IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 1, 2019, accepted April 21, 2019, date of publication April 23, 2019, date of current version May 3, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2912913

A Novel Neutrosophic Data Analytic Hierarchy Process for Multi-Criteria Decision Making Method: A Case Study in Kuala Lumpur Stock Exchange

DESMOND JUN YI TEY[1], YEE FEI GAN[1], GANESHSREE SELVACHANDRAN[1], SHIO GAI QUEK[2], FLORENTIN SMARANDACHE[3], LE HOANG SON[4], MOHAMED ABDEL-BASSET[5], AND HOANG VIET LONG[6,7]

[1]Department of Actuarial Science and Applied Statistics, Faculty of Business & Information Science, UCSI University, Kuala Lumpur 56000, Malaysia
[2]A-Level Academy, UCSI College KL Campus, Kuala Lumpur 56000, Malaysia
[3]Department of Mathematics, University of New Mexico, Gallup, NM 87301, USA
[4]VNU Information Technology Institute, Vietnam National University, Hanoi 010000, Vietnam
[5]Department of Operations Research, Faculty of Computers and Informatics, Zagazig University, Zagazig 44519, Egypt
[6]Division of Computational Mathematics and Engineering, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City 700000, Vietnam
[7]Faculty of Mathematics and Statistics, Ton Duc Thang University, Ho Chi Minh City 700000, Vietnam

Corresponding author: Hoang Viet Long (hoangvietlong@tdtu.edu.vn)

This work was supported by the Ministry of Education, Malaysia, under Grant FRGS/1/2017/STG06/UCSI/03/1.

ABSTRACT This paper proposes a multi-criteria decision making method called the neutrosophic data analytic hierarchy process (NDAHP) for the single-valued neutrosophic set (SVNS). This method is an extension of the neutrosophic analytic hierarchy process (NAHP) designed to handle actual datasets which consist of crisp values. The proposed NDAHP method uses an objective weighting mechanism whereas all other existing versions of the AHP, fuzzy AHP, and other fuzzy based AHP method in literature such as the NAHP and picture fuzzy AHP uses a subjective weighting mechanism to arrive at the decision. This makes the proposed NDAHP method effective as the weightage of the criteria which forms the input of the evaluation matrix are determined in an objective manner using actual data collected for the problem, and hence will not change according to the opinions of different decision makers which are subjective. The proposed NDAHP method is applied to a multi-criteria decision making problem related to the ranking of the financial performance of five public listed petrochemical companies trading in the main board of the Kuala Lumpur Stock Exchange (KLSE). Actual dataset of 15 financial indices for the five petrochemical companies for 2017 obtained from Yahoo! Finance was used in this paper. Following this, a brief comparative study is conducted to evaluate the performance of our NDAHP algorithm against the results of other existing SVNS-based decision making methods in the literature. The results are compared against actual results obtained from KLSE. To further verify the rankings obtained through each method, the Spearman and Pearson ranking tests are carried out on each of the decision making methods that are studied. It is proved that NDAHP produces the most accurate results, and this was further verified from the results of the Spearman and Pearson ranking tests.

INDEX TERMS Single-valued neutrosophic set, analytic hierarchy process (AHP), multi-criteria decision making, neutrosophic AHP, neutrosophic decision making.

I. INTRODUCTION

Fuzzy set theory [1] is an extension of classical set theory which was developed as a tool to deal with the uncertainty and vagueness that exists in most of the situations that we encounter on a daily basis. Fuzzy sets are characterized by a single membership value which indicates the degree of belongingness of the elements to a set. The fuzzy set model provided solutions when solving problems where the information is imprecise due to the non-sharply determined

The associate editor coordinating the review of this manuscript and approving it for publication was Victor Hugo Albuquerque.

criteria of the membership classes. Developments made in the application of fuzzy set theory led to a greater demand for advanced studies in this area. This and the deficiencies in fuzzy set theory led to the development of many similar models with the most commonly used ones being the intuitionistic fuzzy set [2], interval-valued fuzzy set [3], interval-valued intuitionistic fuzzy set [4], vague set [5], neutrosophic set [6], hesitant fuzzy set [7] and picture fuzzy set [8].

The inability of fuzzy sets and intuitionistic fuzzy sets (IFSs) in dealing with the inconsistency and indeterminacy components of any information, both of which are inevitably present in most real world situations was one of the factors that led to the introduction of the neutrosophic set in 1995. The neutrosophic set (NS) is an extension of the IFS model, and was introduced to solve problems with inconsistent, incomplete and indeterminate information. The NS model has a triple membership structure that consists of a truth, indeterminacy and falsity membership function, each of which expresses the degree of belongingness, degree of indeterminacy and degree of non-belongingness of an object to a set, respectively. Another significant difference between the NS and other fuzzy based models is the independent nature of the three membership functions in the NS model. Although the initial NS model was developed to take on values in the non-standard subinterval of $]0, 1+[$ which was fine in the study of philosophy, it was found to be unsuitable to be used in solving real-life problems related to engineering and science. This shortcoming of the NS model led to the inception of the single-valued neutrosophic set (SVNS) by Wang *et al.* [9] which is a special case of the NS with membership values in the standard unit interval of [0, 1]. This makes the SVNS model more suitable and convenient to be used in problem solving as it is more compatible with the structure of fuzzy sets and other fuzzy-based models whose membership functions are also defined in the interval of [0, 1] (see [51]–[63] for details). This paper is concerned with developing a decision making method for the SVNS model based on the analytic hierarchy process (AHP).

The analytic hierarchy process (AHP) was first introduced by Saaty [10] as a mathematical tool that is used to make a decision from several alternatives, by taking their criteria into consideration. After the evaluation process is done using AHP, decision makers can then obtain the results which ranks the alternatives from the most desirable to the least desirable. Nowadays, AHP had been widely accepted as an effective tool to handle multi-criteria decision making (MCDM) problems. The AHP method is a relatively simple and practical tool to be used as it does not involve advanced mathematical theory, but rather converts the thinking process of the decision maker into quantitative and qualitative data, and subsequently analyses the multi-criteria data by using simple mathematical tools. Also, the pair-wise comparison between different criteria and construction of a matrix does not require advanced mathematical knowledge [11]. AHP also requires lesser quantitative data compared to other MCDM methods as it is more focused on the criteria involved in the evaluation process, and the evaluation of the importance of these criteria by the decision makers. However, this lack of numerical data also poses a problem as the entire decision making process is dependent on the subjective opinions of the decision makers which can be inconsistent and may vary from one decision maker to another depending on their prior experiences and personal opinions. As such, the results obtained for a problem using the opinions of a set of decision makers may not be convincing for other decision makers. Although, we can compute the consistency ratio and use this to determine the consistency of the opinions (i.e. weightage of the criteria) given by the decision makers, it is still not reliable enough and actually lengthens the decision making process. This is because we need to continuously modify the opinions given by the decision makers until a consistency index of zero or at least a sufficiently small value close to zero is reached. This may also increase the chances of getting erroneous results and lead to the decision makers making a wrong decision. These disadvantages of the traditional AHP methods can be overcome by modifying the algorithm of the AHP to use actual datasets as the input for the AHP method instead of using the subjective opinions of the decision makers as the input for the AHP method. This is the feature of our proposed AHP method based on SVNSs which will be expounded in the subsequent sections.

Another major disadvantage of the AHP method is its inability to handle the subjectivity and vagueness of human judgment or behavior [12]. The fuzzy set model and other fuzzy based models on the other hand, have the advantage of being able to capture the fuzziness of the criteria and other decision parameters in an efficient manner. This led to the introduction of the fuzzy analytic hierarchy process (FAHP) method by Van Laarhoven and Pedrycz [13]. A lot of studies had been done to examine the reliability and credibility of the FAHP. Some of the recent studies in this area are due to Nguyen *et al.* [14] who used FAHP to determine the ranking of the importance of parameters in a transportation project. Ruiz-Padillo *et al.* [15] applied FAHP to study the factors that contributed to traffic noise problem in a region, whereas Calabrese *et al.* [16] applied FAHP in the selection of criteria that affects the performance of a company.

Xu and Liao [17] proposed the intuitionistic fuzzy analytic hierarchy process (IFAHP) by combining the AHP method and the IFS model to improve the capability of FAHP without affecting its originality and inherent characteristics. Many researchers have acknowledged the advantages of IFAHP and have applied it in various problems in different areas. Abdullah, Jaafar and Taib [18], [19] studied the ranking of Human Capital Indicators using IFAHP, and evaluated the criteria involved in sustainable energy technology in Malaysia, respectively. Kaur [20] applied IFAHP to evaluate and select the best vendor for a company, while Nguyen [21] employed the IFAHP method to estimate and subsequently eliminate the potential risks faced by a shipping system.

Apart from the above, other fuzzy based AHP methods have been introduced in literature. These include the interval-valued fuzzy analytic hierarchy process (IVFAHP) by Mirzaei *et al.* [22] and the interval-valued intuitionistic fuzzy analytic hierarchy process (IVIFAHP) by Abdullah and Najib [23]. Mirzaei *et al.* [22] applied his proposed IVFAHP to select the best cargo terminals for a logistics problem, whereas Fahmi *et al.* [24] applied the IVIFAHP to a human resource management problem to select the best candidate for university position. The rapid development in neutrosophic theory led to the introduction of the neutrosophic analytic hierarchy process (NAHP) by Radwan *et al.* [25] who then applied this method to the selection of the most suitable learning management system for an educational institution.

The remainder of this paper is organized as follows. In Section 2, we recapitulate some of the fundamental concepts related to SVNSs and the NAHP method. In Section 3, **we introduce the proposed neutrosophic data analytic hierarchy process** (NDAHP) based on the SVNS model. In Section 4, the proposed decision-making method is then applied to a problem related to the evaluation of the performance of a company based on 15 financial parameters. Actual data for the five companies that were studied were obtained from Yahoo! Finance for the year 2017. In Section 5, a comprehensive comparative analysis of the results obtained via our proposed method and other recent SVNS based decision making methods are presented. We further verify the results obtained via our proposed NDAHP method using the Pearson and Spearman rank tests. It is proved that our proposed NDAHP method is more effective and produces more reliable results compared to the other SVNS based decision making method. Concluding remarks are given in Section 6, followed by the acknowledgements and list of references.

II. PRELIMINARIES

In this section, we recapitulate some important concepts pertaining to the theory of SVNSs, and some of the recent developments related to SVNS based decision making. We refer the readers to [6]–[9] for further details pertaining to the NS and SVNS theory, respectively.

The single-valued neutrosophic set (SVNS) model [9] is a special case of the general neutrosophic set where the range of each of the three membership functions are in the standard unit of interval of [0, 1], instead of the non-standard interval of]−0, 1+[. The SVNS model is one of the most commonly used versions of the NS model, and a lot of research related to SVNS based decision making can be found in literature [26]–[44].

The formal definition of the classical NS introduced by Smarandache [6] is given below.

Let U be a universe of discourse, with a class of elements in U denoted by x.

Definition 1 [6]: A neutrosophic set A is an object having the form $A = \{\langle x, T_A(x), I_A(x), F_A(x)\rangle : x \in U\}$, where the functions $T, I, F : U \to ^{-}0, 1^{+}$ denote the truth, indeterminacy, and falsity membership functions, respectively, of the element $x \in U$ with respect to A. The membership functions must satisfy the condition

$$^{-}0 \leq T_A(x) + I_A(x) + F_A(x) \leq 3^{+}.$$

Definition 2 [6]: A neutrosophic set A is contained in another neutrosophic set B, if $T_A(x) \leq T_B(x)$, $I_A(x) \geq I_B(x)$, and $F_A(x) \geq F_B(x)$, for all $x \in U$. This relationship is denoted as $A \subseteq B$.

The SVNS [9] is a specific form of the NS with values of the membership functions defined in the standard interval of [0, 1]. The formal definition of the SVNS is presented below, and this is followed by the definitions of some of the important concepts and set theoretic operations of the SVNS.

Definition 3 [9]: A SVNS A is a neutrosophic set that is characterized by a truth-membership function $T_A(x)$, an indeterminacy-membership function $I_A(x)$, and a falsity-membership function $F_A(x)$, where $T_A(x), I_A(x), F_A(x) \in [0, 1]$.$\mathrm{F_A(x)} \in$ This set A can thus be written as

$$A = \{(x, T\_A(x), I\_A(x), F\_A(x)) : x \in U\}. \quad (1)$$

The sum of $T_A(x)$, $I_A(x)$ and $F_A(x)$ must fulfill the condition $0 \leq T_A(x) + I_A(x) + F_A(x) \leq 3$. For a SVNS A in U, the triplet $(T_A(x), I_A(x), F_A(x))$ is called a single-valued neutrosophic number (SVNN). For the sake of convenience, we simply let $x = (T_x, I_x, F_x)$ to represent a SVNN as an element in the SVNS A.

Definition 4 [9]: Let A and B be two SVNSs over a universe U.

1) A is contained in B, if $T_A(x) \leq T_B(x)$, $I_A(x) \geq I_B(x)$, and $F_A(x) \geq F_B(x)$, for all $x \in U$. This relationship is denoted as $A \subseteq B$.
2) A and B are said to be equal if $A \subseteq B$ and $B \subseteq A$.
3) $A^c = (x, (F_A(x), 1 - I_A(x), T_A(x)))$, for all $x \in U$.
4) $A \cup B = (x, (\max(T_A, T_B), \min(I_A, I_B), \min(F_A, F_B)))$, for all $x \in U$.
5) $A \cap B = (x, (\min(T_A, T_B), \max(I_A, I_B), \max(F_A, F_B)))$, for all $x \in U$.

Definition 5 [9]: Let $x = (T_x, I_x, F_x)$ and $y = (T_y, I_y, F_y)$ be two SVNNs. The operations for SVNNs can be defined as follows:

1) $x \bigoplus y = (T_x + T_y - T_x * T_y, I_x * I_y, F_x * F_y)$
2) $x \bigoplus y = (T_x * T_y, I_x + I_y - I_x * I_y, F_x + F_y - F_x * F_y)$
3) $\lambda x = (1 - (1 - T_x)^{\lambda}, (I_x)^{\lambda}, (F_x)^{\lambda})$, where $\lambda > 0$
4) $x^{\lambda} = ((T_x)^{\lambda}, 1 - (1 - I_x)^{\lambda}, 1 - (1 - F_x)^{\lambda})$, where $\lambda > 0$.

Definition 6 [45]: Let A and B be two SVNSs over a finite universe $U = \{x_1, x_2, \ldots, x_n\}$. Then the various distance measures between A and B are defined as follows:

(i) The Hamming distance between A and B are defined as:

$$d_H(A, B) = \sum_{i=1}^{n} \{|T_A(x_i) - T_B(x_i)| + |I_A(x_i) - I_B(x_i)| + |F_A(x_i) - F_B(x_i)|\} \quad (2)$$

$$d_E(A,B)=\sqrt{\sum_{i=1}^{n}\left\{(T_A(x_i)-T_B(x_i))^2+(I_A(x_i)-I_B(x_i))^2+(F_A(x_i)-F_B(x_i))^2\right\}} \quad (4)$$

$$d_E^N(A,B)=\sqrt{\frac{1}{3n}\sum_{i=1}^{n}\left\{(T_A(x_i)-T_B(x_i))^2+(I_A(x_i)-I_B(x_i))^2+(F_A(x_i)-F_B(x_i))^2\right\}} \quad (5)$$

(ii) The normalized Hamming distance between A and B are defined as:

$$d_H^N(A,B)=\frac{1}{3n}\sum_{i=1}^{n}\{|T_A(x_i)-T_B(x_i)|+|I_A(x_i)-I_B(x_i)|+|F_A(x_i)-F_B(x_i)|\} \quad (3)$$

(iii) The Euclidean distance between A and B are defined in (4), as shown at the top of this page.

(iv) The normalized Euclidean distance between A and B are defined in (5), as shown at the top of this page.

III. THE PROPOSED NDAHP METHOD BASED ON SVNS

In this section, we present the decision making algorithm for our proposed neutrosophic data analytic hierarchy process (NDAHP). The important components of our proposed NDAHP method such as the formula for the pairwise comparison step and the formula to convert the crisp data to SVNN are also presented and explained.

Neutrosophic Data Analytic Hierarchy Process (NDAHP): Previous research related to NAHP (Radwan *et al.* [25], Abdel-Basset *et al.* [46], and Alava *et al.* [47]) highlighted the practicality of NAHP by applying it to solve various MCDM problems. However, all of these researches only consider experts' opinions which can be very subjective and the importance of a criterion evaluated by an expert may be subverted by actual data. Besides, the experts' may not have consensus with each other, as one expert may not necessarily agree with the importance of a criteria as determined by another expert.

To overcome this problem, we propose a new AHP method based on the SVNS model called the neutrosophic data analytic hierarchy process (NDAHP). The main difference between our NDAHP method and the NAHP method is that the NDAHP uses actual data to obtain the weightage of the criteria, instead of relying on experts' opinion to obtain the weightage of the criteria. Hence, the results obtained through the NDAHP model will be more accurate as the weightage and importance of each criteria and alternative is determined objectively by using actual datasets. Therefore, our proposed method produces input and output values that better reflect the actual situation as per the law of input argument.

The decision making method for the NDAHP method and the procedure to apply in MCDM problems is described as follows:

Step 1 (Construct Hierarchical Model): The framework of the application needs to be constructed in order to give the decision maker a clearer idea about the application. First, the objective need to be determined because that is important for the decision maker to determine the criteria and alternatives of the problem. Next, the decision maker needs to select the criteria and alternatives that are related to the objective. Involvement of unrelated criteria and alternatives will result in inaccurate results being obtained.

Step 2 (Obtain Actual Datasets for the Problem From Reliable Source(s)): The necessary data need to be exported from reliable and verified source(s). Any datasets sourced from unverified sources may contain wrong information and this will affect the accuracy of the results obtained.

Step 3 (Convert Crisp Data Into Single-Valued Neutrosophic Numbers (SVNN)): The crisp data needs to be converted into single-valued neutrosophic number (SVNN) using Eq. (6) and (7) that was introduced by Nirmal and Bhatt [48].
Beneficial criteria:

$$R_{ij}=\frac{X_{ij}-MinX_{ij}}{MaxX_{ij}-MinX_{ij}} \quad (6)$$

Non-beneficial criteria:

$$R_{ij}=\frac{MaxX_{ij}-X_{ij}}{MaxX_{ij}-MinX_{ij}} \quad (7)$$

Beneficial criteria refers to criteria which are preferable when the value is higher, for example, revenue and quality. Non-beneficial criteria refer to criteria which are preferable when the value is lower, for example cost and debt.

After obtaining the value of R_{ij}, the corresponding SVNNs are then computed using Eq. (8) and (9) which are also due to Nirmal and Bhatt [48].
Beneficial criteria:

$$\left(t_p, i_p, f_p\right)=\left(R_{ij}, 1-R_{ij}, 1-R_{ij}\right) \quad (8)$$

Non-beneficial criteria:

$$\left(t_p, i_p, f_p\right)=\left(1-R_{ij}, R_{ij}, R_{ij}\right) \quad (9)$$

Step 4 (Pairwise Comparison): In this step, the SVNN of each criterion need to be compared to the other criteria to determine their relative importance. Here we introduce a formula to calculate the comparison values in the pairwise comparison matrix. Eq. (10) is proposed as no other formula are available in the existing literature for the purpose of

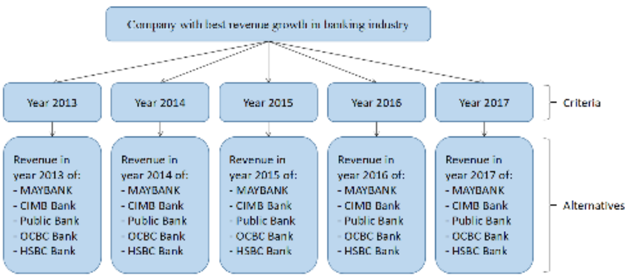

FIGURE 1. An example of a NDAHP structure.

TABLE 1. Comparison matrix.

Criteria	θ_1	θ_2	$\cdots$	θ_n
θ_1	$\frac{\theta_1-\theta_1+1}{2}$	$\frac{\theta_1-\theta_2+1}{2}$	$\cdots$	$\frac{\theta_1-\theta_n+1}{2}$
θ_2	$\frac{\theta_2-\theta_1+1}{2}$	$\frac{\theta_2-\theta_2+1}{2}$	$\cdots$	$\frac{\theta_2-\theta_n+1}{2}$
$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$
θ_n	$\frac{\theta_n-\theta_1+1}{2}$	$\frac{\theta_n-\theta_2+1}{2}$	$\cdots$	$\frac{\theta_n-\theta_n+1}{2}$

calculating the comparison values in the comparison matrix using actual data.

$$a_{ij} = \frac{\theta_i - \theta_j + 1}{2} \tag{10}$$

where θ_i, θ_j and a_{ij} denotes the SVNN of the criteria i, SVNN of the criteria j and the SVNN in the comparison matrix, respectively.

The comparison values obtained are to be placed in a comparison matrix in the form given in Table 1.

Step 5 (Consistency Checking): The purpose of this step is to check the consistency of the matrix and determine the acceptability of the matrix.

Given a SVNS $A = (a_{ij})_{n\times n}$, where each a_{ij} represents a neutrosophic number (T_{ij}, I_{ij}, F_{ij}) and a consistency matrix $C = (c_{ij})_{n\times n} = (T'_{ij}, I'_{ij}, F'_{ij})_{n\times n}$. The procedure to determine the consistency is as outlined below.

(i) For $j > i + 1$, where $k = i + 1$.

(i) For $j = i + 1$, $c_{ij} = (T_{ij}, I_{ij}, F_{ij})$, where $k = i + 1$.

(ii) For $j < i$, $c_{ij} = (F'_{ji}, 1 - I'_{ji}, T'_{ji})$, where $k = i + 1$.

By applying the above formula, the consistency index (CI) of the data will be obtained in the form of a matrix. The decision maker will then need to apply Eq. (11) to obtain the consistency ratio (CR):

$$CR = \frac{1}{2(n-1)(n-2)} \times \sum_{i=1}^{n}\sum_{j=1}^{n}\left(\left|T'_{ij} - T_{ij}\right| + \left|I'_{ij} - I_{ij}\right| \left|F'_{ij} - F_{ij}\right|\right) \tag{11}$$

The matrix is said to be acceptable and can be further processed if the value of the CR is less than 0.1, otherwise, the data is considered inconsistent and requires reconstruction.

Remarks : This consistency checking step is done to examine the validity of the alternatives' preference when the comparison matrix is constructed. The consistency ratio tends to be large when the relative importance is determined by the subjective opinions of human experts and, as a result the comparison matrix tends to become inconsistent. As our proposed NDAHP method uses actual datasets to obtain the weightage and pairwise comparison values which is very objective, this consistency checking step is not necessary to be carried out.

Step 6 (Compute Relative Weightage): After the consistency is checked, and found to be acceptable, the weightage of criteria is calculated. Since the weightage of the criteria are in the form SVNNs, some of the properties and concepts pertaining to SVNS given in Eqs. (12) to (16) need to be used. These formula are due to Radwan *et al.* [25]; here A_1, A_2 denote SVNSs, and N denotes the number of alternatives or criteria.

$$(i)\ A_1 + A_2 = (t_1 + t_2 - t_1t_2, i_1i_2, f_1f_2) \tag{12}$$

$$(ii)\ A_1 \times A_2 = (t_1t_2, i_1 + i_2 - i_1i_2, f_1 + f_2 - f_1f_2) \tag{13}$$

$$(iii)\ \frac{A_1}{A_2} = \left(\frac{t_1}{t_2}, \frac{i_1 - i_2}{1 - i_2}, \frac{f_1 - f_2}{1 - f_2}\right) \tag{14}$$

$$(iv)\ A_1 \times N = \left(1 - (1 - t_1)^N, i_1^N, f_1^N\right) \tag{15}$$

$$(v)\ \frac{A_1}{N} = \left(1 - (1 - t_1)^{\frac{1}{N}}, i_1^{\frac{1}{N}}, f_1^{\frac{1}{N}}\right) \tag{16}$$

These operations are going to be used in the computation of weightage for the criteria. A pairwise comparison matrix is constructed, and each of the element in the matrix is a SVNN. The procedure to obtain the weightage is as described below.

First, sum up the SVNN in the column using Eq. (12). The result of the summation of the SVNNs forms a new matrix of

$$T'_{ij} = \frac{\sqrt[j-i-1]{T_{ik} \times T_{kj} \times T_{i(j-1)} \times T_{(j-1)j}}}{\sqrt[j-i-1]{T_{ik} \times T_{kj} \times T_{i(j-1)} \times T_{(j-1)j}} + \sqrt[j-i-1]{(1 - T_{ik}) \times (1 - T_{kj}) \times (1 - T_{i(j-1)}) \times (1 - T_{(j-1)j})}}$$

$$I'_{ij} = \frac{\sqrt[j-i-1]{I_{ik} \times I_{kj} \times I_{i(j-1)} \times I_{(j-1)j}}}{\sqrt[j-i-1]{I_{ik} \times I_{kj} \times I_{i(j-1)} \times I_{(j-1)j}} + \sqrt[j-i-1]{(1 - I_{ik}) \times (1 - I_{kj}) \times (1 - I_{i(j-1)}) \times (1 - I_{(j-1)j})}}$$

$$F'_{ij} = \frac{\sqrt[j-i-1]{F_{ik} \times F_{kj} \times F_{i(j-1)} \times F_{(j-1)j}}}{\sqrt[j-i-1]{F_{ik} \times F_{kj} \times F_{i(j-1)} \times F_{(j-1)j}} + \sqrt[j-i-1]{(1 - F_{ik}) \times (1 - F_{kj}) \times (1 - F_{i(j-1)}) \times (1 - F_{(j-1)j})}},$$

TABLE 2. Procedure to obtain the overall weightage.

Criteria	Alternatives	Weightage A	Weightage B	Weightage C
θ_1	W_{A_1}	$\theta_1 W_{A_1}$	$\theta_1 W_{B_1}$	$\theta_1 W_{C_1}$
	W_{B_1}			
	W_{C_1}			
θ_2	W_{A_2}	$\theta_2 W_{A_2}$	$\theta_2 W_{B_2}$	$\theta_2 W_{C_2}$
	W_{B_2}			
	W_{C_2}			
θ_3	W_{A_3}	$\theta_3 W_{A_3}$	$\theta_3 W_{B_3}$	$\theta_3 W_{C_3}$
	W_{B_3}			
	W_{C_3}			
Total		$\sum_{i=1}^{n} \theta_i W_{A_i}$	$\sum_{i=1}^{n} \theta_i W_{B_i}$	$\sum_{i=1}^{n} \theta_i W_{C_i}$

dimension $(1 \times n)$. Next, divide every element in the matrix by the corresponding element in matrix$B$ using Eq. (15). As a result, a matrix A' of dimension $(n \times n)$ is formed. Lastly, the weightage is obtained by calculating the average value of the SVNNs that represent the different criteria row by row using Eq. (12) and Eq. (16).

Step 7 (Obtain Overall Ranking): In this step, the decision maker needs to repeat step 3 to step 6 described above to calculate the weightage of the sub-criteria and alternatives. After the weightage of the criteria, sub-criteria and alternatives have been obtained, the overall weightage can be calculated. The concept of the method to obtain the overall weightage is the same as the method used to calculate the overall weightage in the AHP method. The procedure to obtain the overall weightage are shown in Table 2.

From Table 2, the notation θ_i denotes the weightage of criteria i while W_{X_i} denotes the weightage of alternative X with respect to criteria i. Note that the overall weightage obtained is in SVNN form. Eq. (17) is then used to convert the SVNNs to crisp values.

$$S\left(A_j\right) = \frac{3 + t_j - 2i_j - f_j}{4} \tag{17}$$

where t_j, i_j and f_j denotes the truth, indeterminacy and falsity membership value for alternative A_j.

Step 8 (Determine Overall Ranking): At the end of step 7, a weightage is obtained for every alternative. At this final step, the decision maker has to arrange the weightage obtained for each alternative in descending order, and subsequently make a decision.

IV. APPLICATION OF THE NDAHP METHOD IN A MCDM PROBLEM

In this section, the utility and practicality of our proposed NDAHP method are demonstrated by applying the NDAHP method to a MCDM problem related to the ranking of the financial performance of five selected petrochemical companies in Malaysia.

A. RANKING THE FINANCIAL PERFOMANCE OF PETROCHEMICAL COMPANIES IN MALAYSIA

The performance of a company is measured using the financial indicators of the company, and this is an important factor that contributes to investor confidence and the performance of the company in the stock market. Here, we consider five public listed petrochemical companies that are trading in the main board of the Kuala Lumpur Stock Exchange (KLSE). The companies are Hengyuan Refining Company Berhad (HENGYUAN), Petron Malaysia Refining and Marketing Berhad (PETRONM), Barakah Offshore Petroleum Berhad (BARAKAH), Sapura Energy Berhad (SAPURA) and Perdana Petroleum Berhad (PERDANA), and these companies form the set of alternatives for this problem. The objective of the study is to rank the five companies based on their financial performance in the year 2017. To examine this, 15 financial ratios and financial indicators for the five companies are considered. These are the sales growth, asset growth, shareholder's equity growth, accounts receivable turnover, fixed assets turnover, equity turnover, total asset turnover, debt ratio, debt to equity ratio, ROA, ROE, net profit margin, current ratio, quick ratio and cash ratio, and these form the set of criteria for this problem. Actual datasets for the financial ratios for the financial year 2017 for these five companies were used in this study. These datasets were obtained from the official annual reports of the respective companies that were obtained from the Securities Commission of Malaysia and/or the official websites of the companies.

The above-mentioned datasets were applied to our proposed NDAHP method and the results obtained are as given in Table 3.

TABLE 3. Results obtained from our proposed NDAHP method.

Petrochemical company	Weightage	Ranking
HENGYUAN	0.223344084	1
PETRONM	0.218360145	2
BARAKAH	0.186326396	3
SAPURA	0.186265568	4
PERDANA	0.185703807	5

B. DISCUSSION OF RESULTS

The consistency of the comparison between alternatives and criteria was examined and the average consistency ratio is 1.88494×10^{-16} which means that the comparison matrices will not be affected by the consistency and can be further processed.

Financial ratio is a useful tool for investors and analysts to evaluate the financial performance of a company.

In this study, we propose the use of the NDAHP method to evaluate the financial performance of five petrochemical companies in the year 2017 by taking into consideration 15 financial ratios namely sales growth, asset growth, shareholder's equity growth, accounts receivable turnover, fixed asset turnover, equity turnover, total assets turnover, debt ratio, debt to equity ratio, ROA, ROE, net profit margin, current ratio, quick ratio and cash ratio.

The results obtained corroborates the actual results obtained from the Edge financial newspaper. In the following, we provide explanations to support our results. It was found that HENGYUAN has the best financial performance among the five petrochemical companies with a weightage of 0.223344084. HENGYUAN performed well in the growth ratios, liquidity ratios and profitability ratios components in the petrochemical sector. The net profit of HENGYUAN in the financial year 2017 is RM930 million, which is a triple of the RM335 million net profit recorded in the previous financial year. This was mainly contributed by the 38.47% growth in revenue of the company from RM8.37 billion in 2016 to RM11.58 billion in 2017. HENGYUAN also recorded a higher production output thanks to the higher level of plant reliability in 2017. Several major hurricane and fire incidents that happened in the US had caused a number of major refineries in the US and Netherlands to shut down, and this had eventually caused an increase in global product prices. This higher profit margins for the refining was fully capitalized by HENGYUAN.

PETRONM recorded the second best financial performance among the five selected petrochemical companies with a weightage of 0.218360145. PETRONM is good in managing the financial leverage ratio in which the debt to equity ratio was constantly maintained at below one. A low debt to equity ratio indicates that the assets in PETRONM was fund by their equities instead of debt. The increase in oil prices and sales volume had contributed a RM405.2 million net profit in the financial year 2017. The sales volume increased by 9% from 2016 to 2017 which was contributed by the high demand of aviation and industrial sector sales of their Turbo Diesel Euro 5 and Blaze 100 Euro 4M products.

BARAKAH had a net loss of RM217 million in financial year 2017 compared with a RM14.53 million net profit made in financial year 2016. The revenue was decreased a lot in the fourth quarter of financial year 2017 due to the cost overruns in their on-going projects. Besides these, BARAKAH also had a major financial concern as their loan of RM38.53 million taken in 2017 had to be settled within 12 months, and overall there was a RM71.83 million negative cash flow recorded. All in all, BARAKAH had a negative growth ratio and profitability ratio for 2017, and the company was incurring losses.

SAPURA suffered from financial problems which were mainly due to material uncertainties which meant that the company was not confident enough to maintain its solvency. The current liabilities exceeded the current assets for the financial period ending June 30, 2017, and some major impairment needed to be made on their plants and equipment.

PERDANA was re-listed on the main board of the KLSE since the middle of August 2017. Their goal was to improve offshore support vessel (OSV) utilization rate in 2017, which was affected by decreasing oil prices in 2016, thus resulting in a low vessel utilization rate. This issue negatively impacted the financial performance of PERDANA, ad resulted in PERDANA having a negative growth ratio and profitability ratio. To improve on this situation and cut down on their recurring losses, PERDANA began having joint ventures with some major players in the petrochemical sector such as Petronas and Shell.

V. COMPARATIVE STUDIES

In this section, we present a brief but comprehensive comparative analysis of some of the recent works in this area and our proposed method. These recent approaches are applied to our case study related to the evaluation of financial performance of the five petrochemical companies done in Section 4.1. The existing methods that were chosen for this comparative studies are the neutrosophic Technique for Order Preference by Similarity to an Ideal Solution (NTOPSIS) by Biswas *et al.* [43], neutrosophic correlation coefficient (NCC) by Ye [26], neutrosophic cross-entropy (NCE) by Pramanik *et al.* [49], neutrosophic Evaluation based on Distance from Average Solution (NEDAS) by Peng and Liu [31] and the improved single valued neutrosophic weighted averaging geometric aggregation operator (ISVNWAGAO) by Mandal and Basu [50]. These five methods will be applied to our case study and the results obtained will be compared to the results obtained from our proposed NDAHP method in a bid to verify the effectiveness of our proposed MCDM method.

A. COMPARISON OF RESULTS OBTAINED THROUGH DIFFERENT METHODS

See Table 4.

B. DISCUSSION OF RESULTS

From the results obtained in Table 4, it can be observed that different rankings and optimal alternatives were obtained from the different methods that were compared. These differences are due to a number of reasons which are summarized briefly below:

(i) In the NDAHP method, we use the hierarchical principal in which we compare the pairwise values between the criteria and between the alternatives. The criteria weights are needed to be determined to rank the alternatives. However, we use the distance principal for NEDAS method in which the distance is between the alternatives and the average solution. This is the reason for the difference in the results obtained via the NDAHP and NEDAS methods.

(ii) The NDAHP method provides the weightage of different criteria under different alternatives. For example,

TABLE 4. The results obtained using different methods for the case study in Section 4.1.

Method	The final ranking
NTOPSIS [43]	HENGYUAN ≽ PETRONM ≽ PERDANA ≽ BARAKAH ≽SAPURA
NCC [26]	HENGYUAN ≽ PETRONM ≽ SAPURA ≽ BARAKAH ≽ PERDANA
NCE [49]	HENGYUAN ≽ PETRONM ≽ BARAKAH ≽ PERDANA ≽ SAPURA
NEDAS [31]	PETRONM ≽ HENGYUAN ≽ SAPURA≽ PERDANA ≽ BARAKAH
ISVNWAGAO [50]	HENGYUAN ≽ PETRONM ≽ SAPURA ≽ BARAKAH ≽ PERDANA
Our proposed NDAHP method	HENGYUAN ≽ PETRONM ≽ BARAKAH ≽ SAPURA≽ PERDANA
Actual ranking	HENGYUAN ≽ PETRONM ≽ BARAKAH ≽ SAPURA ≽ PERDANA

in our case study related to the ranking of the financial performance of five selected petrochemical companies, the NDAHP method provides the weightage of the different criteria for the companies HENGYUAN, PETRONM, BARAKAH, SAPURA and PERDANA. Decision makers can observe the comparative advantage of a company through the differences in the weightage of the different criteria. For examples, the weightage of sales growth under HENGYUAN is 0.20507543 which is much higher than the other companies, which makes it clear to the decision makers that HENGYUAN has the highest sales growth among the five petrochemical companies that are studied.

C. FURTHER VERIFICATION OF RESULTS USING SPEARMAN'S RANK AND PEARSON COEFFICIENT CORRELATION

Correlation is an analysis that examine the strength of the relationship between two variables. A rank test can help users to examine how strong are the relationship between two variables. The result obtained from the rank test is range from between −1 to 1. A value of −1 indicates that the two variables are negatively correlated, i.e. for every increase in the first variable, there will a certain amount of decrease in the second variable. A value of 1 indicates that the two variables are positively correlated, i.e. for every increase in the first variable, there will be a certain amount of increase in the second variable. When the result obtained is 0, it means that there is no relationship between the two variables.

Here, the correlation between the results obtained from the decision making methods used in Table 4 and the actual ranking will be examined to determine how strong is the relationship between the result obtained by decision making method and the actual ranking. The rank test used here will be the Spearman's rank correlation coefficient and Pearson correlation coefficient. The result of Spearman's rank correlation coefficient is determined by using the ranking while the Pearson correlation coefficient is determined by using weightage or the value used to determine the ranking. The formula used to determine the correlation between the two variables are as given below:

i) Spearman's rank correlation coefficient

$$\text{Correlation} = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n\left(n^2-1\right)} \tag{18}$$

ii) Pearson correlation coefficient

$$\text{Correlation} = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}\sqrt{n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2}} \tag{19}$$

The results obtained from the rank test are presented in Table 5.

TABLE 5. Correlation between the results of the ranking of financial performance.

Ranking	Spearman's rank correlation coefficient		Pearson correlation coefficient	
1	1.0	NDAHP	0.922317	NCC
2	0.9	NCC	0.91458	ISVNWAGAO
3	0.9	NCE	0.906758	NDAHP
4	0.9	ISVNWAGAO	0.888549	NTOPSIS
5	0.7	NTOPSIS	0.556343	NEDAS
6	0.6	NEDAS	-0.88332	NCE

From the results obtained from Spearman's rank correlation coefficient, it can be clearly seen that our proposed NDAHP method is perfectly correlated with the actual ranking while the NCC, NCE and ISVNWAGAO are slightly less correlated to the actual ranking compared to the NDAHP method, whereas the NTOPSIS and NEDAS methods have the worst correlation with the actual ranking.

From the results obtained from Pearson coefficient correlation, the results obtained from decision making methods of NDAHP, NCC, ISVNWAGAO and NTOPSIS are strongly correlated with the actual ranking. However, the results obtained from the NEDAS method has a very low consistency with the actual ranking, whereas the results obtained from the NCE method is negatively correlated with the actual ranking with a Pearson correlation coefficient of −0.88332.

It is therefore clearly proven that our proposed NDAHP method is the approach that produces results that are most consistent with the actual ranking.

VI. CONCLUSION AND REMARKS

The concluding remarks and the significant contributions that were made by the work in this paper are summarized below:

(i) A novel AHP method for the single-valued neutrosophic set (SVNS) model called the neutrosophic data analytic hierarchy process (NDAHP) is introduced. Our proposed NDAHP method holds the distinction of being the only AHP based method in literature that is designed to handle actual datasets i.e. data in the form of crisp values. This makes it novel and more comprehensive compared to existing AHP methods in literature as these are only able to handle subjective information in the form of opinions collected from the users and decision makers based on their individual opinions and experiences.

(ii) The NAHP method uses the opinions of experts to determine the relative importance of each criteria, whereas our proposed NDAHP method has a step incorporated into it which is able to convert the crisp values in actual datasets. Therefore, our proposed NDAHP method uses an objective weighting mechanism whereas all other existing versions of the AHP, fuzzy AHP and other fuzzy based AHP method in literature such as the NAHP and picture fuzzy AHP uses a subjective weighting method in the process of determining the weights of the criteria. Furthermore, the formula used in our method to convert the crisp values in the real-life datasets to single-valued neutrosophic numbers is also able to differentiate between the beneficial and non-beneficial criteria. This makes our proposed NDAHP method a very objective one as the weightage of the criteria and evaluation matrix are determined in an objective manner using the actual data collected for the problem, and hence will not change according to the opinions of the different decision makers which are subjective. This also makes it unnecessary to determine the consistency of the evaluation matrix as our method uses an objective weighting mechanism.

(iii) Through thorough analysis using the Spearman's rank correlation coefficient and Pearson's correlation coefficient tests, we have proven that our proposed NDAHP method produces results that are consistent with the actual results. This clearly indicates that our proposed method is not only an effective decision making algorithm but one that is also highly reliable and accurate.

ACKNOWLEDGMENTS

The authors would like to thank the Prof. Victor Albuquerque and the anonymous reviewers for their valuable comments and suggestions.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

[1] L. A. Zadeh, "Fuzzy sets," *Inf. Control*, vol. 8, no. 3, pp. 338–353, Jun. 1965.
[2] K. T. Atanassov, "Intuitionistic fuzzy sets," *Fuzzy Sets Syst.*, vol. 20, no. 1, pp. 87–96, 2019.
[3] M. B. Gorzalczany, "A method of inference in approximate reasoning based on interval-valued fuzzy sets," *Fuzzy Sets Syst.*," vol. 21, no. 1, pp. 1–17, Jan. 1987.
[4] K. Atanassov and G. Gargov, "Interval valued intuitionistic fuzzy sets," *Fuzzy Sets Syst.*, vol. 31, no. 3, pp. 343–349, 1965.
[5] W. L. Gau and D. J. Buehrer, "Vague sets," *IEEE Trans. Syst., Man, Cybern.*, vol. 23, no. 2, pp. 610–614, Apr. 2013.
[6] F. Smarandache, *A Unifying Field in Logics, Neutrosophy: Neutrosophic Probability, Set and Logic*. Rehoboth, NM, USA: American Research Press, 1999.
[7] V. Torra, "Hesitant fuzzy sets," *Int. J. Intell. Syst.*, vol. 25, no. 6, pp. 529–539, 2010.
[8] B. C. Cuong, "Picture fuzzy sets," *J. Comput. Sci. Cybern.*, vol. 30, no. 4, pp. 409–420, 2014.
[9] H. Wang, F. Smarandache, Y. Q. Zhang, and R. Sunderraman, "Single valued neutrosophic sets," *Multispace Multistruct.*, vol. 4, pp. 410–413, Jun. 2018.
[10] T. L. Saaty, "How to make a decision: The analytic hierarchy process," *Eur. J. Oper. Res.*, vol. 48, pp. 9–26, Sep. 1990.
[11] R. V. Vargas, *Using the Analytic Hierarchy Process (AHP) to Select and Prioritize Projects in a Portfolio*. Newtown Square, PA, USA: Project Manage. Inst., 2010.
[12] A. Ishizaka, "Comparison of fuzzy logic, AHP, FAHP and hybrid fuzzy AHP for new supplier selection and its performance analysis," *Int. J. Integr. Supply Manage.*, vol. 9, nos. 1–2, pp. 1–22, 2014.
[13] L. P. van Laarhoven and W. Pedrycz, "A fuzzy extension of Saaty's priority theory," *Fuzzy Sets Syst.*, vol. 11, nos. 1–3, pp. 229–241, 1983.
[14] A. T. Nguyen, L. D. Nguyen, L. L. Hoai, and C. N. Dang, "Quantifying the complexity of transportation projects using the fuzzy analytic hierarchy process," *Int. J. Project Manage.*, vol. 33, no. 6, pp. 1364–1376, Aug. 2015.
[15] A. Ruiz-Padillo, D. P. Ruiz, A. J. Torija, and A. Ramos-Ridao, "Selection of suitable alternatives to reduce the environmental impact of road traffic noise using a fuzzy multi-criteria decision model," *Environ. Impact Assessment Rev.*, vol. 61, pp. 8–18, Nov. 2016.
[16] A. Calabrese, R. Costa, N. Levialdi, and T. Menichini, "A fuzzy analytic hierarchy process method to support materiality assessment in sustainability reporting," *J. Cleaner Prod.*, vol. 121, pp. 248–264, May 2016.
[17] Z. Xu and H. Liao, "Intuitionistic fuzzy analytic hierarchy process," *IEEE Trans. Fuzzy Syst.*, vol. 22, no. 4, pp. 749–761, Aug. 2014.
[18] L. Abdullah, S. Jaafar, and I. Taib, "Intuitionistic fuzzy analytic hierarchy process approach in ranking of human capital indicators," *J. Appl. Sci.*, vol. 13, no. 3, pp. 423–429, 2013.
[19] L. Abdullah and L. Najib, "Sustainable energy planning decision using the intuitionistic fuzzy analytic hierarchy process: Choosing energy technology in Malaysia," *Int. J. Sustain. Energy*, vol. 35, no. 4, pp. 360–377, Apr. 2016.
[20] P. Kaur, "Selection of vendor based on intuitionistic fuzzy analytical hierarchy process," *Adv. Oper. Res.*, vol. 8, pp. 1–10, 2014. doi: 10.1155/2014/987690.
[21] H. Nguyen, "An application of intuitionistic fuzzy analytic hierarchy process in ship system risk estimation," *J. KONES*, vol. 23, no. 3, pp. 365–372, 2016.
[22] E. Mirzaei, Y. Minatour, H. Bonakdari, and A. Javadi, "Application of interval-valued fuzzy analytic hierarchy process approach," *Int. J. Eng.*, vol. 28, no. 3, pp. 387–395, 2015.
[23] L. Abdullah and L. Najib, "A new preference scale MCDM method based on interval-valued intuitionistic fuzzy sets and the analytic hierarchy process," *Soft Comput.*, vol. 20, no. 2, pp. 511–523, Feb. 2016.
[24] A. Fahmi, A. Derakhshan, and C. Kahraman, "Human resources management using interval valued intuitionistic fuzzy analytic hierarchy process," in *Proc. IEEE Int. Conf. Fuzzy Syst.*, Aug. 2015, pp. 1–5.
[25] N. M. Radwan, M. B. Senousy, and A. E. D. M. Riad, "Neutrosophic AHP multi criteria decision making method applied on the selection of learning management system," *Int. J. Advancements Comput. Technol.*, vol. 8, no. 5, pp. 95–105, 2016.
[26] J. Ye, "Multicriteria decision-making method using the correlation coefficient under single-valued neutrosophic environment," *Int. J. Gen. Syst.*, vol. 42, pp. 386–394, Mar. 2013.
[27] J. Ye, "Improved correlation coefficients of single valued neutrosophic sets and interval neutrosophic sets for multiple attribute decision making," *J. Intell. Fuzzy Syst.*, vol. 27, pp. 2453–2462, Jan. 2014.

[28] J. Ye, "Clustering methods using distance-based similarity measures of single-valued neutrosophic sets," *J. Intell. Syst.*, vol. 23, pp. 379–389, Dec. 2014.
[29] J. Ye, "Multiple attribute group decision-making method with completely unknown weights based on similarity measures under single valued neutrosophic environment," *J. Intell. Fuzzy Syst.*, vol. 27, no. 6, pp. 2927–2935, 2014.
[30] H. L. Huang, "New distance measure of single-valued neutrosophic sets and its application," *Int. J. Intell. Syst.*, vol. 31, no. 10, pp. 1021–1032, Oct. 2016.
[31] X. Peng and C. Liu, "Algorithms for neutrosophic soft decision making based on EDAS, new similarity measure and level soft set," *J. Intell. Fuzzy Syst.*, vol. 32, pp. 955–968, Jan. 2017.
[32] H. L. Yang, Z. L. Guo, Y. H. She, and X. W. Liao, "On single valued neutrosophic relations," *J. Intell. Fuzzy Syst.*, vol. 30, pp. 1045–1056, Feb. 2016.
[33] S. Broumi, F. Smarandache, M. Talea, and A. Bakali, "Single valued neutrosophic graphs: Degree, order and size," in *Proc. IEEE Int. Conf. Fuzzy Syst.*, Jul. 2016, pp. 2444–2451.
[34] S. Broumi, A. Bakali, M. Talea, and F. Smarandache, "Isolated single valued neutrosophic graphs," *Neutrosophic Sets Syst.*, vol. 11, pp. 74–78, May 2016.
[35] S. Broumi, M. Talea, A. Bakali, and F. Smarandache, "Single valued neutrosophic graphs," *J. New Theory*, vol. 10, pp. 86–101, Dec. 2016.
[36] S. Broumi, F. Smarandache, M. Talea, and A. Bakali, "An introduction to bipolar single valued neutrosophic graph theory," *Appl. Mech. Mater.*, vol. 841, pp. 184–191, Sep. 2016.
[37] S. Broumi, M. Talea, A. Bakali, and F. Smarandache, "On bipolar single valued neutrosophic graphs," *J. New Theory*, vol. 11, pp. 84–102, Mar. 2016.
[38] A. Hassan, M. A. Malik, S. Broumi, A. Bakali, M. Talea, and F. Smarandache, "Special types of bipolar single valued neutrosophic graphs," *Ann. Fuzzy Math. Inform.*, vol. 14, no. 1, pp. 55–73, Jul. 2017.
[39] Z. P. J. Tian, J. Wang, H. Y. Zhang, and J. Q. Wang, "Multi-criteria decision-making based on generalized prioritized aggregation operators under simplified neutrosophic uncertain linguistic environment," *Int. J. Mach. Learn. Cybern.*, vol. 9, no. 3, pp. 523–539, 2018.
[40] X. H. Wu, J. Wang, J. J. Peng, and X. H. Chen, "Cross-entropy and prioritized aggregation operator with simplified neutrosophic sets and their application in multi-criteria decision- making problems," *Int. J. Fuzzy Syst.*, vol. 18, no. 6, pp. 1104–1116, Dec. 2016.
[41] R. Sahin and A. Küçük, "Subsethood measure for single valued neutrosophic sets," *J. Intell. Fuzzy Syst.*, vol. 29, no. 2, pp. 525–530, 2015.
[42] J. Ye, "An extended TOPSIS method for multiple attribute group decision making based on single valued neutrosophic linguistic numbers," *J. Intell. Fuzzy Syst.*, vol. 28, no. 1, pp. 247–255, 2015.
[43] P. Biswas, S. Pramanik, and B. C. Giri, "TOPSIS method for multi-attribute group decision-making under single-valued neutrosophic environment," *Neural Comput. Appl.*, vol. 27, no. 3, pp. 727–737, 2016.
[44] G. Selvachandran, S. G. Quek, F. Smarandache, and S. Broumi, "An extended technique for order preference by similarity to an ideal solution (TOPSIS) with maximizing deviation method based on integrated weight measure for single-valued neutrosophic sets," *Symmetry*, vol. 10, no. 7, p. 236, 2018.
[45] P. Majumdar and S. K. Samanta, "On similarity and entropy of neutrosophic sets," *J. Intell. Fuzzy Syst.*, vol. 26, no. 3, pp. 1245–1252, 2014.
[46] M. Abdel-Basset, M. Mohamed, and F. Smarandache, "An extension of neutrosophic AHP-SWOT analysis for strategic planning and decision-making," *Symmetry*, vol. 10, no. 4, p. 116, Apr. 2018.
[47] M. V. Alava, D. Figueroa, B. Alcivar, and M. L. Vázquez, "Single valued neutrosophic numbers and analytic," *Neutrosophic Sets Syst.*, vol. 21, pp. 122–130, Sep. 2018.
[48] N. P. Nirmal and M. G. Bhatt, "Selection of automated guided vehicle using single valued neutrosophic entropy based on novel multi attribute decision making technique," in *New Trends in Neutrosophic Theory and Applications*. PANS Edition, 2016, pp. 105–114.
[49] S. Pramanik, S. Dalapati, S. Alam, F. Smarandache, and T. K. Roy, "NS-cross entropy-based MAGDM under single-valued neutrosophic set environment," *Information*, vol. 9, no. 2, p. 37, Feb. 2018.
[50] K. Mandal and K. Basu, "Multi criteria decision making method in neutrosophic environment using a new aggregation operator, score and certainty function," in *New Trends in Neutrosophic Theory and Applications*. PANS Edition, 2016, pp. 141–159.
[51] S. Jha, L. H. Son, R. Kumar, I. Priyadarshini, F. Smarandache, and H. V. Long, "Neutrosophic image segmentation with dice coefficients," *Measurement*, vol. 134, pp. 762–772, Feb. 2019.
[52] G. N. Nguyen, L. H. Son, A. S. Ashour, and N. Dey, "A survey of the state-of-the-arts on neutrosophic sets in biomedical diagnoses," *Int. J. Mach. Learn. Cybern.*, vol. 10, no. 1, pp. 1–13, Jan. 2019.
[53] S. Jha, R. Kumar, L. H. Son, J. M. Chatterjee, M. Khari, and N. Yadav, "Neutrosophic soft set decision making for stock trending analysis," *Evolving Syst.*, vol. 18, pp. 1–7, Jul. 2019.
[54] T. M. Tuan, P. M. Chuan, M. Ali, T. T. Ngan, M. Mittal, and L. H. Son, "Fuzzy and neutrosophic modeling for link prediction in social networks," *Evolving Syst.*, vol. 31, pp. 1–6, Aug. 2019.
[55] H. V. Long, M. Ali, L. H. Son, M. Khan, and D. N. Tu, "A novel approach for fuzzy clustering based on neutrosophic association matrix," *Comput. Ind. Eng.*, vol. 127, pp. 687–697, Jan. 2019.
[56] N. T. Thong, L. Q. Dat, L. H. Son, N. D. Hoa, M. Ali, and F. Smarandache, "Dynamic interval valued neutrosophic set: Modeling decision making in dynamic environments," *Comput. Ind.*, vol. 108, pp. 45–52, Jun. 2019.
[57] S. Jha, R. Kumar, L. H. Son, F. Chiclana, V. Puri, and I. Priyadarshini, "Neutrosophic approach for enhancing quality of signals," *Multimedia Tools Appl.*, vol. 45, pp. 1–32, Mar. 2019. doi: 10.1007/s11042-019-7375-0.
[58] N. T. K. Son, N. P. Dong, L. H. Son, and H. V. Long, "Towards granular calculus of single-valued neutrosophic functions under granular computing," *Multimedia Tools Appl.*, vol. 27, pp. 1–37, Mar. 2019. doi: 10.1007/s11042-019-7388-8.
[59] L. Q. Dat *et al.*, "Linguistic approaches to interval complex neutrosophic sets in decision making," *IEEE Access*, vol. 7, pp. 38902–38917, 2019. doi: 10.1109/ACCESS.2019.2902841.
[60] M. Ali, L. H. Son, M. Khan, and N. T. Tung, "Segmentation of dental X-ray images in medical imaging using neutrosophic orthogonal matrices," *Expert Syst. Appl.*, vol. 91, pp. 434–441, Jan. 2018.
[61] M. Ali, L. Q. Dat, L. H. Son, and F. Smarandache, "Interval complex neutrosophic set: Formulation and applications in decision-making," *Int. J. Fuzzy Syst.*, vol. 20, no. 3, pp. 986–999, 2018.
[62] M. Ali, L. H. Son, N. D. Thanh, and N. V. Minh, "A neutrosophic recommender system for medical diagnosis based on algebraic neutrosophic measures," *Appl. Soft Comput.*, vol. 71, pp. 1054–1071, Oct. 2018.
[63] M. Khan, L. H. Son, M. Ali, H. T. M. Chau, N. T. N. Na, and F. Smarandache, "Systematic review of decision making algorithms in extended neutrosophic sets," *Symmetry*, vol. 10, no. 8, p. 314, Aug. 2018.
[64] P. Ji, H.-Y. Zhang, and J.-Q. Wang, "A fuzzy decision support model with sentiment analysis for items comparison in e-commerce: The case study of PConline.com," *IEEE Trans. Syst., Man, Cybern. Syst.*, to be published. doi: 10.1109/TSMC.2018.2875163.
[65] Y. Y. Li, J. Q. Wang, and T. L. Wang, "A linguistic neutrosophic multi-criteria group decision-making approach with EDAS method," *J. Sci. Eng.*, vol. 44, no. 3, pp. 2737–2749, Mar. 2019.
[66] P. Ji, H. Y. Zhang, and J. Q. Wang, "Selecting an outsourcing provider based on the combined MABAC-ELECTRE method using single-valued neutrosophic linguistic sets," *Comput. Ind. Eng.*, vol. 120, pp. 429–441, Jun. 2018.
[67] P. Ji, H. Y. Zhang, and J. Q. Wang, "Fuzzy decision-making framework for treatment selection based on the combined QUALIFLEX-TODIM method," *Int. J. Syst. Sci.*, vol. 48, no. 14, pp. 3072–3086, 2017.
[68] J. Li, J. Q. Wang, and J. H. Hu, "Multi-criteria decision-making method based on dominance degree and BWM with probabilistic hesitant fuzzy information," *Int. J. Mach. Learn. Cybern.* doi: 10.1007/s13042-018-0845-2.
[69] S. M. Mousavi, H. Gitinavard, and A. Siadat, "A new hesitant fuzzy analytical hierarchy process method for decision-making problems under uncertainty," in *Proc. IEEE Int. Conf. Ind. Eng. Manage.*, Dec. 2014, pp. 622–626.
[70] H. Gitinavard and M. A. Shirazi, "An extended intuitionistic fuzzy modified group complex proportional assessment approach," *J. Ind. Syst. Eng.*, vol. 11, no. 3, pp. 229–246, 2018.
[71] S. Ebrahimnejad, H. Gitinavard, and S. Sohrabvandi, "A new extended analytical hierarchy process technique with incomplete interval-valued information for risk assessment in IT outsourcing," *Int. J. Eng.*, vol. 30, no. 5, pp. 739–748, 2017.
[72] H. Gitinavard, M. S. Pishvaee, and F. Jalalvand, "A hierarchical multi-criteria group decision-making method based on TOPSIS and hesitant fuzzy information," *Int. J. Appl. Decis. Sci.*, vol. 10, no. 3, pp. 213–232, 2017.

DESMOND JUN YI TEY is currently pursuing the degree with UCSI University, Kuala Lumpur, Malaysia, in the area of actuarial science. This research is a part of his undergraduate research project.

YEE FEI GAN is currently pursuing the degree with UCSI University, Kuala Lumpur, Malaysia, in the area of actuarial science. This research is a part of her undergraduate research project.

GANESHSREE SELVACHANDRAN received the B.Sc. degree (Hons.) in mathematics and the M.Sc. and Ph.D. degrees in pure mathematics from the National University of Malaysia (UKM). She has nine years of teaching experience. She is currently an Associate Professor with the Faculty of Business and Information Science, UCSI University, Kuala Lumpur, Malaysia. She has published close to 50 research articles in various international journals and has presented many papers at national and international conferences. Her areas of interests include fuzzy computing, multi-criteria decision making (MCDM), soft computing, neutrosophic set theory, applications of fuzzy and soft computing in engineering, economics and pattern recognition, as well as fuzzy algebra and hyperalgebra.

SHIO GAI QUEK received the B.Edu. degree in mathematics and the Ph.D. degree in pure mathematics from Universiti Malaya (UM), Malaysia. He has four years of teaching experience. He is currently a Lecturer in mathematics with the UCSI College, Kuala Lumpur, Malaysia. He has published several research articles in journals and conferences. His areas of interests include fuzzy algebraic and hyperalgebraic theory, fuzzy computing, soft computing and applications of fuzzy computing in engineering, decision-making, and robotics.

FLORENTIN SMARANDACHE received the M.Sc. degree in mathematics and computer science from the University of Craiova, Romania, and the Ph.D. degree in mathematics from the State University of Kishinev, and held the post-doctoral position in applied mathematics from the Okayama University of Sciences, Japan. He is currently a Professor of mathematics with the University of New Mexico, USA. He has been the Founder of neutrosophic set, logic, probability and statistics, since 1995, and has published over 100 papers on neutrosophic physics, superluminal and instantaneous physics, unmatter, absolute theory of relativity, redshift and blueshift due to the medium gradient and refraction index besides the Doppler effect, paradoxism, outerart, neutrosophy as a new branch of philosophy, law of included multiple-middle, degree of dependence and independence between the neutrosophic components, refined neutrosophic over-under-off-set, neutrosophic overset, neutrosophic triplet and duplet structures, DSmT, and so on to many peer-reviewed international journals and many books and he presented papers and plenary lectures to many international conferences around the world.

LE HOANG SON received the Ph.D. degree in mathematics (informatics) from the VNU University of Science, Vietnam National University (VNU), in 2013. He has been promoted to Associate Professor in information technology, since 2017. He was a Senior Researcher and the Vice Director with the Center for High Performance Computing, VNU University of Science, VNU, from 2007 to 2018. Since 2018, he has been the Head of the Department of Multimedia and Virtual Reality, VNU Information Technology Institute, VNU. His major fields include artificial intelligence, data mining, soft computing, fuzzy computing, fuzzy recommender systems, and geographic information systems. He is a member of the International Association of Computer Science and Information Technology (IACSIT), the Vietnam Society for Applications of Mathematics (Vietsam), and the Key Laboratory of Geotechnical Engineering and Artificial Intelligence in University of Transport Technology (Vietnam). He serves as an Editorial Board of *Applied Soft Computing* (ASOC, in SCIE), the *International Journal of Ambient Computing and Intelligence* (IJACI, in SCOPUS), and the *Vietnam Journal of Computer Science and Cybernetics* (JCC). He is an Associate Editor of the *Journal of Intelligent and Fuzzy Systems* (JIFS, in SCIE), the IEEE ACCESS (in SCIE), *Neutrosophic Sets and Systems* (NSS), *Vietnam Research and Development on Information and Communication Technology* (RD-ICT), the *VNU Journal of Science: Computer Science and Communication Engineering* (JCSCE), and *Frontiers in Artificial Intelligence*.

MOHAMED ABDEL-BASSET received the B.Sc. degree in information systems and technology and the M.Sc. and Ph.D. degrees in operations researcher and decision support from the Faculty of Computers and Informatics, Zagazig University, Egypt. He is working on the application of multi-objective and robust meta-heuristic optimization techniques. He has published more than 150 articles in international journals and conference proceedings. His current research interests are optimization, operations research, data mining, computational intelligence, applied statistics, decision support systems, robust optimization, engineering optimization, multi-objective optimization, swarm intelligence, evolutionary algorithms, and artificial neural networks. He holds the program chair in many conferences in the fields of decision making analysis, big data, optimization, complexity and the internet of things, as well as editorial collaboration in some journals of high impact. He is also an/a Editor/reviewer in different international journals and conferences.

HOANG VIET LONG received the Ph.D. Diploma degree in computer science from the Hanoi University of Science and Technology, in 2011, where he defended his thesis in fuzzy and soft computing field. He is currently the Head of the Faculty of Information Technology, People's Police University of Technology and Logistics, Bac Ninh, Vietnam. He is also a Researcher with the Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam. He has been promoted to Associate Professor in information technology, since 2017. Recently, he has been concerning in cybersecurity, machine learning, bitcoin and block chain and published more than 20 papers in ISI-covered journal.