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A Border Approximation Area Approach Considering Bipolar Neutrosophic Linguistic Variable for Sustainable Energy Selection

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Abstract: In the last few decades, the computational methods under Multi-Criteria Decision-Making (MCDM) have experienced significant growth in research interests from various scientific communities. Multi-Attributive Border Approximation area Comparison (MABAC) is one of the MCDM methods where its computation procedures are based on distances and areas, and able to express a complex decision systematically. Previous literature have suggested the combination of MABAC with fuzzy sets, in which this combination is used to solve problems that are characterized by uncertain and incomplete information. Differently from the fuzzy MABAC, which directly used single membership, this paper proposes bipolar neutrosophic MABAC of which the positive and negative of truth, indeterminate and false memberships of bipolar neutrosophic set are introduced to enhance decision in sustainable energy selection. Fourteen criteria and seven alternatives of sustainable energy are the main MCDM structures that need to be solved using the proposed method. A group of experts were invited to provide rating of performance values of criteria and alternatives of sustainable energy problem using a bipolar neutrosophic linguistic scale. The distances of alternatives from the Border Approximation Area of bipolar neutrosophic MABAC are the main output of the proposed method prior to making the final decision. The computational results show that ‘Biomass’ is the optimal alternative to sustainable energy selection. Comparable results are also presented to check the consistency of the proposed method.

Keywords: decision making; bipolar neutrosophic set; MABAC; sustainable energy; border approximation area

1. Introduction

Sustainable energy is one of the global goals in the 2030 Agenda for Sustainable Development, and plays a key role in ensuring accessibility to affordable, reliable, sustainable and modern energy for all [1]. In other words, sustainable energy plays an important role in the economic growth and social development of a country and the living quality of people [2,3]. The sector of sustainable energy has to balance energy production and consumption, and has no or minimal, negative impact on the environment, but at the same time, gives the opportunity for a country to increase the productivity of its social and economic activities [4]. Under a biophysical and ecological view, energy plays an important role in income determination and economic activities in which these activities will be significantly affected by changes in every energy consumption [5]. According to Qi et al. [6], efficient use of energy and sustainable production of energy industry are one of the most important factors for emerging economies. A study on impact of energy on productivity suggests that is not possible without energy use for the traditional growth model, which is treating energy as a secondary factor

and production [7]. In the history of development economics, energy is central to productivity, social development and improved quality of life for all countries particularly for jobs, security, food production or income generation.

Nowadays, debate continues about the best strategies in dealing with the energy crisis. Worldwide energy crisis simultaneously threatens climate change, greenhouse effects, toxic pollutants and air pollutants, especially for developing countries [3]. The main environmental problem is the emission of toxic chemical pollutants, greenhouse gases like CO₂ and other air pollutants that may cause climate change and environmental pollutants of air, land and water. These environmental problems would bring negative impacts on the health and the living quality of humans [8,9]. Due to the growing evidence toward the effects of the environment, the management of waste, energy, and resources take special attention to investigate especially effect on the sustainable performance manufacturing firms [10]. Climate change is manifested in higher average global temperature, rising global mean sea levels, melting ice caps and increased intensity and frequency of extreme weather events [11]. Human activities and greenhouse gas (GHG) emissions, like carbon dioxide, methane oxide and nitrous oxide in the atmosphere contribute global warming [12]. The world's energy is currently produced and consumed in ways that could not be sustained if technology remained constant and if overall quantities were to increase substantially [13]. One of the possible strategies to deal with energy crisis is to revisit factors and sources of energy that become determinants in energy management. For example, rapid growth of the economy needs plenty of energy resources to support the industrial sector and to enhance productivity. The increasing demands of energy can also be associated with industrialization, population growth and urbanization [14]. Apart from social and economic factors, there are many tangible and intangible factors that can be associated with the energy demand. Therefore, energy management is a multi-criteria problem where many criteria need to be considered in discussing the demand and also sources of sustainable energy. However, the evidence for the relationship between criteria and alternatives of sustainable energy is inconclusive.

A more practical solution for this problem is solving sustainable energy management using a multi-criteria decision-making (MCDM) approach. MCDM methods are particularly useful when facing the problem of determining or expressing preferences, and when decisions have to be made based on several contradictory indicators or factors of competing for importance. Then, MCDM methods help to reconcile contradictory questions and choose the best solution based on the selected criteria or alternatives. Very often, decision-makers face the problem of selecting alternatives that have conflicting criteria. Selecting sustainable energy sources is a particular MCDM problem where many competing intangible criteria need to be considered. In this paper, sustainable energy decision-making, using a MCDM method, provides a technique to eliminate the difficulty in selecting sustainable energy sources. The energy related issues and MCDM is not uncommonly seen in many literature. The successful implementation of MCDM method can be seen in energy optimization modelling [15], energy planning and selection [16–19], and alternative of bioenergy systems [20]. In short, MCDM methods have been increasingly used to deal with various decision problems including energy management. However, few of the literature have been able to draw a conclusive MCDM method particularly for sustainable energy selection.

There are many MCDM methods that are available in literature, and the multi-attributive border approximation area comparison (MABAC) method is one of them. The MABAC is a distance based MCDM method proposed by a group of researchers in Belgrade [21]. The MABAC method is a particularly pragmatic and reliable tool for rational decision-making because it has simple computation and stable solutions. This basic principle of MABAC is defined by the distance of the criterion function of each alternative from the border approximation area (BAA), and divides the performance of each criterion function into Upper Approximation Area (UAA), containing ideal alternatives and Lower Approximation Area (LAA) containing anti-ideal alternatives. Performance of alternatives is subjected to the proportion of UAA and LAA, hence the MABAC method is germane to be used to select the optimal alternative.

Before proceeding to discuss various extensions of MABAC based methods, it is good to recall the fuzzy sets and their affiliations in which this set has been successfully combined with many MCDM methods. The fuzzy set theory has been introduced in many MCDM methods to solve problems with uncertain information. Zadeh [22] proposed the concept of a fuzzy set to deal with problems that are characterized by imprecision, vagueness, and uncertainty. The gradation of membership of fuzzy sets is said to be able to imitate thinking and perception using linguistic information. Then, the intuitionistic fuzzy set (IFS) was proposed by Atanassov [23] as a generalization of the fuzzy set, which is considered membership degree and non-membership degree. In the real environment, IFS can deal only with vague information but not incongruous information. Owing to this, Atanassov and Gargov [24], generalized the IFS in the spirit of ordinary interval-valued fuzzy sets (IVFS) and introduced the concept of interval-valued intuitionistic fuzzy sets (IVIFSs). Besides that, Zhang [25] extended a fuzzy set to the bipolar fuzzy set with the grade of membership from $[-1, 1]$. The membership grade $[-1, 0]$ is fairly fulfils the couched stand-property in the section while the membership grade $[0, 1]$ of a section shows that the section fairly fulfils the matter and the membership grade 0 of a section presents that the section is unrelated to the parallel property.

Having discussed the development of fuzzy sets, this section continues with another kind of set. The neutrosophic set was introduced by Smarandache [26] as extensions of the concept classic set, fuzzy set, intuitionistic fuzzy set and interval-valued intuitionistic set. Neutrosophic set is a part of neutrosophy, which is a branch of philosophy that studies the origin, nature and scope of neutralities as well as their interactions with different ideational spectra. There are three elements of neutrosophic which are truth membership (T), indeterminacy membership (I) and falsity membership (F). Each member value is a real standard or non-standard subset of the unit interval $]0^-, 0^+[$ in the neutrosophic set. Then, Wang et al. [27] proposed single-valued neutrosophic set (SVNS) that is an extension of neutrosophic set which takes the value from the subset of $[0, 1]$. There are many researchers that have paid particular attention on the T, I, F components which later lead to define a particular case of neutrosophic sets such as rough neutrosophic set [28], interval-valued neutrosophic sets [29], trapezoidal neutrosophic sets [30], multi-valued neutrosophic set [31], simplified neutrosophic sets [32], and bipolar neutrosophic sets [33].

Bipolarity refers to the propensity of the human mind to reason and make decisions on the basis of positive and negative effects [34]. Positive information is all about possible, satisfactory, permitted, desired or considered that being acceptable, while impossible, rejected or forbidden are negative information. In addition, positive preferences correspond to the wishes as they specify which objects are more desirable than others without rejecting those that do not meet the wishes but negative preferences correspond to the constraints as they specify which values or objects have to be rejected. In Chinese medicine, the concept of yin and yang are two sides in which yang is the masculine or positive side of a system and yin is the feminine or negative side of a system. It is believed that most of the human decision-making is based on double-sided or bipolar judgment thinking which is the positive side and negative side. Based on these premises, Deli et al. [33] extended the ideas of bipolar fuzzy sets and neutrosophic sets to bipolar neutrosophic sets in which positive membership degree, negative membership degree, and its operations were studied. Bipolar fuzzy sets are of great value to deal with uncertain real-life problems and prove to help in dealing with the positive, as well as the negative membership values. Thus, in this paper, we combine bipolar neutrosophic with MCDM method to enhance the decision by considering bipolarity judgements. In particular, this paper aims to propose a new bipolar neutrosophic MABAC where positive and negative memberships of T, I, F are combined with the MABAC. Furthermore, the effectiveness of the proposed method is applied to the case of sustainable energy selection.

To sum up, this paper proposes a new bipolar neutrosophic MABAC in which several key features arise from our proposed method. The first feature is the introduction of new linguistic variables using bipolar neutrosophic numbers. The second feature is the use of bipolar neutrosophic numbers to the MABAC method in which the direct relation matrix was aggregated using bipolar neutrosophic

weighted aggregation operator. Finally, this paper provides evidence on the feasibility of the proposed method in sustainable energy selection. This paper is organized as follows. In Section 2, we review the related research of MABAC. Section 3 briefly defines and describes some basic concept of neutrosophic set, single-valued neutrosophic set and bipolar neutrosophic set. In Section 4, we propose bipolar neutrosophic set for the MABAC method. A case study of sustainable energy selection is presented in Section 5. The comparative analysis is given in Section 6. Finally, we conclude the paper in Section 7.

2. Literature Review

There are many researchers who proposed various decision-making methods based on MABAC and applied in solving various fields. Pamučar and Ćirović [21], for example, proposed the application of new combination Decision Making Trial and Evaluation Laboratory (DEMATEL) with MABAC model to select the optimal transport handling units in the logistics center. Božanić et al. [35] presented the application of MABAC to support in making a decision on using forces in a defensive operation of Land Forces and formulation of a decision strategy. The combination of four tools; Geographic Information Systems, DEMATEL, Analytic Network Process and MABAC was proposed [36] to identify locations for the installation of wind farms, which will provide significant support to planners in the strategy for the development and management of wind energy. Xue et al. [37] introduced the MABAC approach for material selection problems with incomplete weight information under IVIFSs, Pythagorean fuzzy sets and MABAC applied by Peng and Yang [38] to a research and development project selection problem to find the best project. MABAC method, based on trapezoidal interval type-2 fuzzy numbers, proposed to select the most suitable candidate for a software company, which leads to hiring a system analysis engineer based on few attributes [39]. Recently, Xu et al. [40] applied the combination of heterogeneous criteria information and extended MABAC method in green supplier selection model.

The application of a hybrid model using the fuzzyficated Saaty's scale, the analytic hierarchy process method and MABAC method was developed to select the locations for the development of laying-up positions by Božanić et al. [41]. Then, Debnath et al. [42] used several decision-making aspects in the unique mechanism of MABAC method. A novel hybrid method encompassing factor relationship and MABAC proposed by Chatterjee et al. [43] for selection and evaluation of non-traditional machining processes. For assessing and prioritizing medical tourism destinations in an uncertain environment, the analytic hierarchy process (AHP) and MABAC method in a rough number proposed [44]. Sharma et al. [45] modified rough AHP-MABAC model for ranking the Indian railway stations based on the decision maker's performance. The hybrid of fuzzy AHP method and fuzzy MABAC proposed in the selection of the locations for river crossing by tanks with a deep wading technique [46]. An interval type-2 fuzzy numbers similarity based MABAC presented by Hu et al. [47] for selection of the suitable medical treatment under a patient-centered environment.

Ali et al. [48] introduced the concept of neutrosophic cubic set and defined some new notions neutrosophic set to apply in pattern recognition problems. The simplified neutrosophic sets have been proposed by Peng et al. [32] for addressing issues with a set of specific numbers. Radwan et al. [49] developed neutrosophic AHP and applied numerical experiment for learning management system selection. To solve green product design selection problems, Tian et al. [50] simplified neutrosophic linguistic information and developed an innovative multi-criteria group decision-making approach that incorporates power aggregating operators and TOPSIS based QUALIFLEX method. Ye [51] presented the concepts of neutrosophic linear equations and applied the effectiveness of handling the indeterminate traffic flow problem. The neutrosophic set for the DEMATEL method designed by Abdel-Basset et al. [52] to analyze and determine the factors influencing the selection of supply chain management suppliers. Awang et al. [53] proposed Shapley weighting vector based on a single-valued neutrosophic aggregating operator in the DEMATEL method and applied the proposed method to the coastal erosion problem. The two types of single-valued neutrosophic covering rough set models introduced by Wang and Zhang [54].

In recent years, there are many researchers developed and applied bipolar neutrosophic sets to solve MCDM problems. Deli et al. [33] developed a bipolar neutrosophic MCDM approach based on bipolar neutrosophic weighted average and geometric operators including score, uncertainty and accuracy functions. TOPSIS method with bipolar neutrosophic information proposed by Dey et al. [55] to solve MCDM problems. Uluçays et al. [56] introduced some similarity measures for bipolar neutrosophic sets and their application to multiple criteria decision making. The bipolar neutrosophic projection, bidirectional projection and hybrid projection measured for solving MCDM problems [57]. Then, Pramanik et al. [58] also defined the TODIM method in bipolar neutrosophic environment to handle multi-attribute group decision-making problems and showed applicability and effectiveness of the proposed method. Bipolar neutrosophic TOPSIS method and bipolar neutrosophic ELECTRE-I method was proposed by Akram et al. [59] and applied to solve MCDM problems where the best possible alternative was selected.

3. Preliminaries

This section introduces the definitions and some concepts related to neutrosophic set, single valued neutrosophic set and bipolar neutrosophic set.

3.1. Neutrosophic Set

Definition 1 [26] Let X be a space of points (objects) with generic elements in X denoted by x , then, the neutrosophic set (N) in X is defined as,

$$N = \{x, \langle T_N(x), I_N(x), F_N(x) \rangle : x \in X\}$$

which is characterized by a truth-membership function $T_N(x) \rightarrow]0^-, 1^+[$ an indeterminacy-membership function $I_N(x) \rightarrow]0^-, 1^+[$ and a falsity-membership function $F_N(x) \rightarrow]0^-, 1^+[$. There is no restriction on the sum of $T_N(x)$, $I_N(x)$ and $F_N(x)$ so $0^- \leq \sup T_N(x) + \sup I_N(x) + \sup F_N(x) \leq 3^+$.

3.2. Single Valued Neutrosophic Set

Definition 2 [27] Let X be universal space of points with a generic element in X denoted by x . A single valued neutrosophic set (S) in X is defined as:

$$S = \{x, \langle T_S(x), I_S(x), F_S(x) \rangle : x \in X\}$$

which is characterized by a truth-membership function $T_S(x) \rightarrow [0, 1]$, an indeterminacy-membership function $I_S(x) \rightarrow [0, 1]$ and a falsity-membership function $F_S(x) \rightarrow [0, 1]$. There is no restriction on the sum of $T_S(x)$, $I_S(x)$ and $F_S(x)$, so $0 \leq \sup T_S(x) + \sup I_S(x) + \sup F_S(x) \leq 3$.

3.3. Bipolar Neutrosophic Set

Definition 3 [33] Let X be a universal space of points. A bipolar neutrosophic set (B) in X is defined as an object of the form:

$$B = \{x, \langle T_B^+(x), I_B^+(x), F_B^+(x), T_B^-(x), I_B^-(x), F_B^-(x) \rangle : x \in X\}$$

where $T^+, I^+, F^+ : X \rightarrow [0, 1]$ and $T^-, I^-, F^- : X \rightarrow [-1, 0]$ The positive membership degree $T^+(x)$, $I^+(x)$, $F^+(x)$ denotes a truth-membership, an indeterminacy-membership and a falsity-membership of an element $x \in X$ corresponding to a bipolar neutrosophic set (B) while the negative membership degree $T^-(x)$, $I^-(x)$, $F^-(x)$ denotes the truth-membership, an indeterminacy-membership and a falsity-membership of an element $x \in X$ to some implicit counter property corresponding to B .

3.4. The Properties of Bipolar Neutrosophic Set

Definition 4 [33] Let $B_1 = \{x, \langle T_1^+(x), I_1^+(x), F_1^+(x), T_1^-(x), I_1^-(x), F_1^-(x) \rangle\}$ and $B_2 = \{x, \langle T_2^+(x), I_2^+(x), F_2^+(x), T_2^-(x), I_2^-(x), F_2^-(x) \rangle\}$ be two bipolar neutrosophic sets. Then, the inequality property defined as $B_1 \subseteq B_2$ if and only if $T_1^+(x) \leq T_2^+(x), I_1^+(x) \leq I_2^+(x), F_1^+(x) \geq F_2^+(x)$ and $T_1^-(x) \geq T_2^-(x), I_1^-(x) \geq I_2^-(x), F_1^-(x) \leq F_2^-(x)$ for all $x \in X$.

Definition 5 [33] Let $B_1 = \{x, \langle T_1^+(x), I_1^+(x), F_1^+(x), T_1^-(x), I_1^-(x), F_1^-(x) \rangle\}$ and $B_2 = \{x, \langle T_2^+(x), I_2^+(x), F_2^+(x), T_2^-(x), I_2^-(x), F_2^-(x) \rangle\}$ be two bipolar neutrosophic sets. Then, the equality property defined as $B_1 = B_2$ if and only if $T_1^+(x) = T_2^+(x), I_1^+(x) = I_2^+(x), F_1^+(x) = F_2^+(x)$ and $T_1^-(x) = T_2^-(x), I_1^-(x) = I_2^-(x), F_1^-(x) = F_2^-(x)$ for all $x \in X$.

Definition 6 [33] Let $B_1 = \{x, \langle T_1^+(x), I_1^+(x), F_1^+(x), T_1^-(x), I_1^-(x), F_1^-(x) \rangle\}$ and $B_2 = \{x, \langle T_2^+(x), I_2^+(x), F_2^+(x), T_2^-(x), I_2^-(x), F_2^-(x) \rangle\}$ be two bipolar neutrosophic sets. Then, the union defined as: $(B_1 \cup B_2) = \left(\begin{array}{l} \max(T_1^+(x), T_2^+(x)), \frac{I_1^+(x) + I_2^+(x)}{2}, \min(F_1^+(x), F_2^+(x)), \\ \min(T_1^-(x), T_2^-(x)), \frac{I_1^-(x) + I_2^-(x)}{2}, \max(F_1^-(x), F_2^-(x)) \end{array} \right)$ for all $x \in X$.

Definition 7 [33] Let $B_1 = \{x, \langle T_1^+(x), I_1^+(x), F_1^+(x), T_1^-(x), I_1^-(x), F_1^-(x) \rangle\}$ and $B_2 = \{x, \langle T_2^+(x), I_2^+(x), F_2^+(x), T_2^-(x), I_2^-(x), F_2^-(x) \rangle\}$ be two bipolar neutrosophic sets. Then, their intersection is defined as: $(B_1 \cap B_2) = \left(\begin{array}{l} \min(T_1^+(x), T_2^+(x)), \frac{I_1^+(x) + I_2^+(x)}{2}, \max(F_1^+(x), F_2^+(x)), \\ \max(T_1^-(x), T_2^-(x)), \frac{I_1^-(x) + I_2^-(x)}{2}, \min(F_1^-(x), F_2^-(x)) \end{array} \right)$ for all $x \in X$.

Definition 8 [33] Let $B = \{x, \langle T_B^+(x), I_B^+(x), F_B^+(x), T_B^-(x), I_B^-(x), F_B^-(x) \rangle : x \in X\}$ be a bipolar neutrosophic set in X . Then, the complement of B is denoted by B^c and is defined by $T_{Ac}^+(x) = \{1^+\} - T_A^+(x), I_{Ac}^+(x) = \{1^+\} - I_A^+(x), F_{Ac}^+(x) = \{1^+\} - F_A^+(x)$ and $T_{Ac}^-(x) = \{1^-\} - T_A^-(x), I_{Ac}^-(x) = \{1^-\} - I_A^-(x), F_{Ac}^-(x) = \{1^-\} - F_A^-(x)$ for all $x \in X$.

Definition 9 [33] Let $\tilde{b}_1 = \langle T_1^+, I_1^+, F_1^+, T_1^-, I_1^-, F_1^- \rangle$ and $\tilde{b}_2 = \langle T_2^+, I_2^+, F_2^+, T_2^-, I_2^-, F_2^- \rangle$ two bipolar neutrosophic numbers, then

- i. $\lambda \tilde{b}_1 = \langle 1 - (1 - T_1^+)^{\lambda}, (I_1^+)^{\lambda}, (F_1^+)^{\lambda}, -(-T_1^-)^{\lambda}, -(-I_1^-)^{\lambda}, -(1 - (1 - (F_1^-)))^{\lambda} \rangle$
- ii. $\tilde{b}_1^{\lambda} = \langle (T_1^+)^{\lambda}, 1 - (1 - I_1^+)^{\lambda}, 1 - (1 - F_1^+)^{\lambda}, -(1 - (1 - (-T_1^-)))^{\lambda}, -(-I_1^-)^{\lambda}, -(-F_1^-)^{\lambda} \rangle$
- iii. $\tilde{b}_1 + \tilde{b}_2 = \langle T_1^+ + T_2^+ - T_1^+ T_2^+, I_1^+ I_2^+, F_1^+ F_2^+, -T_1^- T_2^-, -(-I_1^- - I_2^- - I_1^- I_2^-), -(F_1^- - F_2^- - F_1^- F_2^-) \rangle$
- iv. $\tilde{b}_1 \tilde{b}_2 = \langle T_1^+ T_2^+, I_1^+ + I_2^+ - I_1^+ I_2^+, F_1^+ + F_2^+ - F_1^+ F_2^+, -(-T_1^- - T_2^- - T_1^- T_2^-), -I_1^- I_2^-, -F_1^- F_2^- \rangle$

where $\lambda > 0$.

Definition 10 [33] Let $\tilde{b}_1 = \langle T_1^+, I_1^+, F_1^+, T_1^-, I_1^-, F_1^- \rangle$ be a bipolar neutrosophic number. Then, the score function $s(\tilde{b}_1)$, accuracy function $a(\tilde{b}_1)$ and certainty function $c(\tilde{b}_1)$ are defined as follows:

- i. $s(\tilde{b}_1) = (T_1^+ + 1 - I_1^+ + 1 - F_1^+ + 1 + T_1^- - I_1^- - F_1^-)/6$
- ii. $a(\tilde{b}_1) = T_1^+ - F_1^+ + T_1^- - I_1^-$
- iii. $c(\tilde{b}_1) = T_1^+ - F_1^+$

3.5. Fundamental of MABAC

Definition 11 [21] Alternative could belong to the border approximation area ($\tilde{G}$) upper approximation area ($\tilde{G}^+$) or lower approximation area ($\tilde{G}^-$) that is $A_i \in \{\tilde{G} \vee \tilde{G}^+ \vee \tilde{G}^-\}$. The $\tilde{G}^+$ presents the area where ideal

alternative is located A^+ while the $\tilde{G}^-$ presents the area where the anti-ideal alternative is located A^- . Illustration of areas and alternatives are shown in Figure 1.

Figure 1. Presentation of $\tilde{G}$, $\tilde{G}^+$ and $\tilde{G}^-$ approximation areas.

Definition 12 [21] The belonging of alternative to the approximation area is $\tilde{G}$, $\tilde{G}^+$ or $\tilde{G}^-$ determined using the equation:

$$A_i \in \begin{cases} \tilde{G}^+, \tilde{q} > 0 \\ \tilde{G}, \tilde{q} = 0 \\ \tilde{G}^-, \tilde{q} < 0 \end{cases}$$

where $\tilde{q}$ are the distance from the approximation border area ($\tilde{q}_{ij}$). According to the principle of MABAC method, we know that if $\tilde{q} = 0$, the alternative could belong to the $\tilde{G}$; if $\tilde{q} > 0$, the alternative belongs to the $\tilde{G}^+$ and if $\tilde{q} < 0$, the alternative belongs to the $\tilde{G}^-$. The alternative (A_i) should belong to the $\tilde{G}^+$ by as many criteria as possible to be selected the best one from the set.

4. Proposed Bipolar Neutrosophic MABAC

In this section, computational procedures of the proposed method are presented. The proposed method comprises three stages where in the first stage, the new linguistic variable for bipolar neutrosophic set is proposed. In the second stage, we utilize the bipolar neutrosophic weighted aggregation operators to aggregate the direct relation matrix and deneutrosophication for bipolar neutrosophic is introduced to find the crisp number. Finally, in the third stage, we rank alternatives based on distances between alternatives and BAA. Figure 2 presents the overall framework and stages of the proposed method.

Figure 2. Framework of the proposed method.

4.1. Stage 1: Linguistic Variable for Bipolar Neutrosophic

Step 1. Construct bipolar neutrosophic linguistic variables.

Linguistic variable is a variable whose values are not numbers but words or sentences in a natural or artificial language [60]. In the early days, most research used to adopt 3-scale linguistic variables

and 4-scale linguistic variables. For example, Gabus and Fontela [61] adopted a 4-scale linguistic variable that was used for the DEMATEL method. However, the other linguistic variables such as the 5-scale linguistic variable or even the 8-scale linguistic variable have been used by many researchers. In the case of using single-valued neutrosophic numbers (SVNNs), Biswas et al. [62] used five-scale linguistic variables in a TOPSIS based research. Table 1 shows the linguistic variable and its respective single-valued neutrosophic number.

Table 1. Linguistic variable and its respective single-valued neutrosophic number [59].

Influences Scores	Linguistic Variable	SVNNs
0	No Influence	$\langle 0.10, 0.80, 0.90 \rangle$
1	Low Influence	$\langle 0.35, 0.60, 0.70 \rangle$
2	Medium Influence	$\langle 0.50, 0.40, 0.45 \rangle$
3	High Influence	$\langle 0.80, 0.20, 0.15 \rangle$
4	Very High Influence	$\langle 0.90, 0.10, 0.10 \rangle$

Information in Table 1 are become the basis of constructing the new linguistic variable of bipolar neutrosophic number. The new bipolar neutrosophic linguistic variable is shown in Table 2.

Table 2. The new bipolar neutrosophic linguistic variable.

Scores	Linguistic Variable	Scale
0	Very Poor	$\langle 0.10, 0.10, 0.90, -0.10, -0.10, -0.90 \rangle$
1	Poor	$\langle 0.35, 0.20, 0.70, -0.35, -0.20, -0.70 \rangle$
2	Medium	$\langle 0.50, 0.40, 0.45, -0.50, -0.40, -0.45 \rangle$
3	Good	$\langle 0.80, 0.60, 0.15, -0.80, -0.60, -0.15 \rangle$
4	Very Good	$\langle 0.90, 0.80, 0.10, -0.90, -0.80, -0.10 \rangle$

In Definition 3 [33] (see page 5), let $X = \{x_1, x_2, x_3, x_4, x_5\}$ is the linguistic variable, then

$$B = \left\{ \begin{array}{l} \langle x_1, 0.10, 0.10, 0.90, -0.10, -0.10, -0.90 \rangle \\ \langle x_2, 0.35, 0.20, 0.70, -0.35, -0.20, -0.70 \rangle \\ \langle x_3, 0.50, 0.40, 0.45, -0.50, -0.40, -0.45 \rangle \\ \langle x_4, 0.80, 0.60, 0.15, -0.80, -0.60, -0.15 \rangle \\ \langle x_5, 0.90, 0.80, 0.10, -0.90, -0.80, -0.10 \rangle \end{array} \right\}$$

is a bipolar neutrosophic subset of X where $T^+, I^+, F^+ : X \rightarrow [0, 1]$ and $T^-, I^-, F^- : X \rightarrow [-1, 0]$.

These numbers comply the conditions $0.10, 0.10, 0.90 \rightarrow [0, 1]$ and $-0.10, -0.10, -0.90 \rightarrow [-1, 0]$.

To provide evidences of the proposed numbers, some properties of numbers are examined as follows:

- Inequality Property** The linguistic variable of bipolar neutrosophic is verified using Definition 4 [33]. Let $B_1 = \{\langle x_1, 0.10, 0.10, 0.90, -0.10, -0.10, -0.90 \rangle\}$ and $B_2 = \{\langle x_2, 0.35, 0.20, 0.70, -0.35, -0.20, -0.70 \rangle\}$ are two bipolar neutrosophic numbers. Then, the inequality property is defined as $B_1 \subseteq B_2$ if and only if $0.10 \leq 0.35, 0.10 \leq 0.20, 0.90 \geq 0.70$ and $-0.10 \geq -0.35, -0.10 \geq -0.20, -0.90 \leq -0.70$ for all $x \in X$
- Complement Property** The linguistic variable of bipolar neutrosophic is verified using Definition 5 [33]. Let $X = \{x_1, x_2, x_3, x_4, x_5\}$. Then, B be a bipolar neutrosophic set in X . Therefore, we have a complement of B denoted by B^c verified as:

$$B^c = \left\{ \begin{array}{l} \langle x_1, 0.90, 0.90, 0.10, -0.90, -0.90, -0.10 \rangle \\ \langle x_2, 0.65, 0.80, 0.30, -0.65, -0.80, -0.30 \rangle \\ \langle x_3, 0.50, 0.60, 0.55, -0.50, -0.60, -0.55 \rangle \\ \langle x_4, 0.20, 0.40, 0.85, -0.20, -0.40, -0.85 \rangle \\ \langle x_5, 0.10, 0.20, 0.90, -0.10, -0.20, -0.90 \rangle \end{array} \right\}$$

for all $x \in X$.

Finally, based on the above properties, we propose the new linguistic variable of bipolar neutrosophic number for MABAC method using the 5-scale linguistic variable of “very poor” until “very good”. Table 2 presents the new linguistic variable and its respective bipolar neutrosophic numbers.

The defined linguistic variable is intended to be used in MABAC. Aggregation and deneutrosophication of the proposed method is presented as follows:

4.2. Stage 2: Aggregation and Deneutrosophication of Bipolar Neutrosophic

Step 2. Aggregated direct relation matrix.

In this step, the bipolar neutrosophic weighted average operator is used to aggregate the bipolar neutrosophic information. Let $\tilde{a} = \langle T_j^+, I_j^+, F_j^+, T_j^-, I_j^-, F_j^- \rangle$, ($j = 1, 2, \dots, n$) be a family of bipolar neutrosophic numbers. Bipolar neutrosophic weighted average operator (A_w) is defined as:

$$A_w(\tilde{a}_1, \tilde{a}_2, \dots, \tilde{a}_n) = \sum_{j=1}^n w_j \tilde{a}_j = \left\langle \left(1 - \prod_{j=1}^n (1 - T_j^+)^{w_j}\right), \prod_{j=1}^n (I_j^+)^{w_j}, \prod_{j=1}^n (F_j^+)^{w_j}, -\prod_{j=1}^n (-T_j^-)^{w_j}, -\left(1 - \prod_{j=1}^n (1 - (-I_j^-))^{w_j}\right), -\left(1 - \prod_{j=1}^n (1 - (-F_j^-))^{w_j}\right) \right\rangle \quad (1)$$

where w_j is weight for neutrosophic information.

Step 3. Deneutrosophication of bipolar neutrosophic.

Deneutrosophication is the process to obtain crisp numbers from neutrosophic numbers. Deneutrosophication of bipolar neutrosophic set in X can be defined as a process of mapping B into the neutrosophic set. Therefore, deneutrosophication can be obtained using Equation (2).

$$\mu_B(x) = \begin{cases} 1 - \left[\frac{1}{2} \sqrt{\left(\frac{(1-T^+(x))^2 + (I^+(x))^2 + (F^+(x))^2}{3} \right)} + \left(\frac{(1-(-T^-(x)))^2 + (-I^-(x))^2 + (-F^-(x))^2}{3} \right) \right] \\ 0 \end{cases} \quad (2)$$

The final stage is obtaining the rank of alternatives. This stage is detailed out as follows:

4.3. Stage 3: Obtain the Ranking of Alternatives

Step 4. Construction of the initial decision matrix.

The first step of the MABAC method is to evaluate alternatives with respect to criteria. We show the alternative in the form of vectors $A_i = (x_{i1}, x_{i2}, \dots, x_{in})$, where x_{ij} is the value of the i -th alternative according to the j -th criterion ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$). It is arranged as Equation (3):

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad (3)$$

where m indicates the total number of the alternative and n indicates the total number of criteria.

Step 5. Normalization of the elements from the initial matrix:

$$\tilde{N} = \begin{bmatrix} \tilde{n}_{11} & \tilde{n}_{12} & \cdots & \tilde{n}_{1n} \\ \tilde{n}_{21} & \tilde{n}_{22} & \cdots & \tilde{n}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{n}_{m1} & \tilde{n}_{m2} & \cdots & \tilde{n}_{mn} \end{bmatrix} \quad (4)$$

The elements of the normalized matrix are determined using Equation (5) or Equation (6) depending on criteria types.

- i. For benefit type criteria which is higher value of the criterion,

$$\tilde{n}_{ij} = \frac{\tilde{x}_{ij} - \tilde{x}_i^-}{\tilde{x}_i^+ - \tilde{x}_i^-} \quad (5)$$

- ii. For cost type criteria which is higher value of the criterion,

$$\tilde{n}_{ij} = \frac{\tilde{x}_{ij} - \tilde{x}_i^+}{\tilde{x}_i^- - \tilde{x}_i^+} \quad (6)$$

where $\tilde{x}_{ij}$, $\tilde{x}_i^+$ and $\tilde{x}_i^-$ are the elements from the initial decision matrix for which $\tilde{x}_i^+$ and $\tilde{x}_i^-$ are defined as: $\tilde{x}_i^+ = \max(\tilde{x}_1, \tilde{x}_2, \dots, \tilde{x}_m)$ is the maximum value of the observed criterion according to the alternatives and $\tilde{x}_i^- = \min(\tilde{x}_1, \tilde{x}_2, \dots, \tilde{x}_m)$ is the minimum value of the observed criterion with respect to alternatives.

Step 6. Calculation of elements of weighted matrix.

The elements from the weighted matrix ($\tilde{V}$) are calculated using Equation (7).

$$\tilde{v}_{ij} = \tilde{n}_{ij} \cdot \tilde{w}_i \cdot (\tilde{n}_{ij} + 1) \quad (7)$$

where $\tilde{n}_{ij}$ are the elements of the normalized matrix, $\tilde{w}_i$ is the weight coefficients of the criteria. We can obtain the weighted matrix using Equation (8).

$$\tilde{V} = \begin{bmatrix} \tilde{v}_{11} & \tilde{v}_{12} & \cdots & \tilde{v}_{1n} \\ \tilde{v}_{21} & \tilde{v}_{22} & \cdots & \tilde{v}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{v}_{m1} & \tilde{v}_{m2} & \cdots & \tilde{v}_{mn} \end{bmatrix} \quad (8)$$

Step 7. Determining the border approximation area (BAA) matrix.

The BAA for each criterion is determined using Equation (9),

$$\tilde{g}_i = \left(\prod_{j=1}^m \tilde{v}_{ij} \right)^{\frac{1}{m}} \quad (9)$$

where $\tilde{v}_{ij}$ are the elements of the weighted matrix. Then, a BAA matrix is given in matrix $n \times 1$ (n columns and one row):

$$\tilde{G} = \begin{bmatrix} \tilde{g}_1 & \tilde{g}_2 & \cdots & \tilde{g}_n \end{bmatrix} \quad (10)$$

Step 8. Calculation of the distance of alternatives from the BAA for each element of the matrix:

$$\tilde{Q} = \begin{bmatrix} \tilde{q}_{11} & \tilde{q}_{12} & \cdots & \tilde{q}_{1n} \\ \tilde{q}_{21} & \tilde{q}_{22} & \cdots & \tilde{q}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{q}_{m1} & \tilde{q}_{m2} & \cdots & \tilde{q}_{mn} \end{bmatrix} \quad (11)$$

The distance from the approximation border area ($\widetilde{q}_{ij}$) is determined as the difference of weighted matrix elements ($\widetilde{V}$) and the values of border approximation area ($\widetilde{G}$).

$$\widetilde{Q} = \widetilde{V} - \widetilde{G} \quad (12)$$

which can be written:

$$\widetilde{Q} = \begin{bmatrix} \widetilde{v}_{11} & \widetilde{v}_{12} & \cdots & \widetilde{v}_{1n} \\ \widetilde{v}_{21} & \widetilde{v}_{22} & \cdots & \widetilde{v}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{v}_{m1} & \widetilde{v}_{m2} & \cdots & \widetilde{v}_{mn} \end{bmatrix} - \begin{bmatrix} \widetilde{g}_1 & \widetilde{g}_2 & \cdots & \widetilde{g}_n \\ \widetilde{g}_1 & \widetilde{g}_2 & \cdots & \widetilde{g}_n \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{g}_1 & \widetilde{g}_2 & \cdots & \widetilde{g}_n \end{bmatrix} \quad (13)$$

where $\widetilde{g}_{ij}$ is the BAA for criterion.

Step 9. Ranking the alternatives.

The values of the criterion functions for the alternative is obtained as the sum of the distance of the alternative from the BAA. We obtain the final values of the criterion functions for the alternative by calculating the sum of element of matrix by rows:

$$\widetilde{S}_i = \sum_{j=1}^n \widetilde{q}_{ij}, (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (14)$$

Application of the proposed method is made to the problem of sustainable energy selection. In this problem, the alternatives of sustainable energy are evaluated with respect to the criteria that normally used in sustainable energy. Detailed implementation of the problem is presented in the following section.

5. Sustainable Energy Selection

The best three experts in the field of sustainable energy were invited to provide linguistic evaluation over the sustainable energy criteria. Two experts are academicians from the Department of Electrical Engineering and Department of Environment Science at a public university in Malaysia. The third expert is an engineer from the Department of Environment at a government ministry in Malaysia. The experts were asked to make evaluation on alternatives of sustainable energy with respect to fourteen criteria using the predefined linguistic variables (see Table 2). Table 3 shows the fourteen criteria and seven alternatives that were used in the evaluation.

Data was collected from the experts, then used as the input for the proposed method. In this section, the detailed computation procedures of bipolar neutrosophic MABAC method are implemented according to the following steps:

Step 1. Construct bipolar neutrosophic linguistic scale.

The group of experts need to evaluate by rating the alternatives with respect to criteria using the proposed five linguistic scales varying from 'very poor' to 'very good' and converted into bipolar neutrosophic linguistic scales accordingly.

Step 2. Aggregated direct-relation matrix.

Assume that the weights of experts are $\omega = [0.3742, 0.2516, 0.3742]^T$ where $\sum_{j=1}^3 \omega_j = 1$.

The aggregated direct-relation matrix can be obtained using bipolar neutrosophic weighted average operator (see Equation (1)). Table 4 presents the aggregated direct relation matrix.

Table 3. The criteria and alternatives for sustainable energy selection [25].

Criteria		Alternative	
C ₁	Efficiency	A ₁	Biomass energy
C ₂	Exergy efficiency	A ₂	Biogas energy
C ₃	Safety	A ₃	Geothermal energy
C ₄	NO _x emission	A ₄	Hydro energy
C ₅	CO ₂ emission	A ₅	Solar energy
C ₆	CO emission	A ₆	Tidal energy
C ₇	Land use	A ₇	Wind energy
C ₈	Noise		
C ₉	Social acceptability		
C ₁₀	Job creation		
C ₁₁	Investment cost		
C ₁₂	Operation and maintenance cost		
C ₁₃	Fuel cost		
C ₁₄	Electric cost		

Table 4. Aggregated direct relation matrix.

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	..	C ₁₄
A ₁	<0.5000,	<0.5000,	<0.5000,	<0.4659,	<0.7182,	..	<0.5818,
	0.4000,	0.4000,	0.4000,	0.3360,	0.5155,		0.3017,
	0.4500,	0.4500,	0.4500,	0.5029,	0.2263,		0.3933,
	−0.5000,	−0.5000,	−0.5000,	−0.4571,	−0.6710,		−0.4769,
	−0.4000,	−0.4000,	−0.4000,	−0.3550,	−0.5345,		−0.3828,
	−0.4500>	−0.4500>	−0.4500>	−0.5278>	−0.2778>		−0.5570>
A ₂	<0.6451,	<0.4484,	<0.7182,	<0.6029,	<0.8000,	..	<0.5168,
	0.4655,	0.3086,	0.5155,	0.4430,	0.6000,		0.2637,
	0.2983,	0.5309,	0.2263,	0.3413,	0.1500,		0.4751,
	−0.5961,	−0.4375,	−0.6710,	−0.5628,	−0.8000,		−0.4309,
	−0.4845,	−0.3318,	−0.5345,	−0.4582,	−0.6000,		−0.3280,
	−0.3527>	−0.5616>	−0.2778>	−0.3863>	−0.1500>		−0.6101>
A ₃	<0.8457,	<0.8000,	<0.8000,	<0.9000,	<0.7182,	..	<0.7182,
	0.6682,	0.6000,	0.6000,	0.8000,	0.5155,		0.5155,
	0.1289,	0.1500,	0.1500,	0.1000,	0.2263,		0.2263,
	−0.8360,	−0.8000,	−0.8000,	−0.9000,	−0.6710,		−0.6710,
	−0.6914,	−0.6000,	−0.6000,	−0.8000,	−0.5345,		−0.5345,
	−0.1316>	−0.1500>	−0.1500>	−0.1000>	−0.2778>		−0.2778>
A ₄	<0.5000,	<0.6451,	<0.8057,	<0.8057,	<0.4108,	..	<0.5053,
	0.4000,	0.4655,	0.6034,	0.6034,	0.2592,		0.2637,
	0.4500,	0.2983,	0.1699,	0.1699,	0.5933,		0.4424,
	−0.5000,	−0.5961,	−0.7428,	−0.7428,	−0.4000,		−0.3082,
	−0.4000,	−0.4845,	−0.6582,	−0.6582,	−0.2816,		−0.3694,
	−0.4500>	−0.3527>	−0.2217>	−0.2217>	−0.6236>		−0.6757>
A ₅	<0.8704,	<0.6029,	<0.4108,	<0.6029,	<0.4659,	..	<0.5168,
	0.7184,	0.4430,	0.2592,	0.4430,	0.3360,		0.2637,
	0.1164,	0.3413,	0.5933,	0.3413,	0.5029,		0.4751,
	−0.8612,	−0.5628,	−0.4000,	−0.5628,	−0.4571,		−0.4309,
	−0.7408,	−0.4582,	−0.2816,	−0.4582,	−0.3550,		−0.3280,
	−0.1190>	−0.3863>	−0.6236>	−0.3863>	−0.5278>		−0.6101>
A ₆	<0.6029,	<0.6029,	<0.5818,	<0.7826,	<0.7182,	..	<0.3500,
	0.4430,	0.4430,	0.3017,	0.5741,	0.5155,		0.2000,
	0.3413,	0.3413,	0.3933,	0.1944,	0.2263,		0.7000,
	−0.5628,	−0.5628,	−0.4769,	−0.7012,	−0.6710,		−0.3500,
	−0.4582,	−0.4582,	−0.3828,	−0.6408,	−0.5345,		−0.2000,
	−0.3863>	−0.3863>	−0.5570>	−0.2622>	−0.2778>		−0.7000>
A ₇	<0.6451,	<0.6029,	<0.7826,	<0.8000,	<0.7481,	..	<0.4108,
	0.4655,	0.4430,	0.5741,	0.6000,	0.5418,		0.2592,
	0.2983,	0.3413,	0.1944,	0.1500,	0.1978,		0.5933,
	−0.5961,	−0.5628,	−0.7012,	−0.8000,	−0.7108,		−0.4000,
	−0.4845,	−0.4582,	−0.6408,	−0.6000,	−0.5570,		−0.2816,
	−0.3527>	−0.3863>	−0.2622>	−0.1500>	−0.2382>		−0.6236>

Step 3. Deneutrosophication of bipolar neutrosophic.

Deneutrosophication can be obtained using Equation (2). It is shown in Table 5.

Table 5. Deneutrosophication of bipolar neutrosophic.

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄
A ₁	0.4816	0.4816	0.4628	0.4853	0.4560	0.4560	0.4953	0.4951	0.4840	0.4473	0.4418	0.4646	0.4646	0.4951
A ₂	0.4726	0.4858	0.4166	0.4778	0.4194	0.4194	0.4194	0.4194	0.4953	0.4643	0.4418	0.4194	0.4194	0.4953
A ₃	0.3977	0.4194	0.4194	0.3597	0.4560	0.4752	0.4876	0.4790	0.4254	0.4790	0.4607	0.4876	0.4752	0.4560
A ₄	0.4816	0.4726	0.4262	0.4262	0.4840	0.3827	0.4049	0.5116	0.4858	0.4702	0.4752	0.4442	0.4859	0.5157
A ₅	0.3827	0.4778	0.4840	0.4778	0.4853	0.5136	0.4790	0.4790	0.4953	0.4853	0.4663	0.4696	0.4790	0.4953
A ₆	0.4778	0.4778	0.4951	0.4381	0.4560	0.4560	0.4790	0.4951	0.4988	0.4840	0.4568	0.5199	0.5199	0.4752
A ₇	0.4726	0.4778	0.4381	0.4194	0.4455	0.4560	0.4951	0.4986	0.4904	0.4726	0.4750	0.4790	0.4840	0.4840

Step 4. Construct the initial decision matrix.

The MABAC method is used to evaluate alternatives with respect to criteria. The alternatives are arranged in the form $A_i = (x_{i1}, x_{i2}, \dots, x_{in})$ where x_{ij} is the value of the i -th alternative with respect to the j -th criterion ($i = 1, 2, \dots, 7; j = 1, 2, \dots, 14$) (see Equation (3)).

$$\tilde{X} = \begin{bmatrix} 0.4816 & 0.4816 & \cdots & 0.4951 \\ 0.4726 & 0.4858 & \cdots & 0.4953 \\ \vdots & \vdots & \ddots & \vdots \\ 0.4726 & 0.4778 & \cdots & 0.4840 \end{bmatrix}$$

Step 5. Normalization of the elements from the initial decision matrix.

In this step, C₁ until C₁₀ are the benefit type criteria and C₁₁ until C₁₄ are the cost type criteria by Equation (6). Elements of the normalized matrix of benefit type criteria and cost type criteria are determined using Equations (5) and (6) respectively. Elements of the normalized matrix are shown in Table 6.

Table 6. Normalized initial matrix.

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄
A ₁	1.0000	0.9372	0.5888	1.0000	0.5550	0.5599	1.0000	0.8213	0.7991	0.0000	1.0000	0.5503	0.5503	0.3445
A ₂	0.9086	1.0000	0.0000	0.9405	0.0000	0.2806	0.1604	0.0000	0.9530	0.4460	1.0000	1.0000	1.0000	0.3411
A ₃	0.1520	0.0000	0.0359	0.0000	0.5550	0.7065	0.9146	0.6465	0.0000	0.8341	0.4345	0.3214	0.4450	1.0000
A ₄	1.0000	0.8009	0.1228	0.5297	0.9806	0.0000	0.0000	1.0000	0.8225	0.6030	0.0000	0.7536	0.3384	0.0000
A ₅	0.0000	0.8807	0.8587	0.9405	1.0000	1.0000	0.8195	0.6465	0.9530	1.0000	0.2671	0.5010	0.4070	0.3411
A ₆	0.9621	0.8807	1.0000	0.6245	0.5550	0.5599	0.8195	0.8213	1.0000	0.9663	0.5507	0.0000	0.0000	0.6784
A ₇	0.9086	0.8807	0.2744	0.4754	0.3956	0.5599	0.9977	0.8592	0.8854	0.6640	0.0072	0.4070	0.3570	0.5303

Step 6. Obtain the elements of weighted normalized decision matrix.

The elements of weighted matrix ($\tilde{V}$) are calculated using Equation (7). Table 7 shows the weighted normalized decision matrix.

Table 7. Weighted normalized decision matrix.

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄
A ₁	0.2080	0.1317	0.1095	0.1612	0.1096	0.1061	0.1334	0.1197	0.1252	0.0705	0.1318	0.1028	0.1019	0.0936
A ₂	0.1985	0.1360	0.0689	0.1564	0.0705	0.0871	0.0774	0.0657	0.1359	0.1019	0.1318	0.1326	0.1314	0.0933
A ₃	0.1198	0.0680	0.0714	0.0806	0.1096	0.1160	0.1277	0.1082	0.0696	0.1293	0.0945	0.0876	0.0949	0.1392
A ₄	0.2080	0.1225	0.0774	0.1233	0.1396	0.0680	0.0667	0.1314	0.1268	0.1130	0.0659	0.1163	0.0879	0.0696
A ₅	0.1040	0.1279	0.1281	0.1564	0.1410	0.1360	0.1214	0.1082	0.1359	0.1410	0.0835	0.0995	0.0924	0.0933
A ₆	0.2041	0.1279	0.1378	0.1309	0.1096	0.1061	0.1214	0.1197	0.1392	0.1386	0.1022	0.0663	0.0657	0.1168
A ₇	0.1985	0.1279	0.0878	0.1189	0.0984	0.1061	0.1332	0.1222	0.1312	0.1173	0.0664	0.0933	0.0892	0.1065

Step 7. Determining the BAA matrix.

Table 8 shows the BAA for each criterion. It is obtained using Equation (9):

Table 8. BAA matrix.

Criteria	$\tilde{g}$
C ₁	0.0000006192
C ₂	0.0000000446
C ₃	0.0000000092
C ₄	0.0000000872
C ₅	0.0000000257
C ₆	0.0000000159
C ₇	0.0000000247
C ₈	0.0000000252
C ₉	0.0000000533
C ₁₀	0.0000000344
C ₁₁	0.0000000088
C ₁₂	0.0000000122
C ₁₃	0.0000000086
C ₁₄	0.0000000140

Step 8. Calculate distance of alternatives.

The distances of the alternatives from the BAA for the matrix elements are obtained using Equation (12). The results are presented in Table 9.

Table 9. Distance of the alternative from BAA matrix.

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄
A ₁	0.2080	0.1317	0.1095	0.1612	0.1096	0.1061	0.1334	0.1197	0.1252	0.0705	0.1318	0.1028	0.1019	0.0936
A ₂	0.1985	0.1360	0.0689	0.1564	0.0705	0.0871	0.0774	0.0657	0.1359	0.1019	0.1318	0.1326	0.1314	0.0933
A ₃	0.1198	0.0680	0.0714	0.0806	0.1096	0.1160	0.1277	0.1082	0.0696	0.1293	0.0945	0.0876	0.0949	0.1392
A ₄	0.2080	0.1225	0.0774	0.1233	0.1396	0.0680	0.0667	0.1314	0.1268	0.1130	0.0659	0.1163	0.0879	0.0696
A ₅	0.1040	0.1279	0.1281	0.1564	0.1410	0.1360	0.1214	0.1082	0.1359	0.1410	0.0835	0.0995	0.0924	0.0933
A ₆	0.2041	0.1279	0.1378	0.1309	0.1096	0.1061	0.1214	0.1197	0.1392	0.1386	0.1022	0.0663	0.0657	0.1168
A ₇	0.1985	0.1279	0.0878	0.1189	0.0984	0.1061	0.1332	0.1222	0.1312	0.1173	0.0664	0.0933	0.0892	0.1065

Step 9. Ranking the alternative.

The final values for each alternative can be obtained by calculating the sum of the distance of alternatives from the BAA using Equation (14). The final ranking of the alternative is given in Table 10.

Table 10. Sum of the distance of alternatives from the BAA and ranking of alternatives.

Alternative	$\tilde{s}$	Ranking
A ₁	1.7049	1
A ₂	1.5875	5
A ₃	1.4165	7
A ₄	1.5164	6
A ₅	1.6686	3
A ₆	1.6862	2
A ₇	1.5968	4

Based on the sum of distance of alternative from the BAA in Table 10, ranking of the alternatives are accomplished as A₁ > A₆ > A₅ > A₇ > A₂ > A₄ > A₃. Therefore, A₁ is the best alternative of the sustainable energy.

6. Comparative Analysis

The results obtained from the proposed method are subjected to comparative analysis. Using the original MABAC method as a benchmark method, the comparative analysis is implemented. The linguistic variables used in the proposed method are substituted with crisp numbers of MABAC, then the computational procedures of MABAC are iterated. In the original MABAC method, crisp

numbers are not converted into bipolar neutrosophic linguistic scales. Apart from that, no aggregation and deneutrosophication computational steps are needed. The initial decision matrix of the original MABAC is shown in Table 11.

Table 11. Initial decision matrix.

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄
A ₁	2.0000	2.0000	2.0000	1.6667	2.6667	2.6667	1.6667	1.6667	1.3333	2.6667	2.6667	2.6667	1.6667	1.6667
A ₂	2.3333	1.6667	2.6667	2.3333	3.0000	3.3333	3.0000	3.0000	1.6667	2.3333	2.6667	3.0000	2.3333	1.6667
A ₃	3.3333	3.0000	3.0000	4.0000	1.6667	1.0000	2.0000	2.3333	3.3333	2.3333	1.6667	2.0000	2.3333	2.6667
A ₄	2.0000	2.3333	3.0000	3.0000	2.6667	3.6667	3.3333	1.3333	1.6667	2.6667	3.0000	3.0000	1.3333	1.6667
A ₅	3.6667	2.3333	1.3333	2.3333	3.0000	2.3333	2.3333	2.3333	1.6667	1.6667	2.6667	2.6667	2.3333	1.6667
A ₆	2.3333	2.3333	1.6667	3.0000	2.6667	2.6667	2.3333	1.6667	2.0000	1.3333	2.0000	2.0000	1.6667	1.0000
A ₇	2.3333	2.3333	3.0000	3.0000	3.0000	2.6667	1.6667	1.3333	2.0000	2.3333	2.3333	2.3333	1.3333	1.3333

This initial decision matrix is indeed the average of expert scores in which these scores are computed further using a normalization equation (see Step 5). The normalized matrix obtained from the initial decision matrix is shown in Table 12.

Table 12. Normalized initial matrix.

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄
A ₁	0.0000	0.2500	0.4000	0.0000	0.7500	0.6250	0.0000	0.2000	0.0000	1.0000	0.2500	0.3333	0.6667	0.6000
A ₂	0.2000	0.0000	0.8000	0.2857	1.0000	0.8750	0.8000	1.0000	0.1667	0.7500	0.2500	0.0000	0.0000	0.6000
A ₃	0.8000	1.0000	1.0000	1.0000	0.0000	0.0000	0.2000	0.6000	1.0000	0.7500	1.0000	1.0000	0.0000	0.0000
A ₄	0.0000	0.5000	1.0000	0.5714	0.7500	1.0000	1.0000	0.0000	0.1667	1.0000	0.0000	0.0000	1.0000	0.6000
A ₅	1.0000	0.5000	0.0000	0.2857	1.0000	0.5000	0.4000	0.6000	0.1667	0.2500	0.2500	0.3333	0.0000	0.6000
A ₆	0.2000	0.5000	0.2000	0.5714	0.7500	0.6250	0.4000	0.2000	0.3333	0.0000	0.7500	1.0000	0.6667	1.0000
A ₇	0.2000	0.5000	1.0000	0.5714	1.0000	0.6250	0.0000	0.0000	0.3333	0.7500	0.5000	0.6667	1.0000	0.8000

Computation is continued further with step 6 until step 9, and the sum of the distance of alternatives from the BAA($\tilde{S}$) are obtained using Equation (14). Table 13 presents the distance and ranking of alternatives as the result of implementation MABAC method.

Table 13. Sum of the distance of alternatives from the BAA and ranking of alternatives.

Alternative	$\tilde{S}$	Ranking MABAC
A ₁	1.3477	7
A ₂	1.4707	5
A ₃	1.6081	1
A ₄	1.5261	3
A ₅	1.4412	6
A ₆	1.5022	4
A ₇	1.5574	2

The final ranking results of MABAC and the propose method are put side by side to observe the consistency. Table 14 presents the comparative results of the two methods.

Table 14. Comparative results of the proposed methods against the MABAC method.

Alternative	MABAC	Bipolar Neutrosophic MABAC
A ₁	7	1
A ₂	5	5
A ₃	1	7
A ₄	3	6
A ₅	6	3
A ₆	4	2
A ₇	2	4

As shown in Table 14, it can be seen that the two methods offer inconsistency results. It is mainly attributed to the different rating numbers, which subsequently affect the distances. In this study, a group of experts applied the bipolar neutrosophic numbers in linguistic evaluation, while in computational procedures of MABAC method, crisp numbers based linguistic variables are used. Furthermore, the proposed bipolar neutrosophic MABAC method needs to reduce the bipolar neutrosophic numbers to crisp numbers through the deneutrosophication. Contrarily, in MABAC method, the process of deneutrosophication are excluded during computation. The result of bipolar neutrosophic MABAC shows that A_1 is an optimal alternative while A_3 is the optimal alternative for the MABAC method. The comparative result showed the significance of the proposed method in decision enhancement.

7. Conclusions

This paper proposed a combination of bipolar neutrosophic set and the MABAC method to solve the MCDM problem. Specifically, the proposed method was applied to sustainable energy selection in which the optimal solution is suggested. The set of fourteen criteria and seven alternatives in sustainable energy were used in this empirical study. Bipolar neutrosophic judgment based on positive and negative sides were judiciously used in this decision. The MABAC method is a particularly pragmatic and reliable tool for rational decision making because it has simple computation and stable solutions.

The proposed method suggests that A_1 is the optimal alternative. This paper has proceeded with a comparative analysis where the rank of alternatives, using the proposed method, is slightly different from the benchmark method. In short, this study provides several significant contributions and modifications to the fundamental MABAC method. Firstly, the new linguistic variable for bipolar neutrosophic was successfully introduced in the evaluation process. Secondly, the direct relation matrix was aggregated using bipolar neutrosophic weighted aggregation operator and introduced deneutrosophication bipolar neutrosophic. Finally, the bipolar neutrosophic MABAC was applied to the sustainable energy selection where ‘biomass energy’ was selected as the optimal alternative. The proposed method provided evidence on the feasibility of bipolar judgment coupled with straightforward computation in offering the optimal solution of sustainable energy selection. Nonetheless, this study has some recommendations for future research. The weighted average operator in aggregating direct-relation matrix could be further enhanced by considering new aggregation methods such as generalized Schweizer-Sklar prioritized aggregation operators [63], normalized weighted Bonferroni mean aggregation operator [64], and picture Dombi aggregation operators [65]. Moreover, the sensitivity of the experts’ weights towards the evaluation results is not investigated in this paper. Therefore, any new sensitivity analysis particularly on the experts’ weights could be explored as a future research direction. The study is not only limited by the computational steps of the proposed method that could be explored for future research, but the bipolar neutrosophic sets also could be combined with other MCDM methods.

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Abbreviations

AHP	Analytic Hierarchy Process
BAA	Border Approximation Area
DEMATEL	Decision Making Trial and Evaluation Laboratory
ELECTRE-I	Elimination ET Choice Translating Reality-I
FAHP	Fuzzyficated Saaty's scale, the Analytic Hierarchy Process
IVIFSs	Interval-Valued Intuitionistic Fuzzy Sets
LAA	Lower Approximation Area
MABAC	Multi-Attributive Border Approximation area Comparison
MCDM	Multi-Criteria Decision-Making
QUALIFLEX	Qualitative Flexible
R&D	Research and Development
SVNNs	Single-Valued Neutrosophic Numbers
TODIM	Interactive Multi-Criteria Decision Making (Acronym in Portuguese)
TOPSIS	Technique for Order of Preference by Similarity to ideal Solution
UAA	Upper Approximation Area

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