Correlation Coefficient for the Interval-valued Neutrosophic Hesitant Fuzzy Set and Its Use in Multi-attribute Decision Making

Chunfang Liu*
College of Automation, Harbin Engineering University, Harbin, Heilongjiang, China
College of Science, Northeast Forestry University, Harbin, Heilongjiang, China

Yuesheng Luo
College of Automation, Harbin Engineering University, Harbin, Heilongjiang, China
College of Science, Harbin Engineering University, Harbin, Heilongjiang, China

ABSTRACT: Interval-valued neutrosophic hesitant fuzzy set (INHFS) is a generalization of the fuzzy set (FS) that is designed for some practical situations in which each element has different truth membership hesitant function, indeterminacy membership hesitant function and falsity membership hesitant function, and permits the membership degrees to have a set of possible interval values. In this paper, we develop the correlation coefficient and the weighted correlation coefficient for INHFSs and study their properties. Then, an approach to multi-attribute decision making (MADM) within the framework of INHFS is developed by the weighted correlation coefficient. Finally, a practical application of the developed approach to the problem of investment is given, and the result shows that our approach is reasonable and effective in dealing with decision making (DM) problems.

Keywords: multi-attribute decision making (MADM); interval-valued neutrosophic hesitant fuzzy set (INHFS); correlation coefficient

1 INTRODUCTION

Fuzzy set was introduced by Zadeh, which has been widely used in decision making, artificial intelligence, pattern recognition, information fusion, etc. [1,2]. On the basis of Zadeh’s work, several high-order fuzzy sets have been proposed as an extension of fuzzy sets, including interval-valued fuzzy set, type-2 fuzzy set, type-n fuzzy set, soft set, rough set, intuitionistic fuzzy set, interval-valued intuitionistic fuzzy set, hesitant fuzzy set, neutrosophic set (NS) and simplified neutrosophic set [3,4,5,6]. So far, the proposed high-order fuzzy sets have been successfully utilized in dealing with different uncertain problems, such as decision making [7], pattern recognition [8], etc.

As a generalization of fuzzy set, the NS was proposed by Smarandache [5] not only to deal with the decision information which is often incomplete, indeterminate and inconsistent but also include the truth membership degree, the falsity membership degree and the indeterminacy membership degree. Since NS contains both non-standard and standard intervals in its theory and related operations which restricts its application in many fields. For simplicity and practical application, Wang proposed the interval NS (INS) and the single valued NS (SVNS) which are the instances of NS and gave some operations on these sets [9,10]. Ye proposed the correlation coefficient of SVNS and applied them to decision making under the environment of SVNS [11]. As another generalization of fuzzy set, HFS was introduced by Torra and Narukawa which is an effective tool to process uncertain information in real decision making and permits the membership degrees to have a set of possible values [4,12]. Chen proposed the interval-valued HFS (IVHFS) which extends the membership degrees to interval values [13]. With the development of these theories, Liu proposed the interval-valued neutrosophic hesitant fuzzy set (INHFS) by combining the interval-valued HFS with interval-valued NS which extends truth membership degree, indeterminacy-membership degree and falsity membership degree.
of an element to a given set having a few different interval values [14].

As an important statistical measure, correlation coefficient has extended to the fuzzy set which reflects how the two sets move in relation to each other. Many researchers have studied the correlation coefficients for different kinds of sets and applied them to decision making, clustering analysis [6,11,13]. Depending on the proposed correlation coefficient, we investigate the correlation coefficient and the weighted correlation coefficient for INHFSs. Then a method to multi-attribute decision making (MADM) within the framework of INHFS is developed by the correlation coefficient. Finally, we use the developed method to the problem of investment.

The rest of this paper is organized as follows. In Section 2, we recall the INS, HFS, IHFS, INHFS and correlation coefficient for HFSs. In Section 3, we propose the correlation coefficient and the weighted correlation coefficient for INHFSs. Meanwhile, we study some useful properties of the correlation coefficient and the weighted correlation coefficient. In Section 4, A multi-attribute decision making method is proposed on the basis of the weighted correlation coefficient defined in Section 3. Section 5 utilizes an example to validate the proposed decision making method introduced in Section 4. Finally, a conclusion is given in Section 6.

2 PRELIMINARIES

2.1 INS

Interval-valued neutrosophic set (INS) improves the ability of NS expressing the uncertainty of information whose membership functions take the form of interval values.

**Definition 1** [9]: Assume X be a universe of discourse, with a generic element in X denoted by x. An interval-valued neutrosophic set A in X is

\[ A = \left\{ x, T_A(x), I_A(x), F_A(x) \right\} | x \in X \]

where \( T_A(x) \), \( I_A(x) \) and \( F_A(x) \) are the truth membership function, indeterminacy membership function and falsity membership function, respectively. For each point x in X, we have \( T_A(x), I_A(x) \) and \( F_A(x) \leq [0,1] \) and \( 0 \leq \text{Sup}T_A(x) + \text{Sup}I_A(x) + \text{Sup}F_A(x) \leq 3 \).

2.2 HFS and IHFS

HFS is an extension of FS introduced by Torra and Narukawa in 2009 [4,12]. HFS allows one to deal with indeterminacy, hesitant information which people have hesitancy in providing their preference over objects. Since HFS was introduced, it has been successfully utilized in dealing with different uncertain decision making problems and clustering analysis [12,13].

**Definition 2** [14]: Assume X be a reference set, a hesitant fuzzy set (HFS) A on X is defined in terms of a function \( h_A(x) \) when applied to X returns a finite subset of \([0,1]\), i.e.,

\[ A = \left\{ x, h_A(x) \right\} | x \in X \]

where \( h_A(x) \) is a set of some different values in \([0,1]\), representing the possible membership degree of the element x to A. For convenience, we call \( h_A(x) \) a hesitant fuzzy element (HFE).

**Definition 3** [13]: Assume X be a reference set, an interval-valued hesitant fuzzy set (IHFS) A on X is defined as:

\[ A = \left\{ x, h_A(x) \right\} | x \in X \]

where \( h_A(x) \) is a set of some interval values in \([0,1]\), representing the possible membership degree of the element x to A.

2.3 INHFS

With the development of the social economy and increased volume of information, the application of MADM to real world problems has become more complex, obscure and uncertain. As a generation of FSs, INHFS is a combination of INS and IHFS which is an effective tool to process the uncertainty, incomplete and inconsistent information.

**Definition 4** [14]: Let X be a non-empty finite set, an interval-valued neutrosophic hesitant fuzzy set (IVNHS) N on X is defined as:

\[ N = \left\{ x, \tilde{i}(x), \tilde{j}(x), \tilde{f}(x) \right\} | x \in X \]

where \( \tilde{i}(x) = [\tilde{g}, \tilde{\eta}] \), \( \tilde{j}(x) = [\tilde{\delta}, \tilde{\eta}] \) and \( \tilde{f}(x) = [\tilde{\eta}, \tilde{\eta}] \) are three sets of some interval values in real unit interval \([0,1]\), which denotes the truth membership hesitant degree, indeterminacy membership hesitant degree and falsity membership hesitant degree of the element x to N, and satisfies these limits:

\[ \tilde{g} = [r^t, r^u] \subseteq [0,1], \tilde{\delta} = [s^t, s^u] \subseteq [0,1], \]

\[ \tilde{\eta} = [\eta^t, \eta^u] \subseteq [0,1] \]

and \( 0 \leq \text{Sup} \tilde{g} + \text{Sup} \tilde{\delta} + \text{Sup} \tilde{\eta} \leq 3 \), where \( \tilde{g} = \cup_{\tilde{g}^\prime}(x) \max \left\{ \tilde{g}^\prime \right\}, \tilde{\delta} = \cup_{\tilde{\delta}^\prime}(x) \max \left\{ \tilde{\delta}^\prime \right\}, \)

\[ \tilde{\eta} = \cup_{\tilde{\eta}^\prime}(x) \max \left\{ \tilde{\eta}^\prime \right\} \]

for x \( \in X \). The \( n = [\tilde{i}(x), \tilde{j}(x), \tilde{f}(x)] \) is called an interval-valued neutrosophic hesitant fuzzy element (INHFE) which is the basic unit of the INHFS and is represented by the symbol \( n = [\tilde{i}, \tilde{j}, \tilde{f}] \).

2.4 Review of correlation coefficient for HFSs

The values of a hesitant fuzzy element are usually
given in a disorder, so we arrange them in a decreasing order. For a HFE $h$, let $\sigma : (1, 2, \ldots, n) \to (1, 2, \ldots, n)$ be a permutation satisfying $h_{\sigma(i)} \geq h_{\sigma(i+1)}$, $i = 1, 2, \ldots, n$ and $h_{\sigma(n)}$ be the $n$th largest value in $h$.

Definition 5[13]: Let $A$ be a hesitant fuzzy set on a universe of discourse $X = \{x_1, x_2, \ldots, x_n\}$ denoted as $A = \{\langle x_i, h_i(x_i) \rangle \mid x_i \in X\}$, the informational energy of $A$ is defined as

$$E_{HFS}(A) = \sum_{i=1}^{n} \left( \frac{1}{l_i} \sum_{j=1}^{l_i} h_{\sigma(j)}^2(x_i) \right)$$

(1)

where $l_i = l(h_i(x_i))$ represent the number of values in $h_i(x_i)$, $x_i \in X$.

Definition 6[13]: Let $A$ and $B$ be two hesitant fuzzy sets on a universe of discourse $X = \{x_1, x_2, \ldots, x_n\}$ denoted as $A = \{\langle x_i, h_i(x_i) \rangle \mid x_i \in X\}$ and $B = \{\langle x_i, h_i(x_i) \rangle \mid x_i \in X\}$, respectively. Then, the correlation between $A$ and $B$ is defined by

$$C_{HFS}(A, B) = \sum_{i=1}^{n} \left( \frac{1}{l_i} \sum_{j=1}^{l_i} h_{\sigma(j)}(x_i) h_{\sigma(j)}(x_i) \right)$$

(2)

where $l_i = \max \{\|h_i(x_i)\|, \|h_i(x_i)\|\}$, $x_i \in X$, $l(h_i(x_i))$ and $l(h_i(x_i))$ represent the number of elements in $h_i(x_i)$ and $h_i(x_i)$, respectively. When $l(h_i(x_i)) \neq l(h_i(x_i))$, one can make them have the same number of elements through adding some elements to the HFS which has less number of elements. According to the optimistics principle, the maximum element will be added. Therefore, If $l(h_i(x_i)) \leq l(h_i(x_i))$, $h_i(x_i)$ should be extended by adding the maximum value in it until it has the same length as $h_i(x_i)$.

Definition 7[13]: Let $A$ and $B$ be two hesitant fuzzy sets on a universe of discourse $X = \{x_1, x_2, \ldots, x_n\}$ denoted as $A = \{\langle x_i, h_i(x_i) \rangle \mid x_i \in X\}$ and $B = \{\langle x_i, h_i(x_i) \rangle \mid x_i \in X\}$, respectively. Then, the correlation coefficient between $A$ and $B$ is defined by

$$\rho_{HFS}(A, B) = \frac{C_{HFS}(A, B)}{\left[C_{HFS}(A, A)\right]^{\frac{1}{2}} \left[C_{HFS}(B, B)\right]^{\frac{1}{2}}}$$

(3)

3 CORRELATION COEFFICIENT FOR INHSSF

3.1 Correlation coefficient for INHFSs

On the basis of the Chen’s work, we propose the correlation coefficient for INHFSs. In this section, we will extend the informational energy, correlation and correlation coefficient from HFS to INHFS. Let $\sigma : (1, 2, \ldots, n) \to (1, 2, \ldots, n)$ be a permutation satisfying, $A_{\sigma(i)} \geq A_{\sigma(i+1)}$, $i = 1, 2, \ldots, n$ and $A_{\sigma(n)}$ be the $n$th largest value in $A_1, A_2, \ldots, A_n$.

Definition 8: Let $A$ be an INHFS on a universe of discourse $X = \{x_1, x_2, \ldots, x_n\}$ denoted as $N = \{\langle x_i, \tilde{f}(x_i) \rangle \mid x_i \in X\}$, the informational energy of $A$ is defined as

$$E_{INHFS}(A) = \sum_{i=1}^{n} \left[ \frac{1}{k_i} \sum_{j=1}^{k_i} \left( r_{\tilde{f}(x_i)}(x_j) + \delta_{\tilde{f}(x_i)}(x_j) \right)^2 \right]$$

(4)

$$+ \frac{1}{m_i} \sum_{s=1}^{m_i} \left[ \eta_{\tilde{f}(x_i)}(x_j) + \delta_{\tilde{f}(x_i)}(x_j) \right]^2 \right]$$

where $k_i = k(\tilde{f}(x_i))$ represents the number of values in $\tilde{f}(x_i)$, $l_i = l(\tilde{f}(x_i))$ represents the number of values in $\tilde{f}(x_i)$, $m_i = m(\tilde{f}(x_i))$ represents the number of values in $\tilde{f}(x_i)$.

Definition 9: Let $A$ and $B$ be two INHFSs on a universe of discourse $X = \{x_1, x_2, \ldots, x_n\}$ denoted as $A = \{\langle x_i, \tilde{f}(x_i) \rangle, \tilde{f}(x_i) \mid x_i \in X\}$, $B = \{\langle x_i, \tilde{f}(x_i) \rangle, \tilde{f}(x_i) \mid x_i \in X\}$, respectively. Then, the correlation between $A$ and $B$ is defined by

$$C_{INHFS}(A, B) = \sum_{i=1}^{n} \left[ \frac{1}{k_i} \sum_{j=1}^{k_i} \left( r_{\tilde{f}(x_i)}(x_j) \right) + r_{\tilde{f}(x_i)}(x_j) \right]^2$$

(5)

$$+ \frac{1}{m_i} \sum_{s=1}^{m_i} \left[ \eta_{\tilde{f}(x_i)}(x_j) + \eta_{\tilde{f}(x_i)}(x_j) \right]^2 \right]$$

where $k_i = \max \{k(\tilde{f}(x_i)), k(\tilde{f}(x_i))\}$, $l_i = \max \{l(\tilde{f}(x_i)), l(\tilde{f}(x_i))\}$, $m_i = \max \{m(\tilde{f}(x_i)), m(\tilde{f}(x_i))\}$, $k(\tilde{f}(x_i)), k(\tilde{f}(x_i))$ represent the number of values in $\tilde{f}(x_i)$, $\tilde{f}(x_i)$; $l(\tilde{f}(x_i)), l(\tilde{f}(x_i))$ represent the number of values in $\tilde{f}(x_i)$, $\tilde{f}(x_i)$; $m(\tilde{f}(x_i)), m(\tilde{f}(x_i))$ represent the number of values in $\tilde{f}(x_i)$, $\tilde{f}(x_i)$. When $k(\tilde{f}(x_i)) \neq k(\tilde{f}(x_i))$, $l(\tilde{f}(x_i)) \neq l(\tilde{f}(x_i))$, $m(\tilde{f}(x_i)) \neq m(\tilde{f}(x_i))$, one can make them have the same number of elements through adding some elements to the INHFS which has less number of elements. According to the optimistic principle, the maximum element will be added. Therefore, if $k(\tilde{f}(x_i)) < k(\tilde{f}(x_i))$ or $l(\tilde{f}(x_i)) < l(\tilde{f}(x_i))$ or...
Based on the above definition, we get the correlation coefficient for INHFSs.

**Definition 10:** Let A and B be two INHFSs on a universe of discourse \( X = \{ x_1, x_2, \ldots, x_n \} \) denoted as
\[
A = \{ (x_i, \tilde{A}_i(x_i), \tilde{A}_i(x_i), \tilde{A}_i(x_i)) | x_i \in X \},
\]
\[
B = \{ (x_i, \tilde{B}_i(x_i), \tilde{B}_i(x_i), \tilde{B}_i(x_i)) | x_i \in X \}.
\]

Then, the correlation coefficient between A and B is defined by
\[
\rho_{\text{INHFS}}(A, B) = \frac{C_{\text{INHFS}}(A, B)}{\sqrt{C_{\text{INHFS}}(A, A)} \sqrt{C_{\text{INHFS}}(B, B)}}.
\]

**Theorem 1:** The correlation coefficient between two INHFSs A and B has the properties:

1. \( \rho_{\text{INHFS}}(A, B) = \rho_{\text{INHFS}}(B, A) \);
2. \( 0 \leq \rho_{\text{INHFS}}(A, B) \leq 1 \);
3. \( \rho_{\text{INHFS}}(A, B) = 1, \) if \( A = B \).

Proof. (1), (3) is obvious, we just prove (2).

\[
C_{\text{INHFS}}(A, B) = \sum_{i=1}^{n} \left\{ \sum_{j=1}^{n} \left( \frac{r_{iA}(x_i) r_{jB}(x_j) + r_{jA}(x_j) r_{iB}(x_i)}{\sqrt{k_i} \sqrt{k_j}} \right) + \sum_{s=1}^{l} \left( \frac{\delta_{iA}(x_i) \delta_{jB}(x_j) + \delta_{jA}(x_j) \delta_{iB}(x_i)}{\sqrt{l_i} \sqrt{l_j}} \right) + \sum_{s=1}^{m} \left( \frac{\eta_{iA}(x_i) \eta_{jB}(x_j) + \eta_{jA}(x_j) \eta_{iB}(x_i)}{\sqrt{m_i} \sqrt{m_j}} \right) \right\}
\]

According to the Cauchy-Schwarz inequality,
\[
(x_1 y_1 + x_2 y_2 + \cdots + x_n y_n)^2 \leq (x_1^2 + x_2^2 + \cdots + x_n^2)(y_1^2 + y_2^2 + \cdots + y_n^2)
\]
We obtain
\[
C_{\text{INHFS}}(A, B)^2 \leq \sum_{i=1}^{n} \left( \sum_{j=1}^{n} \left( \frac{r_{iA}(x_i) r_{jB}(x_j) + r_{jA}(x_j) r_{iB}(x_i)}{\sqrt{k_i} \sqrt{k_j}} \right) + \sum_{s=1}^{l} \left( \frac{\delta_{iA}(x_i) \delta_{jB}(x_j) + \delta_{jA}(x_j) \delta_{iB}(x_i)}{\sqrt{l_i} \sqrt{l_j}} \right) + \sum_{s=1}^{m} \left( \frac{\eta_{iA}(x_i) \eta_{jB}(x_j) + \eta_{jA}(x_j) \eta_{iB}(x_i)}{\sqrt{m_i} \sqrt{m_j}} \right) \right)
\]
Thus we get \( 0 \leq \rho_{\text{INHFS}}(A, B) \leq 1 \).

### 3.2 Correlation coefficient for INHFSs

In practical applications, the elements \( x_i (i = 1, 2, \ldots, n) \) in the universe X have different weights. Let \( w = \left( w_1, w_2, \ldots, w_n \right)^T \) be the weight vector of \( x_i (i = 1, 2, \ldots, n) \) with \( w_i \in [0,1] \) and \( \sum_{i=1}^{n} w_i = 1 \). Then we will extend the informational energy, the correlation and correlation coefficient from INHFSs to the weighted informational energy, the weighted correlation and the weighted correlation coefficient for INHFSs.

\[
E_{\text{WINHFS}}(A) = \sum_{i=1}^{n} w_i \left\{ \frac{1}{k_i} \left( r_{iA}(x_i) r_{jB}(x_j) + r_{jA}(x_j) r_{iB}(x_i) \right) \right\}
\]
\[
+ \frac{1}{m_i} \left( \eta_{iA}(x_i) \eta_{jB}(x_j) + \eta_{jA}(x_j) \eta_{iB}(x_i) \right)
\]

\[
C_{\text{WINHFS}}(A, B) = \sum_{i=1}^{n} \left\{ \frac{1}{k_i} \left( r_{iA}(x_i) r_{jB}(x_j) + r_{jA}(x_j) r_{iB}(x_i) \right) \right\}
\]
\[
+ \frac{1}{m_i} \left( \eta_{iA}(x_i) \eta_{jB}(x_j) + \eta_{jA}(x_j) \eta_{iB}(x_i) \right)
\]

\[
\rho_{\text{INHFS}}(A, B) = \frac{C_{\text{INHFS}}(A, B)}{\sqrt{C_{\text{INHFS}}(A, A)} \sqrt{C_{\text{INHFS}}(B, B)}}.
\]

The weighted correlation coefficient for INHFSs satisfies the following three properties:

1. \( \rho_{\text{INHFS}}(A, B) = \rho_{\text{INHFS}}(B, A) \);
2. \( 0 \leq \rho_{\text{INHFS}}(A, B) \leq 1 \);
3. \( \rho_{\text{INHFS}}(A, B) = 1, \) if \( A = B \).

### 4 Multi-attribute Decision Making Method

Next, we will study the MADM problems which the attribute values take the form of interval-valued neutrosophic hesitant fuzzy numbers. Let \( X = \{ x_1, x_2, \ldots, x_n \} \) be a set of alternatives, \( C = \{ c_1, c_2, \ldots, c_m \} \) be a set of attributes and \( w = (w_1, w_2, \ldots, w_m)^T \) be the weight vector of the attributes with \( w_j \in [0,1] \) and \( \sum_{j=1}^{m} w_j = 1 \). In
MADM environments, the ideal point is used to help the identification of the best alternative in the decision set. Although the ideal point does not exist in real world, it does provide an effective way to evaluate the best alternative. Now we suppose ideal INHFE as 
\[ n^*_i = \left\{ t^*_i, r^*_i, j^*_i \right\} = \left\{ \{1,1,1\}, \{0,0,0\}, \{0,0,0\} \right\} \] in the ideal alternative \( n^*_i = \left\{ t^*_i, r^*_i, j^*_i \right\} \). Then, we utilize the proposed weighted correlation coefficient to develop a method in dealing with MADM problem within the framework of INHFSs, which can be described as follows:

**Step 1.** Calculate the weighted correlation coefficient by (7)-(9).

**Step 2.** Rank the alternatives in accordance with the values of weighted correlation coefficients.

**Step 3.** Choose the best alternatives according to the maximum value of weighted correlation coefficients.

**Step 4.** End.

5 NUMERICAL EXAMPLE AND ANALYSIS

5.1 Numerical example

In this section, an example adapted from [14] is utilized to illustrate the applicability and validity of the proposed MADM method. There is an investment problem concerning a financial company with the following four potential alternatives: (1) car company \( A_1 \); (2) food company \( A_2 \); (3) computer company \( A_3 \); (4) arms company \( A_4 \). The investment problem must take a decision making according to the following three attributes: \( C_1 \) (risk analysis); \( C_2 \) (growth analysis); \( C_3 \) (environmental impact analysis). Meanwhile, Assume that the attributes’ weight vector is \( w = \left( \frac{1}{3}, \frac{1}{3}, \frac{1}{3} \right) \). The interval-valued neutrosophic hesitant fuzzy information is listed as Table 1.

The decision making process is as follows.

**Step 1.** Calculate correlation coefficient \( \rho_{\text{WINHFS}}(A_i, A^*) \) \((i=1,2,3)\) as follows:
\[
\rho_{\text{WINHFS}}(A_1, A^*) = 0.4766, \quad \rho_{\text{WINHFS}}(A_2, A^*) = 0.9285, \\
\rho_{\text{WINHFS}}(A_3, A^*) = 0.6823, \quad \rho_{\text{WINHFS}}(A_4, A^*) = 0.9053.
\]

**Step 2.** Since \( \rho_{\text{WINHFS}}(A_2, A^*) \geq \rho_{\text{WINHFS}}(A_3, A^*) \geq \rho_{\text{WINHFS}}(A_1, A^*) \), we rank the alternative as \( A_2 \succ A_4 \succ A_3 \succ A_1 \).

**Step 3.** The most desirable one is \( A_2 \), which is agreement with the result in [14].

5.2 Analysis

In this section, we have proposed a new method to solve the MADM problem expressed with INHFE information which not only accommodate the INHFE environment but also automatically take into account much more information provided by decision makers than [14]. Moreover, the calculation of the method is more simple and practical.

6 CONCLUSION

We have proposed correlation coefficient for INHFSs on the basis of correlation coefficient for HFSs in this paper. Moreover, we have developed a method to address the MADM problem in which the evaluated values of an alternative take the form of INHFSs. The calculation is simple and provides a new idea for solving DM problems under INHFS. Finally, a practical numerical example is given to verify the developed MADM method and to demonstrate its capacity in dealing with practical and uncertain decision making problems.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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