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*Research Article*

# An Efficient Technique for Algebraic System of Linear Equations Based on Neutrosophic Structured Element

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Neutrosophic logic is frequently applied to the engineering technology, scientific administration, and financial matters, among other fields. In addition, neutrosophic linear systems can be used to illustrate various practical problems. Due to the complexity of neutrosophic operators, however, solving linear neutrosophic systems is challenging. This work proposes a new straightforward method for solving the neutrosophic system of linear equations based on the neutrosophic structured element (NSE). Here unknown and right-hand side vectors are considered as triangular neutrosophic numbers. Based on the NSE, analytical expressions of the solution to this equation and its degrees are also provided. Finally, several examples of the methodology are provided.

## 1. Introduction

In modeling various physical phenomena, we are confronted with two types of uncertainty and indeterminacy: the first category is due to the inability of human knowledge and tools to comprehend the intricacies of an event. For instance, to determine the temperature of a city, thermometers are placed at various locations and the average is then calculated. Obviously, the calculated temperature differs from the actual temperature of that city, for two reasons: first, just a few points of that city were used in the calculations and second, the inaccuracy of the measuring person and the devices generates uncertainty in the reported temperature. The second category relates to a lack of clarity and transparency regarding a certain phenomenon or characteristic. A phenomenon may be fundamentally ambiguous and subjectively determined. For instance, there is no universal definition of what constitutes hot weather, so that one person may regard $30^\circ$ to be hot while another believes $40^\circ$ to be hot. Therefore, to obtain a realistic model, we must consider certainty and uncertainty in the model.

It is commonly recognized that in recent years, when less, incomplete, ambiguous, or imprecise information about variables or parameters has been available, fuzzy set (FS) and its extensions are particularly valuable modeling tools for these types of data [1–5]. Consequently, many physical or real-world issues involving uncertainty and indeterminacy frequently include the systems of linear equations in their solution methods. Numerous industries, including advertising, logistics, finance, optimization, and more, can benefit from this type of systems.

A number of scholars have also put forth models for linear systems in a fuzzy setting. Fuzzy linear systems (FLSs) did not develop until at least 1980 [6]. However, Friedman et al. [7] introduced an embedding approach to solve a FLS with a definite matrix coefficient and an arbitrarily fuzzy number vector on the right-hand side. This model was later modified by further researchers. Allahviranloo [8, 9] studied iterative algorithms for FLS with convergence theorems, including Jacobi, Gauss Seidel, and SOR approaches. Dehghan et al. [10] provided certain ways to solve FLS that are equivalent to well-known methods as

Gaussian elimination, Cramer's rule, Doolittle algorithm, and its simplification.

Muzzioli and Reynaerts [11] examined a dual type of FLS and highlighted the connection between interval linear systems (ILS) and FLS. Wang and Zheng [12] explored an inconsistent FLS and derived the fuzzy and weak fuzzy least squares solutions by applying the generalized inverses of the coefficient matrix. Tian et al. [13] investigated the perturbation analysis of FLS and determined the relative error limitations for FLS solutions. Otadi et al. [14] presented a hybrid method based on fuzzy neural network for approximate solution of FLS. Behera and Chakraverty [15] examined the solution technique for both real and complicated fuzzy systems. Saberi Najafi and Edalatpanah [16] analyzed various existing iterative methods employing the embedding method for finding the solution FLS and devised a numerical method for enhancing these algorithms. They demonstrated that their technique outperforms all previously mentioned numerical iterative algorithms. Lodwick and Dubois [17] argued that ILS is an essential process in the solution of FLS and emphasized four unique definitions of systems of linear equations in which coefficients are substituted by intervals.

Akram et al. [18] defined some concepts, including a bipolar fuzzy number in parametric form and propose a method for the bipolar FLS solution procedure. Fully FLS with trapezoidal and hexagonal fuzzy numbers have been studied by Ziqan et al. [19]. Abbasi and Allahviranloo [20] also investigated and the reported a new concept based on transmission-average-based operations for solving fully FLS. Recently, numerous scholars investigated the system of linear equations for the various types of fuzzy numbers such as horizontal fuzzy numbers [21], LR-bipolar fuzzy numbers [22], thick fuzzy number [23], and fuzzy complex numbers [24]. Although the solution of a system of linear equation with FS) is intriguing, FS only considers the truth membership function of each element. Atanassov [25] proposed intuitionistic fuzzy sets (IFSs), which accounted for both the falsity and truth membership functions, to address this issue.

However, in real-life decision-making problems, both FS and IFS are unable to deal with indeterminacy. In actual decision-making difficulties, both FS and IFS are incapable of handling indeterminacy that in the context of actual decision-making it is highly crucial. In terms of independent truth, falsity, and indeterminacy membership functions, Smarandache [26] created neutrosophic sets (NS) in 1998. Subsequently, several new extensions to NSs have emerged, including NSs [27, 28] defined over a specific interval, bipolar NSs [29] characterized by their dual nature, single-valued NSs [30] consisting of single values, quadripartitioned single valued NSs [31] divided into four partitions, n-refined NSs [32] refined through additional considerations, simplified NSs [33], and pentapartitioned NS [34] introduced for ease of comprehension. These contexts are used in a variety of ways in research and engineering, such as transportation problem [35], statistical analysis [36], management evaluation [37], bioenergy production technologies [38], centrifugal pump [39], waste management [40], etc.

To the best of our knowledge, there have only been a limited number of studies on the system of neutrosophic linear equations [41, 42], despite the fact that there are numerous methods for addressing various issues under NSs. These methods [41, 42] used the $(\alpha, \beta, \gamma)$-cut technique. Some neutrosophic modeling approaches carefully handle the original neutrosophic data, which can easily result in information loss and potentially lead to biased results. These techniques have not strayed too far from the mainstream decision-making domain. Moreover, the calculating procedure is occasionally disrupted by parameter ergodicity issues. For example, the $(\alpha, \beta, \gamma)$-cut technique requires the parameter to be set to [0, 1], which is unrealistic. The neutrosophic structured element (NSE) is among the substantial extensions of NS. Edalatpanah [43] was the founder of the NSE theory, which expresses NS as a linear structure.

NSs can be analyzed and sorted based on the relationship between the truth, indeterminacy, and falsity membership functions, however the formulae are complicated and certain procedures do not satisfy the rational hypothesis of economic phenomenon. However, modeling with NSE can remove these shortcomings. However, simulation with NSE can eliminate these deficiencies. NSE is based on the homeomorphism between a closed NS and a group of restricted functions on $[-1, 1]$. To avoid the ergodicity of the extension idea, the NSE was utilized to represent NSs and their operations. In addition, the NSs transmission of the calculation process and the analytic expression of computed values can be implemented. Therefore, this work proposes a new approach for solving neutrosophic linear systems (NLS) of the form $Ax = b$, where $A$ is a crisp matrix and $b$ is the triangular single-valued neutrosophic number (TSVNN) vector.

The structure of this work is as follows: Section 1 covers the concepts of TSVNN and NSE; Section 2, various notations and definitions are provided; Section 3, both the NLS and the proposed approach have been introduced; Section 4, numerical examples are then solved; Section 5 concludes with the conclusions.

## 2. Preliminaries

Here are provided various notations and definitions pertinent to the presented study [43].

*Definition 1.* Consider $\Lambda = <(\delta_1, \delta_2, \delta_3), (\iota_1, \iota_2, \iota_3), (\xi_1, \xi_2, \xi_3)>$ as the TSVNN. Then the truth $(\mathrm{T}_\Lambda(x))$, indeterminacy $(\Gamma_\Lambda(x))$, and falsity $(\Psi_\Lambda(x))$ membership functionsare described as follows:

$$
\mathrm{T}_{\Lambda}(x)=\begin{cases}\dfrac{(x-\delta_1)}{(\delta_2-\delta_1)} & \delta_1\le x<\delta_2,\\ 1 & x=\delta_2,\\ \dfrac{(\delta_3-x)}{(\delta_3-\delta_2)} & \delta_2<x\le\delta_3,\\ 0 & \text{otherwise.}\end{cases}\quad
\varGamma_{\Lambda}(x)=\begin{cases}\dfrac{(\iota_2-x)}{(\iota_2-\iota_1)} & \iota_1\le x<\iota_2,\\ 0 & x=\iota_2,\\ \dfrac{(x-\iota_2)}{(\iota_3-\iota_2)} & \iota_2<x\le\iota_3,\\ 1 & \text{otherwise.}\end{cases}\quad
\varPsi_{\Lambda}(x)=\begin{cases}\dfrac{(\xi_2-x)}{(\xi_2-\xi_1)} & \xi_1\le x<\xi_2,\\ 0 & x=\xi_2,\\ \dfrac{(x-\xi_2)}{(\xi_3-\iota_2)} & \xi_2<x\le\xi_3,\\ 1 & \text{otherwise.}\end{cases} \tag{1}
$$

where $0\le \mathrm{T}_{\Lambda}(x)+\varGamma_{\Lambda}(x)+\varPsi_{\Lambda}(x)\le 3, x\in\Lambda$.

*Definition 2.* For TSVNN $\Lambda=<(\delta_1,\delta_2,\delta_3),(\iota_1,\iota_2,\iota_3),(\xi_1,\xi_2,\xi_3)>$, there are $p,q,r:[-1,1]\to[0,1]$ such that $\mathrm{T}_{\Lambda}(x)=p_{\Lambda}(x),\varGamma_{\Lambda}(x)=q_{\Lambda}(x)$, and $\varPsi_{\Lambda}(x)=r_{\Lambda}(x)$, where:

$$
p_{\Lambda}(x)=\begin{cases}(\delta_2-\delta_1)x+\delta_2, & -1\le x\le 0,\\ (\delta_3-\delta_2)x+\delta_2, & 0\le x\le 1,\\ 0, & \text{others,}\end{cases} \tag{2}
$$

$$
q_{\Lambda}(E)=\begin{cases}(\iota_2-\iota_1)x+\iota_2, & -1\le x\le 0,\\ (\iota_3-\iota_2)x+\iota_2, & 0\le x\le 1,\\ 0, & \text{others,}\end{cases} \tag{3}
$$

$$
r_{\Lambda}(x)=\begin{cases}(\xi_2-\xi_1)x+\xi_2, & -1\le x\le 0,\\ (\xi_3-\xi_2)x+\xi_2, & 0\le x\le 1,\\ 0, & \text{others,}\end{cases} \tag{4}
$$

where $\Lambda=<p_{\Lambda}(x),q_{\Lambda}(x),r_{\Lambda}(x)>$, is called NSE number (NSEN).

*Definition 3.* For $M=<p_M(x),q_M(x),r_M(x)>$, and $N=<s_N(x),t_N(x),u_N(x)>$, we have:

(i) $M\oplus N=<(p_M+s_N)(x),(q_M+t_N)(x),(r_M+u_N)(x)>$,
(ii) $M-N=<(p_M(x)+s'_N(x)),(q_M(x)+t'_N(x)),(r_M(x)+u'_N(x))>$,
(iii) $\lambda N=\lambda<(s'_N(x)),(t'_N(x)),(u'_N(x))>$,

where

$$
s'_N(x)=-s_N(-x),\ t'_N(x)=-t_N(-x),\ u'_N(x)=-u_N(-x). \tag{5}
$$

## 3. NLS and the Proposed Method

Let us consider a $n\times n$ NLS

$$
[A]\{\widetilde{X}\}=\{\widetilde{b}\}. \tag{6}
$$

Here $[A]=(a_{kj})$ for $1\le k\le n$ and $1\le j\le n$ is a $n\times n$ crisp real matrix, $\{\tilde{b}\}=\{\tilde{b}_k\}$ is a column vector of TSVNN and $\{\tilde{X}\}=\{\tilde{x}_j\}$ is the vector of neutrosophic unknown.

Equation (6) can be represented by the following expressions:

$$
\sum_{j=1}^{n}a_{kj}\tilde{x}_j=\tilde{b}_k,\ \text{for } k=1,\dots,n. \tag{7}
$$

In [43], Edalatpanah studied the solution of $n\times n$ NLS with embedding method, and gave the necessary and sufficient conditions for a unique neutrosophic solution. In this section, instead of using two monotonic functions to represent the neutrosophic numbers in [43], we will use the NSE methodology to study the problem of NLS. Suppose that the solution of the NLS of Equation (6) be $\tilde{x}$ and its NSE form be $\tilde{\varPsi}(x)=<p_{\varPsi}(x),q_{\varPsi}(x),r_{\varPsi}(x)>$. Also, let the NSE form of $\{\tilde{b}\}$ be $\tilde{b}(x)=<s_{\tilde{b}}(x),t_{\tilde{b}}(x),u_{\tilde{b}}(x)>$. Then, in the special case if for each row $a_{kj}\ge 0$ we have:

$$
\sum_{j=1}^{n}a_{kj}\varPsi_j(x)=\tilde{b}_k(x),\ \text{for } k=1,\dots,n, \tag{8}
$$

$$
\sum_{j=1}^{n}a_{kj}\varPsi_j(-x)=\tilde{b}_k(-x),\ \text{for } k=1,\dots,n, \tag{9}
$$

which are two common NLSs and can be solved easily.

Now to solve Equation (7), define:

$$
Y=(\varPsi_1(x),\ \varPsi_2(x),\dots,\varPsi_n(x),\varPsi_1(-x),\ \varPsi_2(-x),\dots,\varPsi_n(-x))^t, \tag{10}
$$

$$
B=(\tilde{b}_1(x),\tilde{b}_2(x),\dots,\tilde{b}_n(x),\tilde{b}_1(-x),\tilde{b}_2(-x),\dots,\tilde{b}_n(-x))^t. \tag{11}
$$

Then Equation (7) can equivalently be written as follows:

$$
HY=B, \tag{12}
$$

where $H=(h_{ij})_{2n\times 2n}$ is as follows:

$$
\begin{cases}a_{ij}\ge 0\to h_{ij}=a_{ij}, & h_{i+n,j+n}=a_{ij},\\ a_{ij}<0\to h_{i,j+n}=h_{ij}, & d_{i+n,j}=h_{ij}\end{cases}. \tag{13}
$$

Furthermore, to specify the truth, indeterminacy, and falsity parts of solution we define:

$$Y = <P_Y(x),\ Q_Y(x),\ R_Y(x)>, \tag{14}$$

$$B = <S_B(x),\ T_B(x),\ U_B(x)>, \tag{15}$$

where

$$P_Y(x) = (p_1(x),\ p_2(x),\ \dots,\ p_n(x),\ p_1(-x),\ p_2(-x),\ \dots,\ p_n(-x))^t, \tag{16}$$

$$Q_Y(x) = (q_1(x),\ q_2(x),\ \dots,\ q_n(x),\ q_1(-x),\ q_2(-x),\ \dots,\ q_n(-x))^t, \tag{17}$$

$$R_Y(x) = (r_1(x),\ r_2(x),\ \dots,\ r_n(x),\ r_1(-x),\ r_2(-x),\ \dots,\ r_n(-x))^t, \tag{18}$$

$$S_B(x) = (s_1(x),\ s_2(x),\ \dots,\ s_n(x),\ s_1(-x),\ s_2(-x),\ \dots,\ s_n(-x))^t, \tag{19}$$

$$Q_B(x) = (q_1(x),\ q_2(x),\ \dots,\ q_n(x),\ q_1(-x),\ q_2(-x),\ \dots,\ q_n(-x))^t, \tag{20}$$

$$U_B(x) = (u_1(x),\ u_2(x),\ \dots,\ u_n(x),\ u_1(-x),\ u_2(-x),\ \dots,\ u_n(-x))^t. \tag{21}$$

Therefore, the three parts of solution of NLS can be obtained by computing the following formulas:

$$P_Y(x) = H^{-1}S_B(x), \tag{22}$$

$$Q_Y(x) = H^{-1}T_B(x), \tag{23}$$

$$R_Y(x) = H^{-1}U_B(x). \tag{24}$$

In the next section sometests have been solved using the proposed method and also compared with existing results for the validation.

## 4. Numerical Examples

*Example 1.* Let us consider a $2 \times 2$ TSVNN system of linear equations as follows:

$$\begin{cases} 4\tilde{x}_1 - \tilde{x}_2 = <(2,\ 3,\ 7),\ (3,\ 5,\ 6),\ (0,\ 1,\ 3)> = \tilde{b}_1(x), \\ \tilde{x}_1 + 3\tilde{x}_2 = <(4,\ 5,\ 6),\ (5,\ 7,\ 9),\ (1,\ 2,\ 4)> = \tilde{b}_2(x). \end{cases} \tag{25}$$

Next using our approach, we have:

$$H = \begin{bmatrix} 4 & 0 & 0 & -1 \\ 1 & 3 & 0 & 0 \\ 0 & -1 & 4 & 0 \\ 0 & 0 & 1 & 3 \end{bmatrix}, \tag{26}$$

$$\tilde{b}_1(x) = \left\langle \begin{cases} x+3, & -1 \le x \le 0, \\ 4x+3, & 0 \le x \le 1, \end{cases}, \begin{cases} 2x+5, & -1 \le x \le 0, \\ x+5, & 0 \le x \le 1, \end{cases}, \begin{cases} x+1, & -1 \le x \le 0, \\ 2x+1, & 0 \le x \le 1, \end{cases} \right\rangle, \tag{27}$$

$$\tilde{b}_1(-x) = \left\langle \begin{cases} -4x+3, & -1 \le x \le 0, \\ -x+3, & 0 \le x \le 1, \end{cases}, \begin{cases} -x+5, & -1 \le x \le 0, \\ -2x+5, & 0 \le x \le 1, \end{cases}, \begin{cases} -2x+1, & -1 \le x \le 0, \\ -x+1, & 0 \le x \le 1, \end{cases} \right\rangle, \tag{28}$$

$$\tilde{b}_2(x) = \left\langle \begin{cases} x+5, & -1 \le x \le 0, \\ x+5, & 0 \le x \le 1, \end{cases}, \begin{cases} 2x+7, & -1 \le x \le 0, \\ 2x+7, & 0 \le x \le 1, \end{cases}, \begin{cases} x+2, & -1 \le x \le 0, \\ 2x+2, & 0 \le x \le 1, \end{cases} \right\rangle, \tag{29}$$

$$\tilde{b}_2(-x) = \left\langle \begin{cases} -x+5, & -1 \le x \le 0, \\ -x+5, & 0 \le x \le 1, \end{cases}, \begin{cases} -2x+7, & -1 \le x \le 0, \\ -2x+7, & 0 \le x \le 1, \end{cases}, \begin{cases} -2x+2, & -1 \le x \le 0, \\ -x+2, & 0 \le x \le 1, \end{cases} \right\rangle. \tag{30}$$

$$\widetilde{b}(x) = <s_{\widetilde{b}}(x),\ t_{\widetilde{b}}(x),\ u_{\widetilde{b}}(x)>. \tag{31}$$

So, using Equations (22)–(24), for $-1 \le x \le 0$:

$$P_Y(x) = \begin{bmatrix} p_1(x) \\ p_2(x) \\ p_1(-x) \\ p_2(-x) \end{bmatrix} = H^{-1} \begin{bmatrix} x+3 \\ x+5 \\ -4x+3 \\ -x+5 \end{bmatrix} = \begin{bmatrix} \frac{35}{143}x + \frac{14}{13} \\ \frac{36}{143}x + \frac{17}{13} \\ -\frac{134}{143}x + \frac{14}{13} \\ -\frac{3}{143}x + \frac{17}{13} \end{bmatrix}. \tag{32}$$

And for $0 \le x \le 1$:

$$P_Y(x) = \begin{bmatrix} p_1(x) \\ p_2(x) \\ p_1(-x) \\ p_2(-x) \end{bmatrix} = H^{-1} \begin{bmatrix} 4x+3 \\ x+5 \\ -x+3 \\ -x+5 \end{bmatrix} = \begin{bmatrix} \frac{134}{143}x + \frac{14}{13} \\ \frac{3}{143}x + \frac{17}{13} \\ -\frac{35}{143}x + \frac{14}{13} \\ -\frac{36}{143}x + \frac{17}{13} \end{bmatrix}. \tag{33}$$

So by setting $x = -1, 0$ in Equation (32) and also set $x = 1$ in Equation (33), we can get the triangular truth part of solution as follows:

$$x_{\text{true}} = \begin{bmatrix} < \frac{119}{143}, \frac{14}{13}, \frac{288}{143} > \\ < \frac{151}{143}, \frac{17}{13}, \frac{190}{143} > \end{bmatrix}. \tag{34}$$

In similar way, we can obtain the indeterminacy, and falsity parts of solution as follows:

$$\begin{aligned} x_{\text{in deter}} &= \begin{bmatrix} < \frac{193}{143}, \frac{22}{13}, \frac{258}{143} > \\ < \frac{174}{143}, \frac{23}{13}, \frac{343}{143} > \end{bmatrix}, \\ x_{\text{fals}} &= \begin{bmatrix} < \frac{38}{143}, \frac{5}{13}, \frac{116}{143} > \\ < \frac{35}{143}, \frac{7}{13}, \frac{152}{143} > \end{bmatrix}. \end{aligned} \tag{35}$$

Therefore, the final solution for NLS (25) is as follows:

$$\widetilde{x} = \left\langle \begin{bmatrix} \left(\frac{119}{143}, \frac{14}{13}, \frac{288}{143}\right) \\ \left(\frac{151}{143}, \frac{17}{13}, \frac{190}{143}\right) \end{bmatrix}, \begin{bmatrix} \left(\frac{193}{143}, \frac{22}{13}, \frac{258}{143}\right) \\ \left(\frac{174}{143}, \frac{23}{13}, \frac{343}{143}\right) \end{bmatrix}, \begin{bmatrix} \left(\frac{38}{143}, \frac{5}{13}, \frac{116}{143}\right) \\ \left(\frac{35}{143}, \frac{7}{13}, \frac{152}{143}\right) \end{bmatrix} \right\rangle. \tag{36}$$

## 5. Conclusions

In this paper, we introduced the NLS with a single-valued triangular neutrosophic number and developed a model based on neutrosophic structural elements for its solution. Using the monotone function on $[-1, 1]$, the $n \times n$ NLS is changed in this manner into $2n \times 2n$ crisp systems. The results demonstrate that the model is effective, straightforward, and involves far less work than the alternatives.

## Data Availability

Data supporting this research article are available from the corresponding author on reasonable request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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