigma \text{ terms}} \otimes (\tilde{\varphi}_{\sigma(\varsigma+1)}^*)^{\ell_{\varsigma+1}}.
\end{aligned}$$

593 Now, it is obvious that  $\tilde{\varphi}_{\sigma(\varsigma+1)}^* = \tilde{\varphi}_{\varsigma+1}^*$  and  $\ell_{\varsigma+1} = \frac{1}{\varsigma+1}$ .

$$594 \quad \text{Thus } PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}) = \underbrace{(\tilde{\varphi}_1)^{\Omega_1} \otimes (\tilde{\varphi}_2)^{\Omega_2} \otimes \dots \otimes (\tilde{\varphi}_{\varsigma})^{\Omega_{\varsigma}}}_{\varsigma \text{ terms}} \otimes (\tilde{\varphi}_{\varsigma+1})^{\Omega_{\varsigma+1}}$$

$$595 \quad = \bigotimes_{j=1}^{\varsigma+1} (\tilde{\varphi}_j)^{\Omega_j} = PyFHWG_{\Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma+1}).$$

596 Thus the theorem is true for  $\hbar = \varsigma + 1$  when it is assumed to be true for  $\hbar = \varsigma$ .

597 Hence, the theorem is valid for all  $\hbar \in \mathbf{N}$  by Mathematical induction.

598 **Theorem 5.12** If  $\Omega = (\frac{1}{\hbar}, \frac{1}{\hbar}, \dots, \frac{1}{\hbar})^T$  then  $PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\hbar}) = PyFHOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\hbar})$

599 **Proof.** Let  $\Omega = (\Omega_1, \Omega_2) = (\frac{1}{2}, \frac{1}{2})^T$  and  $\ell = (\ell_1, \ell_2)^T$  be weight vectors.

600 Now,  $\tilde{\varphi}_j^* = (\tilde{\varphi}_j)^{2\Omega_j}$ , which becomes  $\tilde{\varphi}_j^* = \tilde{\varphi}_j$  for all  $j = 1, 2$ .

601 We suppose, without loss of generality, that  $\tilde{\varphi}_2^* \geq \tilde{\varphi}_1^*$  i.e.,  $\tilde{\varphi}_{\sigma(1)}^* \geq \tilde{\varphi}_{\sigma(2)}^*$ .

$$\begin{aligned}
602 \quad & \text{Now, } PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2) = \bigotimes_{j=1}^2 (\tilde{\varphi}_{\sigma(j)}^*)^{\ell_j} = (\tilde{\varphi}_{\sigma(1)}^*)^{\ell_1} \otimes (\tilde{\varphi}_{\sigma(2)}^*)^{\ell_2} = \bigotimes_{j=1}^2 (\tilde{\varphi}_{\sigma(j)})^{\ell_j} \\
603 \quad & = PyFHOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2). \text{ Thus the theorem is true for } \hbar = 2.
\end{aligned}$$

604 We suppose that the theorem is true for  $\hbar = \varsigma \in \mathbf{N}$ . Then we can write that

$$605 \quad PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}) = PyFHOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}) \text{ i.e., } \bigotimes_{j=1}^{\varsigma} (\tilde{\varphi}_{\sigma(j)}^*)^{\ell_j} = \bigotimes_{j=1}^{\varsigma} (\tilde{\varphi}_{\sigma(j)})^{\ell_j} \text{ and in this case}$$

$$\begin{aligned}
606 \quad & \Omega = (\Omega_1, \Omega_2, \dots, \Omega_{\varsigma})^T = (\frac{1}{\varsigma}, \frac{1}{\varsigma}, \dots, \frac{1}{\varsigma})^T \text{ and } \tilde{\varphi}_j^* = (\tilde{\varphi}_j)^{\varsigma\Omega_j}, \\
607 \quad & j = 1, 2, \dots, \varsigma.
\end{aligned}$$

$$608 \quad \text{Now, } PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}) = \bigotimes_{j=1}^{\varsigma+1} (\tilde{\varphi}_{\sigma(j)}^*)^{\ell_j} = \bigotimes_{j=1}^{\varsigma} (\tilde{\varphi}_{\sigma(j)}^*)^{\ell_j} \otimes (\tilde{\varphi}_{\sigma(\varsigma+1)}^*)^{\ell_{\varsigma+1}}.$$

609 In this case, we have  $\tilde{\varphi}_j^* = (\tilde{\varphi}_j)^{(\varsigma+1)\Omega_j}$ ,  $j = 1, 2, \dots, (\varsigma + 1)$ . Obviously we can write that  $\tilde{\varphi}_{\sigma(\varsigma+1)}^* = \tilde{\varphi}_{\sigma(\varsigma+1)}$  and  
610  $\Omega_{\varsigma+1} = \frac{1}{\varsigma+1}$ .

$$\begin{aligned}
611 \quad & PyFHHG_{\ell, \Omega}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}) = \bigotimes_{j=1}^{\varsigma} (\tilde{\varphi}_{\sigma(j)}^*)^{\ell_j} \otimes (\tilde{\varphi}_{\sigma(\varsigma+1)}^*)^{\ell_{\varsigma+1}} = \bigotimes_{j=1}^{\varsigma+1} (\tilde{\varphi}_{\sigma(j)})^{\ell_j} \\
612 \quad & = PyFHOWG_{\ell}(\tilde{\varphi}_1, \tilde{\varphi}_2, \dots, \tilde{\varphi}_{\varsigma}, \tilde{\varphi}_{\varsigma+1}).
\end{aligned}$$

613 Thus the theorem is valid for  $\hbar = \varsigma + 1$  when it is supposed to be true for  $\hbar = \varsigma$ . Hence, by Mathematical induction,  
614 the theorem is valid for all  $\hbar \in \mathbf{N}$ .

## 615 6 Algorithm for Multi-Attribute Decision Making Using PyFI

616 This section proposes a new approach to the decision-making problem using Pythagorean fuzzy information. In  
617 this approach, experts provide their information in the form of PyFSs.

618 Let  $A = \{A_1, A_2, \dots, A_{\varsigma}\}$  be the set of  $\varsigma$  distinct alternatives and  $B = \{B_1, B_2, \dots, B_{\hbar}\}$  be the set of  $\hbar$  distinct  
619 attributes. Let a specific number of experts (decision makers) give their decisions towards different alternatives in  
620 PyFE based on predefined attributes. Let  $\tilde{P}_{ij} = \{\langle \mathfrak{T}_{\tilde{P}_{ij}}, \mathfrak{N}_{\tilde{P}_{ij}} \rangle : i = 1, 2, \dots, \varsigma \text{ and } j = 1, 2, \dots, \hbar\}$  be the PyFI given  
621 by the experts in aggregated form towards the  $i$ -th alternative to the basis of  $j$ -th attribute. In this way, we can form  
622 a matrix called decision-making matrix  $D = [\tilde{P}_{ij}]_{\varsigma \times \hbar}$ .

623 Our target is to aggregate the PyFI obtained in the decision-making matrix corresponding to each alternative and  
624 find the best alternative. Different attributes are assigned different weights during the evaluation of aggregated values

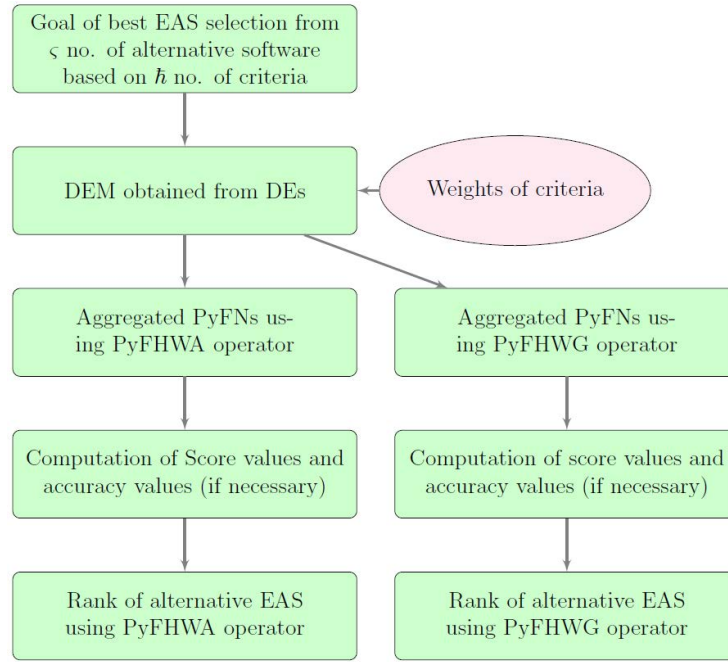
corresponding to each alternative to fulfil the expected requirements of the decision-makers. Let  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  be a weight vector such that  $\ell_i$  be the weight assigned to the  $j$ -th attribute and  $\sum_{j=1}^h \ell_j = 1, \ell_j \in [0, 1]$ .

The algorithm of the solution to the multi-attribute decision-making problem is as follows:

**Step-1:** In this step, we get collective information in the decision-making matrix form in PyFE. Then we aggregate that information using the proposed Pythagorean fuzzy Hamacher weighted averaging (PyFHWA) operator and Pythagorean fuzzy Hamacher weighted geometric (PyFHWG) operator with the associated weight vector  $\ell = (\ell_1, \ell_2, \dots, \ell_h)^T$  such that  $\sum_{j=1}^h \ell_j = 1, \ell_j \in [0, 1]$ .

**Step-2:** We find the score values and accuracy values (if needed) of the aggregated PyFN concerning each alternative.

**Step-3:** Construction of rank of the alternatives  $B_i (i = 1, 2, \dots, h)$  based on score values and accuracy values (if needed) and selection of the best alternative occupying maximum rank (See Figure 2).



**Figure 2.** Diagram of the present model.

## 6.1 Numerical Example

Enterprise Application Software (EAS) is also known as Enterprise Software (ES). Let an organization seeking the best EAS among the four reputed EAS companies, namely,  $A_1, A_2, A_3, A_4$  which are assumed as alternatives and  $B_1, B_2, B_3, B_4, B_5$  be the five predetermined criteria (attributes) based on which the best alternative is to be chosen. The EASs mostly used in large business organizations comprising of different rolls and activities. They normally includes sales department, information technology sector, finance sector, juridical part and public dealings. Let  $B_1, B_2, B_3, B_4, B_5$  represent the attributes Credibility, Agility, User-friendliness, Compatibility, and Less market price, respectively. The organization determines the weight  $\ell_j (j = 1, 2, 3, 4, 5)$  corresponding to the attribute  $B_j (j = 1, 2, 3, 4, 5)$  so that their importance on specific attribute in best alternative selection be fulfilled.

The DEM  $D = [\tilde{P}_{ij}]_{4 \times 5}$  containing the PyFI provided by the specific number of experts towards the different alternatives is given in Table 2.

### Case-1:

**Step-1:** Now we use the PyFHWA operator to determine the aggregated performance of  $A_i (i = 1, 2, 3, 4)$  based on the attributes  $B_j (j = 1, 2, 3, 4, 5)$ . These performances are shown in Table 3 with respect to the weight vector  $\ell = (0.25, 0.15, 0.10, 0.35, 0.15)^T$  and parameter  $\kappa = 1$ .

From Table 3, we can find the score values corresponding to each aggregated PyFNs under the PyFHWA operator as follows:



**Table 2.** Pythagorean fuzzy DEM in tabular form

	$B_1$	$B_2$	$B_3$	$B_4$	$B_5$
$A_1$	$\langle 0.7, 0.4 \rangle$	$\langle 0.4, 0.5 \rangle$	$\langle 0.6, 0.3 \rangle$	$\langle 0.3, 0.4 \rangle$	$\langle 0.6, 0.4 \rangle$
$A_2$	$\langle 0.7, 0.3 \rangle$	$\langle 0.6, 0.4 \rangle$	$\langle 0.7, 0.3 \rangle$	$\langle 0.6, 0.8 \rangle$	$\langle 0.7, 0.4 \rangle$
$A_3$	$\langle 0.3, 0.2 \rangle$	$\langle 0.7, 0.2 \rangle$	$\langle 0.3, 0.6 \rangle$	$\langle 0.6, 0.5 \rangle$	$\langle 0.6, 0.2 \rangle$
$A_4$	$\langle 0.7, 0.3 \rangle$	$\langle 0.5, 0.4 \rangle$	$\langle 0.5, 0.4 \rangle$	$\langle 0.7, 0.3 \rangle$	$\langle 0.5, 0.4 \rangle$

**Table 3.** Aggregated PyFNs under PyFHWA operator for  $\kappa = 1$ 

	Aggregated value(PyFN)
$A_1$	$\langle 0.5363, 0.4019 \rangle$
$A_2$	$\langle 0.6547, 0.4610 \rangle$
$A_3$	$\langle 0.5480, 0.3076 \rangle$
$A_4$	$\langle 0.6363, 0.3366 \rangle$

$Sc(A_1) = 0.1261, Sc(A_2) = 0.2162, Sc(A_3) = 0.2057, Sc(A_4) = 0.2916$ . Similarly, we can find the same for the other parameter values,  $\kappa = 2, 3, 4, 5, 6, 7, 8, 9, 10$ .

**Step-2 and 3:** The score values of the aggregated PyFNs and their ranks are shown in Table 4.

**Case 2:**

**Step 1:** Now we use the PyFHWG operator to determine the aggregated performance of  $A_i (i = 1, 2, 3, 4)$  based on the attributes  $B_j (j = 1, 2, 3, 4, 5)$ . These performances are shown in Table 5 concerning the weight vector  $\ell = (0.25, 0.15, 0.10, 0.35, 0.15)^T$  and parameter  $\kappa = 1$ . From Table 5, we can find the score values corresponding to each aggregated PyFNs and which are as follows:

$Sc(A_1) = 0.0444, Sc(A_2) = 0.0622, Sc(A_3) = 0.0776, Sc(A_4) = 0.2557$ . Similarly, we can find the same for other  $\kappa$  values.

**Step 2 and 3:** The score values of aggregated PyFNs under the PyFHWG operator and their ranks are shown in Table 6.

**Table 4.** Ranks of aggregated PyFNs under PyFHWA operator

$\kappa$	$Sc(A_1)$	$Sc(A_2)$	$Sc(A_3)$	$Sc(A_4)$	Ranking
1	0.1261	0.2162	0.2057	0.2916	$A_1 < A_3 < A_2 < A_4$
2	0.1147	0.2023	0.1914	0.2866	$A_1 < A_3 < A_2 < A_4$
3	0.1073	0.1955	0.1875	0.2836	$A_1 < A_3 < A_2 < A_4$
4	0.1021	0.1914	0.1826	0.2817	$A_1 < A_3 < A_2 < A_4$
5	0.0981	0.1827	0.1788	0.2803	$A_1 < A_3 < A_2 < A_4$
6	0.0949	0.1868	0.1759	0.2793	$A_1 < A_3 < A_2 < A_4$
7	0.0924	0.1853	0.1735	0.2785	$A_1 < A_3 < A_2 < A_4$
8	0.0903	0.1842	0.1715	0.2779	$A_1 < A_3 < A_2 < A_4$
9	0.0885	0.1833	0.1698	0.2774	$A_1 < A_3 < A_2 < A_4$
10	0.0870	0.1826	0.1684	0.2770	$A_1 < A_3 < A_2 < A_4$

## 6.2 Analysis of Dependency on the Parameter $\kappa$ in MADM Result

To describe the effect of the parameter  $\kappa$  in MADM result, we take ten different values of  $\kappa$  in PyFHWA and PyFHWG operators, and then we calculate the score values of aggregated PyFNs using two different operators corresponding to four alternatives and after that ranks of the alternatives are calculated. Scores and ranks are shown in Table 4 and Table 6, respectively.

From Table 4, it is clear that the ranks remain the same for different values of  $\kappa$  i.e., the result is not affected by the values of  $\kappa$ , and for all  $\kappa$  the rank of the alternatives is  $A_1 < A_3 < A_2 < A_4$ , i.e., the best alternative deduced is  $A_4$  for the MADM problem based on PyFHWA operator.

From Table 6, it is noteworthy that the rank differs after the change of  $\kappa$  values.

For  $1 \leq \kappa \leq 2$ , the rank of the alternatives is  $A_1 < A_2 < A_3 < A_4$  and consequently, the best preferable alternative is  $A_4$ . In this case,  $\kappa$  values do not affect ranks as well as the result of the MADM problem.

Now for  $3 \leq \kappa \leq 10$  the rank of alternatives is  $A_1 < A_3 < A_2 < A_4$  and consequently the best preferable alternative is  $A_4$ . Hence the best alternative is  $A_4$  under the PyFHWG operator. In this case,  $\kappa$  values affect the

**Table 5.** Aggregated PyFNs under PyFHWG operator for  $\kappa = 1$ 

Aggregated value(PyFN)	
$A_1$	$\langle 0.4604, 0.4093 \rangle$
$A_2$	$\langle 0.6481, 0.5982 \rangle$
$A_3$	$\langle 0.4818, 0.3930 \rangle$
$A_4$	$\langle 0.6119, 0.3445 \rangle$

ranking of aggregated PyFNs, but despite this, the results remain the same.

**Table 6.** Ranks of aggregated PyFNs under PyFHWG operator

$\kappa$	$Sc(A_1)$	$Sc(A_2)$	$Sc(A_3)$	$Sc(A_4)$	Rank
1	0.0444	0.0622	0.0776	0.2557	$A_1 < A_2 < A_3 < A_4$
2	0.0522	0.0891	0.0912	0.2607	$A_1 < A_2 < A_3 < A_4$
3	0.0556	0.1049	0.0990	0.2632	$A_1 < A_3 < A_2 < A_4$
4	0.0577	0.1154	0.1044	0.2647	$A_1 < A_3 < A_2 < A_4$
5	0.0591	0.1231	0.1085	0.2657	$A_1 < A_3 < A_2 < A_4$
6	0.0600	0.1290	0.1118	0.2664	$A_1 < A_3 < A_2 < A_4$
7	0.0608	0.1336	0.1145	0.2670	$A_1 < A_3 < A_2 < A_4$
8	0.0614	0.1373	0.1169	0.2675	$A_1 < A_3 < A_2 < A_4$
9	0.0691	0.1404	0.1188	0.2679	$A_1 < A_3 < A_2 < A_4$
10	0.0623	0.1431	0.1206	0.2682	$A_1 < A_3 < A_2 < A_4$

## 7 Conclusion

In this proposed article, we have discussed solving procedure of MADM issues using different averaging (PyFHW, PyFHOWA, PyFHHA) operators and different geometric (PyFHWG, PyFHOWA, PyFHHA) operators. Though the article deals with the averaging and geometric operators separately, the algorithm and an example have been provided based on the PyFHW and PyFHWG operators. This article considers the selection procedure of enterprise application software in the framework of multi-attribute decision-making problems. The four alternative application software are considered in the primary stage. The five criteria are considered for choosing the best software. The DEM proposed by the DEs is in the PyFE. Consequently, each piece of information for each alternative software corresponding to each criterion is PyFN. The aggregation is performed using the PyFHW and PyFHWG operators separately. The score values of the aggregated PyFNs show that  $A_4$  possesses the highest score value 0.2916 under the PyFHW operator and 0.2557 under the PyFHWG operator for  $\kappa = 1$ . Therefore  $A_4$  is the best EAS followed by  $A_2$ ,  $A_3$  and  $A_1$  under the PyFHW operator, and  $A_4$  is also the best EAS under the PyFHWG operator followed by  $A_3$ ,  $A_2$  and  $A_1$ . The Table 4 shows that the parameter  $\kappa$  has no such remarkable effect in ranking orders of alternatives because if we vary  $\kappa$  values 1 to 10 although the score values change the ranking order of alternatives remain unaltered in either case. But,  $\kappa$  has considerable influence in ranking order of alternatives in Table 3 although the highest and lowest EAS remain the same.

The present method is applied in EAS selection, considering four alternatives and five criteria. The proposed method can also be applied in multi-criteria group decision-making techniques where the information might be fuzzy or its extended forms like intuitionistic, Pythagorean, q-rung orthopair, neutrosophic, triangular, trapezoidal fuzzy environment. Experts' DEMs can be converted into a single DEM using Pythagorean fuzzy Hamacher weighted or ordered weighted or hybrid aggregation operators. These extended methods can be utilized in selecting efficient waste-to-energy technology, compatible logistics supplier selection, etcetera.

The present method considers the criteria' weights vector as  $(0.25, 0.15, 0.10, 0.35, 0.15)^T$ , and it is arbitrarily chosen. No method is applied for determining this weight vector. Also, the DEM considered in this article is assumed as aggregated DEM obtained after the aggregation of DEMs of the DEs. The DEMs are not separately proposed by the DEs. Experts' weights are not mentioned explicitly in this article, and they are treated as identical for each DE. Normally, The weights are distributed amongst the DEs based on their expertise in different fields.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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