

Research Article

Single-Valued Neutrosophic DEMATEL for Segregating Types of Criteria: A Case of Subcontractors' Selection

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The decision-making trial and evaluation laboratory (DEMATEL) has been used to solve numerous multicriteria decision-making (MCDM) problems, where real numbers are utilised in defining linguistic variables. Although the DEMATEL has shown its success in solving many decision-making problems, researchers have not fully understood how the DEMATEL works on non-real-number linguistic variables. Recent discovery of single-valued neutrosophic sets (SVNSs) can offer a new method to solve decision-making problems, where three memberships of SVNSs are used to define experts' linguistic judgment. This paper aims to propose a novel MCDM method, where SVNSs and the DEMATEL are fully utilised. Different from the DEMATEL, which directly utilises real numbers, this proposed method introduces SVNSs to better deal with truth, indeterminacy, and falsity in solving MCDM problem. As an application of the proposed method, subcontractors' selection problem is investigated using the proposed method, where four types of criteria are developed. A group of experts were invited to provide opinions and linguistic judgment regarding the degree of influence between criteria of subcontractors' selection. The linguistic evaluations defined in SVNSs were computed using the eight-step procedures of the proposed method. Based on the degree of influence, the computational results successfully segregated all ten criteria into four types, in which two to three criteria are grouped in each type. The results also suggest that "Experience" and "Quality" are the most influential criteria in subcontractors' selection. The segregation based on degree of influence would be greatly significant for the practical implementation of the subcontractors' selection.

1. Introduction

The decision-making trial and evaluation laboratory (DEMATEL) method is one of the many multicriteria decision-making (MCDM) methods available in literature. The DEMATEL was initially developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 and 1976 to resolve the complicated and intertwined problems. Compared with other MCDM techniques such as the analytic hierarchy process (AHP), where evaluation criteria are independent, this method is one of the structural modelling techniques that can identify the interdependencies of criteria through causality diagram and unidirectional analysis. The causal diagram uses digraphs rather than directionless graphs to portray the basic

concept of contextual relationships and the strengths of influence among the elements or criteria [1]. This method has been applied in analysing and developing the cause-and-effect relationship among evaluation criteria [2]. In other words, the DEMATEL is used to derive interrelationship among evaluation criteria or factors [3]. In other words, the DEMATEL is a comprehensive method for developing a basic model that contains causal connections between a number of complex criteria of decision problems. Using the DEMATEL, all evaluation criteria are partitioned into two groups, in which the first group is known as cause group and the second group is called as effect group. Owing to these positive features, the DEMATEL has been successfully applied in many recent decision-making problems (see [4–7]). It is good to note that pairwise comparisons between criteria

in DEMATEL are measured using a scale of real numbers accompanied by five linguistic terms.

Despite all these advantages, the linguistic terms used in DEMATEL suffer from several limitations. The linguistic scales based on real numbers are insufficient to provide a good evaluation or judgment because information is regularly exorbitant and, more importantly, many are vague and incomplete. In addition, elicitation of decision-makers' opinions using these linguistic scales could be misconstrued due to the restricted or incomplete information. In fact, the fuzziness in decision-makers' opinions or insufficient knowledge about an issue could make the decision-making process complicated [8]. In response to the limitation in dealing with incomplete information, neutrosophic sets were introduced [9]. A year later, neutrosophic sets were extended to single-valued neutrosophic sets (SVNSs) as to ease their applications to real scientific and engineering areas [10]. With the simplicity of SVNSs, these sets have been assimilated with other scientific knowledge such as aggregation operators, correlation studies, score functions, distance, and similarity measures. Ye [11], for example, presented the correlation coefficient between SVNSs and applied the proposed method to an illustrative example. Peng et al. [12] pointed out that some SVNS operations defined by Ye [11] may also be invalid and they defined novel operations and aggregation operators and applied them to similarity-measures problems. Peng et al. [13] also defined the multivalued neutrosophic sets and proposed two aggregation operators for the sets. Liu and Wang [14] defined a normalised weighted Bonferroni mean aggregation operator of SVNS. Şahin and Küçük [15] proposed the concept of neutrosophic subsethood based on distance measures for SVNSs. Majumdar and Samanta [16] studied the notions of distance and several similarity measures between two SVNSs as well as entropy of a SVNS. A hybrid model of score accuracy functions and SVNS was developed by Mondal and Pramanik [17], where this hybrid model was applied in teacher recruitment. Ye and Fu [18] proposed similarity measures between SVNSs based on tangent function and applied them to medical diagnosis problems. Very recently, Zhao et al. [19] and Tian et al. [20] proposed some new power Heronian aggregation operators for SVNSs and introduced a novel decision-making method using the proposed operators. Garai et al. [21] presented a new ranking method of SVN numbers based on possibility theory for solving a decision-making problem. The concept of possibility mean of SVN numbers was defined and the properties of single-valued trapezoidal neutrosophic (SVTN) numbers were studied. Finally, they developed a new ranking approach using the concept of weighted possibility mean, and Qin and Wang [22] studied the similarity and entropy measures of SVNS by proposing the axiomatic definitions of similarity and entropy for single-valued neutrosophic values (SVNVs) with respect to a new kind of inclusion relation between SVNVs. On the basis of Hamming distance, cosine function, and cotangent function, three similarity measures and three entropies for SVNVs were constructed. Other

related researches about SVNS and its application in multicriteria decision-making, matrices operations, and similarity measures can be retrieved from [23, 24] and [25], respectively. It can be seen that all these related researches have discussed the theoretical decision analyses or pattern recognition methods such as similarity measures, entropy, accuracy functions, aggregation operators, and distance measures without really applying to a real case data or experiment.

Turning now to related research of neutrosophic sets integrated with a specific MCDM method, Nabeeh et al. [26], for example, developed an integration of AHP-triangular neutrosophic numbers and applied it to estimate influential factors for a successful IoT enterprise. Abdel-Basset et al. [27] proposed a novel type-2 neutrosophic number-TOPSIS strategy by combining type-2 neutrosophic numbers and TOPSIS for supplier selection. Abdel Basset et al. [28] proposed an integration of bipolar neutrosophic numbers with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and applied it to medical device selection. However, the extent of integration between specific type of neutrosophic sets and DEMATEL is yet to be fully understood. The following section provides a brief of latest research that elucidates the merging of neutrosophic sets and DEMATEL. These reviews would provide an insight into the research gap between the recently published works and the proposed work.

2. Related Research and Identification of Research Gap

This section summarises the latest research that elucidates the integration of neutrosophic sets and DEMATEL. These reviews highlighted the type of neutrosophic numbers used, the integration of DEMATEL with other methods, and the fields of applications. Table 1 provides the recent researches that were carried out as well as research gaps.

It seems that little information is available on direct integration of SVNS linguistic variables to DEMATEL method. In addition, there were no researches that applied to subcontractors' selection and, more importantly, the absence of quadrant analysis in the analysis of their respective applications. To bridge these research gaps, this paper aims to propose an integration of SVNS and the DEMATEL (SVN-DEMATEL), where linguistic variables defined in SVNS are merged into the DEMATEL procedures. The integration of DEMATEL and SVNS ensued when linguistic variables used are now defined in three independent memberships of SVNS. In the SVN-DEMATEL framework, the eight-step computational procedures are characterised by truth-membership function, indeterminacy-membership function, and falsity-membership function. To illustrate the proposed method, a case of subcontractors' selection is investigated, where a quadrant analysis supplemented the other typical analysis in DEMATEL. Detailed descriptions of the subcontractors' selection problem, related definitions of SVNS, and the proposed SVN-DEMATEL method are presented in the subsequent sections.

TABLE 1: Summary of related researches and research gaps.

Authors	Type of NS	Method DEMATEL	Application	Research gap
Nabeeh [29]	Neutrosophic sets	DEMATEL method and data envelopment analysis	Technology selection process	Did not consider SVNS -No quadrant analysis An integration method
Abdel-Basset et al. [30]	Trapezoidal neutrosophic number	Integration of DEMATEL and TOPSIS	Project selection	No quadrant analysis -Focused on improving inverse matrix
Awang et al. [31]	Left-right neutrosophic numbers	Multiplicative inverse of decision matrix in DEMATEL	Coastal erosion	No quadrant analysis Many other methods were integrated to DEMATEL
Tan and Zhang [32]	Trapezoidal fuzzy neutrosophic	DEMATEL, fuzzy distance, and linear assignment method	Typhoon disaster evaluation	Did not consider SVNS No quadrant analysis
Tian et al [33]	Single-valued neutrosophic sets	DEMATEL with quality function deployment TODIM	Market segment evaluation and selection	-An integration of DEMATEL with two other methods No quadrant analysis
Feng et al. [34]	Neutrosophic sets	DEMATEL with VIKOR, TOPSIS, and ELECTRE III	Photovoltaic plan selection	An integration of DEMATEL with three other methods No quadrant analysis

3. Preliminaries

In light of the idea of big data as branch of information theory, it is essential to have a tool that can be used for managing vulnerability and irregularity of information. Therefore, Wang et al. [10] coined the concept of SVNS because SVNS is a subclass of the neutrosophic set and is very valuable in engineering application models. To ease the computation of SVNS in real-life applications, theoretical operations between two SVNSs are defined and some fundamental properties of these tasks are studied. This section provides the related definitions of SVNS and its operations.

Definition 1 (see [9]). Let X be a space of points (objects) with generic elements in S denoted by x . A neutrosophic set S in X is characterised by truth-membership function $T_S(x)$, indeterminacy-membership function $I_S(x)$, and falsity-membership function $F_S(x)$. The functions $T_S(x)$, $I_S(x)$ and $F_S(x)$ are real standard or nonstandard subsets of $]0^-, 1^+[$. That is, $T_S(x) \rightarrow]0^-, 1^+[$, $I_S(x) \rightarrow]0^-, 1^+[$, and $F_S(x) \rightarrow]0^-, 1^+[$. Thus, there is no restriction on the sum of $T_S(x)$, $I_S(x)$ and $F_S(x)$, so $0^- \leq \sup T_S(x) + \sup I_S(x) + \sup F_S(x) \leq 3^+$.

Obviously, it is difficult to apply in real scientific and engineering areas because of the nonstandard subsets of neutrosophic set. Hence, Wang et al. [10] introduced the definition of SVNS as follows.

Definition 2 (see [10]). Let X be a space of points (objects) with generic elements in X denoted by x . An SVNS S in X is characterised by truth-membership function $T_S(x)$, indeterminacy-membership function $I_S(x)$, and falsity-membership function $F_S(x)$. Then, an SVNS S can be denoted by $S = \{\langle x, T_S(x), I_S(x), F_S(x) \rangle x \in X\}$, where $T_S(x)$, $I_S(x)$, $F_S(x) \in [0, 1]$ for each point x in X . Therefore, the sum of $T_S(x)$, $I_S(x)$ and $F_S(x)$ satisfies the condition $0 \leq T_S(x) + I_S(x) + F_S(x) \leq 3$.

In decision-making, human language, commonly referred to as linguistic variables, is normally used. Ratings of criteria of decision problems can be expressed using linguistic variables that can be transformed into SVNNs. These SVNNs are a subset or a special case of SVNSs and defined as follows.

Definition 3 (see [10]). If an SVNS S can be denoted by $S = \{\langle x, T_S(x), I_S(x), F_S(x) \rangle x \in X\}$, where $T_S(x)$, $I_S(x)$, $F_S(x) \in [0, 1]$ for each point x in X and the sum of $T_S(x)$, $I_S(x)$ and $F_S(x)$ satisfies the condition $0 \leq T_S(x) + I_S(x) + F_S(x) \leq 3$, for convenience, $\alpha = \langle T_S, I_S, F_S \rangle$ to represent a SVNN.

These three membership functions work under specific arithmetic operations. The basic arithmetic operations of SVNNs are defined as follows.

Definition 4 (see [14]). Arithmetic operations between two SVNNs are defined as follows.

Let $x = (T_1, I_1, F_1)$ and $y = (T_2, I_2, F_2)$ be two SVNNs; then the arithmetic operations are defined as follows:

- (i) $x \oplus y = (T_1 + T_2 - T_1, T_2, I_1, I_2, F_1, F_2)$
- (ii) $x \otimes y = (T_1 T_2, I_1 + I_2 - I_1 I_2, F_1 + F_2 - F_1 F_2)$
- (iii) $\lambda x = ((1 - (1 - T_1)^\lambda), I_1^\lambda, F_1^\lambda)$
- (iv) $x^\lambda = (T_1^\lambda, 1 - (1 - I_1)^\lambda, 1 - (1 - F_1)^\lambda)$

Definition 5 (see [10]). If $x = (T_1, I_1, F_1)$ and $y = (T_2, I_2, F_2)$ are two SVNNs, then some properties of set theoretic operators are defined as follows:

- (i) Commutative:
 $x \cup y = (T_1, I_1, F_1) \cup (T_2, I_2, F_2) = (T_2, I_2, F_2) \cup (T_1, I_1, F_1) = y \cup x$
- (ii) Idempotent:
 $x \cup x = (T_1, I_1, F_1) \cup (T_1, I_1, F_1) = (T_1, I_1, F_1) = x$
 $x \cap y = (T_1, I_1, F_1) \cap (T_1, I_1, F_1) = (T_1, I_1, F_1) = y$

- (iii) Absorption: $x \cup x \cap y = (T_1, I_1, F_1) \cup (T_1, I_1, F_1) \cap (T_2, I_2, F_2) = (T_1, I_1, F_1) = x$
- (iv) De Morgan's laws: $k(x \cup y) = k((T_1, I_1, F_1) \cap k(T_2, I_2, F_2))$; $k(x \cap y) = k((T_1, I_1, F_1) \cup k(T_2, I_2, F_2))$, where k is a constant
- (v) Involution: $k(k(x)) = k(k(T_1, I_1, F_1)) = (T_1, I_1, F_1) = x$, where k is a constant

The definitions of complement, union, and intersection of SVN satisfy most properties of sets. In this paper, the SVN is integrated with the DEMATEL with some of the above definitions and properties being prevalently used in the computational procedures. Detailed description of this integration is presented in the following section.

4. Proposed SVN-DEMATEL

The algorithm of DEMATEL, proposed by Fontela and Gabus [35] and Gabus and Fontela [36], is used as a basis in proposing the SVN-DEMATEL. Different from DEMATEL where real numbers are used in defining linguistic scales, the proposed method used SVNNS instead. Several new innovations are made in this proposed method compared to the DEMATEL and the existing SVN-DEMATEL. Apart from substitution of real numbers with SVNNS, the proposed method also includes relative importance of decision-makers' weight. The importance of each decision-maker is measured using the proportion equation proposed by Boran et al. [37]. Instead of taking equal weights for decision-makers, this proposed method introduced relative weights, where each decision-maker has different weight. Another innovation is the way of transforming SVNNS into real numbers. In this proposed method, the concept of average using the equation proposed by Radwan and Fouda [38] is used. The three memberships of SVNNS are averaged to obtain a real number. This step would avoid the invalidity of finding multiplicative inverse of matrix in DEMATEL. Detailed discussion of validity of multiplicative inverse matrix can be retrieved from Awang et al. [31]. Different from most of the DEMATEL-based methods where the last computational step is drawing a causal-effect diagram, this proposed method extends with another step to establish four types of criteria. In summary, the framework of the proposed method is illustrated in Figure 1.

This flowchart is translated into stepwise algorithm. Our proposed algorithm of SVN-DEMATEL is presented as follows.

Step 1. Construct direct-relation matrix (DRM).

Each DM judgment is collected and pooled into a direct relation matrix $X_{n \times n}$ (total number of criteria is n) which is an assessment of interrelationship between elements utilising a 5-linguistic rating scale. The table indicates the interrelationship of selection of subcontractors and performances on each other.

Step 2. Find relative weights of decision-makers.

Each decision-maker's judgment has a particular weight that must be considered to determine total averaged crisp

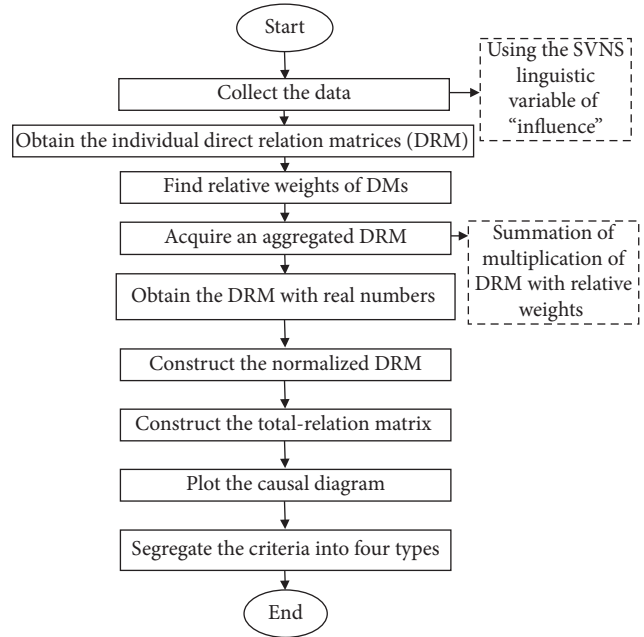


FIGURE 1: Framework of the proposed method.

matrix. As the work experience and knowledge of decision-makers' fluctuate, we assume distinctive overall weights for decision-makers' opinions in deciding the total averaged crisp matrix. Table 2 shows the linguistic variable used for relative importance weights of decision-makers and its respective SVNNS.

Assume that $\lambda_k = (T_k, I_k, F_k)$ is the SVNNS for relative importance weights of k th expert. The value of k th expert can be obtained using the following equation:

$$\lambda_k = \frac{T_k(x) + I_k(x)((T_k(x)/T_k(x) + F_k(x)))}{\sum_{k=1}^l T_k(x) + I_k(x)((T_k(x)/T_k(x) + F_k(x)))}, \quad (1)$$

where $\lambda_k \geq 0$, $\sum_{k=1}^l \lambda_k = 1$.

Step 3. Construct aggregated DRM.

Each decision-maker's opinions need to be aggregated to assemble a collective neutrosophic set decision matrix. Let $z_{ij}^k = (T_{ij}^k, I_{ij}^k, F_{ij}^k)$ be the SVN given by k th expert on the assessment of criterion i on j . The single-valued neutrosophic set weighted aggregation (SVNSWA) operator is used to aggregate single-valued neutrosophic number rating, and x_{ij} represents the influence level of criterion i on j .

$$\begin{aligned} a_{ij} &= \text{SVNSWA}(z_{ij}^1, z_{ij}^2, \dots, z_{ij}^k) \\ &= \sum_{k=1}^l \lambda_k z_{ij}^k = \left\langle 1 - \prod_{k=1}^l (1 - T_j)^{w_j}, \prod_{k=1}^l (I_j)^{w_j}, \prod_{k=1}^l (F_j)^{w_j} \right\rangle \\ & \quad i = 1, 2, \dots, m; \quad j = 1, 2, \dots, n, \end{aligned} \quad (2)$$

where λ_k is the importance weight of k th expert; a_{ij}^k is corresponding to SVN of k th expert's opinion when comparing i to j .

TABLE 2: Linguistic variable for relative importance weight of DM [39].

Linguistic variable	SVNN $\langle T, I, F \rangle$
Very important	$\langle 0.90, 0.10, 0.10 \rangle$
Important	$\langle 0.80, 0.20, 0.15 \rangle$
Medium	$\langle 0.50, 0.40, 0.45 \rangle$
Unimportant	$\langle 0.35, 0.60, 0.70 \rangle$
Very unimportant	$\langle 0.10, 0.80, 0.90 \rangle$

Step 4. Construct DRM with real numbers

Transform the aggregated single neutrosophic relation matrix into real number matrix using the following equation:

$$E(z) = \frac{(3 + T - 2I - F)}{4}. \quad (3)$$

Step 5. Construct normalised DRM.

Calculate the normalised DRM (matrix X) using the following equation:

$$X = k \times A, \quad (4)$$

where

$$k = \min \left(\frac{1}{\max_{1 \leq j \leq n} \sum_{i=1}^n |a_{ij}|}, \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^n |a_{ij}|} \right), i, j \in \{1, 2, 3, \dots, n\}, \quad (5)$$

and A is the normalised DRM.

Step 6. Obtain total-relation matrix (TRM).

The TRM, T, is then calculated using the following equation:

$$T = X(I - X)^{-1}, \quad (6)$$

where I is an identity matrix.

Step 7. Plot causal diagram.

Compute R and D from TRM, T, using equation (7) and equation (8).

Given T,

$$T = [t_y]_{n \times n}, \quad i, j = 1, 2, \dots, n, \quad (7)$$

$$R = \left[\sum_{i=1}^n t_y \right]_{1 \times n} = [t_j]_{1 \times n}, \quad (8)$$

$$D = \left[\sum_{j=1}^n t_y \right]_{n \times 1} = [t_i]_{n \times 1},$$

where R denotes the total of rows for the matrix and D denotes the total of columns for the matrix. A criterion is considered as a cause-and-effect criterion if (R - D) is positive and (R - D) is negative, respectively.

Step 8. Identify types of criteria.

Coordinates of (R + D, R - D) in Cartesian plane are used to segregate criteria into four types.

The proposed eight-step computational procedures are used to establish four types of criteria based on the degree of influence. Detailed implementation of the case of subcontractors' selection is presented in the following section.

4.1. A Case of Subcontractors' Selection. Subcontractors' selection is a critical part of construction or industrial management, where a major challenge is the existence of multiple criteria that the project management team needs to evaluate in the selection process [40, 41]. Subcontractors usually help main contractor to overcome problems related to the need for special expertise, limitation in finances, and shortage in resources. Specialist subcontractor can be utilised, when the main contractor acquires products or administrations, which the main contractor does not deliver or cannot deliver by his own company. Therefore, selecting the deliverable subcontractors is critical in making sure the implementation of the project is successful and completed within the stipulated times.

In solving subcontractors' selection problem, information about criteria, linguistic terms are required other than the algorithm of SVNS-DEMATEL. It is presented in the following sections.

4.2. Criteria, Linguistic Scale, and Decision-Makers.

Criteria that influence subcontractors' selection are retrieved from literature (see [42–44]). In this experiment, ten criteria are Price (C₁), Completing on Time (C₂), Experience (C₃), Financial Stability (C₄), Compliance with Regulations (C₅), Quality (C₆), Performance History (C₇), Safety Management (C₈), Timely Payment to Labour (C₉), and Length of Time in Industry (C₁₀). These evaluation criteria are judged by a group of decision-makers using a five-point linguistic scale. The judgments are made in pairwise comparison manner, in which one criterion is compared to the other criteria in terms of degree of influence. Table 3 presents linguistic variable of "influence," five linguistic terms and their respective SVNS.

In this study, five decision-makers denoted as DM1, DM2, DM3, DM4, and DM5, respectively, are assigned to provide pairwise comparative linguistic judgments of criteria using the defined linguistic scale. All decision-makers are experts in selecting subcontractors and currently hold key positions in a construction company. A formal letter was sent to the decision-makers and they were requested to rate a criterion with respect to other criteria in terms of degree of influence of selecting subcontractors using the linguistic scale. Linguistic data obtained from decision-makers are implemented to the proposed SVNS-DEMATEL.

4.3. Implementation. In accordance with the proposed algorithm (see Section 3), the following computations are implemented.

TABLE 3: Five-point linguistic scale [39].

Linguistic terms	SVNS $\langle T, I, F \rangle$
No influence (NI)	$\langle 0.00, 1.00, 1.00 \rangle$
Extremely low influence (ELI)	$\langle 0.20, 0.85, 0.80 \rangle$
Low influence (LI)	$\langle 0.40, 0.65, 0.60 \rangle$
High influence (HI)	$\langle 0.60, 0.35, 0.40 \rangle$
Extremely high influence (EHI)	$\langle 0.80, 0.15, 0.20 \rangle$

Step 1: construct DRM

All individual decision-makers' DRM are constructed. Table 4 summarises the judgments of DM1 regarding the influences of the criteria on subcontractors' selection.

Similar DRM matrices are constructed for DM2, DM3, DM4, and DM5. It is good to recall that the linguistic terms in the matrices indicate the interrelationship between criteria in subcontractors' selection.

Step 2: find relative weight of decision-makers

Relative weights of the decisionmakers λ_k are computed using equation (1). They are presented in Table 5.

Step 3: construct aggregated DRM

The aggregated DRM is constructed using equation (2). For example,

$$a_{11}1 - \prod_{k=1}^l (1 - T_j)^{\lambda_k} = 1 - ((1 - 0.00) \wedge 0.2913 * (1 - 0.00) \wedge 0.2849 * (1 - 0.00) \wedge 0.2090 * (1 - 0.00) \wedge 0.1618 * (1 - 0.00) \wedge 0.0530)$$

$$= 0.000,$$

$$\prod_{k=1}^l (I_j)^{\lambda_k} = 1 \wedge (0.2913) * 1 \wedge (0.2849) * 1 \wedge (0.2090) * 1 \wedge (0.1618) * 1 \wedge (0.0530) = 1.000,$$

$$\prod_{k=1}^l (F_j)^{\lambda_k} = 1 \wedge (0.2913) * 1 \wedge (0.2849) * 1 \wedge (0.2090) * 1 \wedge (0.1618) * 1 \wedge (0.0530) = 1.000,$$

$$a_{21}1 - \prod_{k=1}^l (1 - T_j)^{\lambda_k} = 1 - ((1 - 0.60) \wedge 0.2913 * (1 - 0.80) \wedge 0.2849 * (1 - 0.60) \wedge 0.2090 * (1 - 0.20) \wedge 0.1618 * (1 - 0.60) \wedge 0.0530)$$

$$= 0.6327,$$

$$\prod_{k=1}^l (I_j)^{\lambda_k} = 0.35 \wedge (0.2913) * 0.15 \wedge (0.2849) * 0.35 \wedge (0.2090) * 0.85 \wedge (0.1618) * 0.35 \wedge (0.0530)$$

$$= 0.3174,$$

$$\prod_{k=1}^l (F_j)^{\lambda_k} = 0.40 \wedge (0.2913) * 0.20 \wedge (0.2929) * 0.40 \wedge (0.2090) * 0.80 \wedge (0.1618) * 0.40 \wedge (0.0530)$$

$$= 0.3673,$$

(9)

Part of the aggregated DRM is shown in Table 6.

Step 4: construct DRM with real numbers

Transform the aggregated SVNS matrix into aggregated real number DRM using equation (3).

TABLE 4: Judgments of criteria (DM1).

Criteria	C1	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀
C1		HI	NI	ELI	ELI	HI	ELI	NI	NI	NI
C2	LI		ELI	NI	NI	ELI	LI	ELI	ELI	LI
C3	HI	HI		ELI	ELI	HI	LI	NI	ELI	HI
...
C ₁₀	ELI	LI	HI	NI	NI	ELI	LI	ELI	NI	LI

TABLE 5: Relative weights of decision-makers.

Decision-makers	DM1	DM2	DM3	DM4	DM5
Lambda, λ _k	0.2913	0.2849	0.2090	0.1618	0.0530

TABLE 6: Aggregated DRM.

Criteria	C ₁	C ₂	C ₃	...	C ₈	C ₉	C ₁₀
C ₁	$\left\langle \begin{matrix} 0.0000, \\ 1.0000, \\ 1.0000 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.5742 \\ 0.3947 \\ 0.4258 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.2566 \\ 0.7754 \\ 0.7434 \end{matrix} \right\rangle$	...	$\left\langle \begin{matrix} 0.2630, \\ 0.7875, \\ 0.7370 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.6289, \\ 0.3296, \\ 0.3711 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.2566, \\ 0.7754, \\ 0.7434 \end{matrix} \right\rangle$
C ₂	$\left\langle \begin{matrix} 0.6327, \\ 0.3174, \\ 0.3673 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.0000, \\ 1.0000, \\ 1.0000 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.3475 \\ 0.6867 \\ 0.6525 \end{matrix} \right\rangle$	...	$\left\langle \begin{matrix} 0.2643, \\ 0.7861, \\ 0.7357 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.5269, \\ 0.4592, \\ 0.4731 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.5777, \\ 0.3796, \\ 0.4223 \end{matrix} \right\rangle$
C ₃	$\left\langle \begin{matrix} 0.7611, \\ 0.1902, \\ 0.2389 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.7925, \\ 0.1569, \\ 0.2075 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.0000, \\ 1.0000, \\ 1.0000 \end{matrix} \right\rangle$	...	$\left\langle \begin{matrix} 0.5759, \\ 0.3861, \\ 0.4241 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.4444, \\ 0.5577, \\ 0.5556 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.6622, \\ 0.2870, \\ 0.3378 \end{matrix} \right\rangle$
...
C ₁₀	$\left\langle \begin{matrix} 0.6424, \\ 0.3184, \\ 0.3576 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.6553, \\ 0.2918, \\ 0.3447 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.7522, \\ 0.1989, \\ 0.2478 \end{matrix} \right\rangle$	...	$\left\langle \begin{matrix} 0.3908, \\ 0.6593, \\ 0.6092 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.4130, \\ 0.5718, \\ 0.5870 \end{matrix} \right\rangle$	$\left\langle \begin{matrix} 0.0000, \\ 1.0000, \\ 1.0000 \end{matrix} \right\rangle$

For C₁, the computations are

$$\begin{aligned}
 a_{11} &= \frac{(3 + 0.0000 - 2 * 1.0000 - 1.0000)}{4} = 0.0000, \\
 a_{21} &= \frac{(3 + 0.6327 - 2 * 0.3174 - 0.3673)}{4} = 0.6577, \\
 a_{31} &= \frac{(3 + 0.7611 - 2 * 0.1902 - 0.2389)}{4} = 0.7855, \\
 a_{41} &= \frac{(3 + 0.4444 - 2 * 0.5577 - 0.5556)}{4} = 0.4433, \\
 a_{51} &= \frac{(3 + 0.4610 - 2 * 0.5185 - 0.5390)}{4} = 0.4713, \\
 a_{61} &= \frac{(3 + 0.7688 - 2 * 0.1791 - 0.2312)}{4} = 0.7949 \\
 a_{71} &= \frac{(3 + 0.6731 - 2 * 0.2735 - 0.3269)}{4} = 0.6998, \\
 a_{81} &= \frac{(3 + 0.6150 - 2 * 0.3455 - 0.3850)}{4} = 0.6347, \\
 a_{91} &= \frac{(3 + 0.4405 - 2 * 0.5406 - 0.5595)}{4} = 0.4499, \\
 a_{101} &= \frac{(3 + 0.6424 - 2 * 0.3184 - 0.3576)}{4} = 0.6620,
 \end{aligned}
 \tag{10}$$

This matrix is presented in Table 7.

Step 5: construct normalised DRM

In order to construct normalised DRM, summation of rows and summation of columns of DRM are computed first. The summation of rows and summation of columns are shown in Table 8.

The maximum numbers from summation of rows and summation of columns are identified (bold). With these maximum numbers, *k* is calculated using equation (4).

$$k = 0.1586. \tag{11}$$

The DRM in Table 6 is normalised by multiplying with *k*. The maximum numbers from summation of rows and summation of columns have been chosen, respectively, as

$$\begin{aligned}
 k &= \min\left(\frac{1}{5.8834}, \frac{1}{6.3056}\right) \\
 &= \min(0.1700, 0.1586) \\
 &= 0.1586.
 \end{aligned}
 \tag{12}$$

Multiply the Direct-Relation Matrix with *k* to normalise it.

TABLE 7: Aggregated DRM with real numbers.

Criteria	C_1	C_2	C_3	...	C_8	C_9	C_{10}
C_1	0.0000	0.5898	0.2406	...	0.2378	0.6496	0.2406
C_2	0.6577	0.0000	0.3304	...	0.2391	0.5339	0.5991
C_3	0.7855	0.8178	0.0000	...	0.5949	0.4433	0.6876
C_4	0.4433	0.7484	0.1870	...	0.5345	0.6818	0.2378
C_5	0.4713	0.7333	0.3295	...	0.7738	0.6152	0.5373
C_6	0.7949	0.7727	0.5391	...	0.5019	0.3798	0.4959
C_7	0.6998	0.6797	0.7018	...	0.4959	0.5165	0.5535
C_8	0.6347	0.6922	0.4657	...	0.0000	0.2489	0.4250
C_9	0.4499	0.5901	0.4235	...	0.2300	0.0000	0.3919
C_{10}	0.6620	0.6818	0.7766	...	0.3657	0.4206	0.0000

TABLE 8: Summation of rows and columns.

Criteria	Summation of rows	Summation of columns
C_1	4.1834	5.5991
C_2	4.1228	6.3056
C_3	5.8834	3.9943
C_4	3.8961	4.0049
C_5	4.8499	3.9644
C_6	5.4122	4.3552
C_7	5.0220	5.4200
C_8	4.6333	3.9735
C_9	3.4352	4.4896
C_{10}	4.8369	4.1686

C_1 :

$$\begin{aligned}
 a_{11} &= 0.0000 * 0.1586 = 0.0000, \\
 a_{21} &= 0.5898 * 0.1586 = 0.0935, \\
 a_{31} &= 0.2406 * 0.1586 = 0.0382, \\
 a_{41} &= 0.6508 * 0.1586 = 0.1032, \\
 a_{51} &= 0.4206 * 0.1586 = 0.0667, \\
 a_{61} &= 0.7855 * 0.1586 = 0.1246, \\
 a_{71} &= 0.3682 * 0.1586 = 0.0584, \\
 a_{81} &= 0.2378 * 0.1586 = 0.0377, \\
 a_{91} &= 0.6496 * 0.1586 = 0.1030, \\
 a_{101} &= 0.2406 * 0.1586 = 0.0382.
 \end{aligned}
 \tag{13}$$

The normalised DRM is shown in Table 9.

The ten-by-ten matrix represents the normalised DRM with real numbers.

Step 6: obtain total-relation matrix (TRM)

The TRM is obtained using equation (6). This is the matrix obtained as a result of multiplicative inverse of DRM with differences of identity matrix and DRM.

TABLE 9: Normalised DRM.

Criteria	C_1	C_2	C_3	...	C_8	C_9	C_{10}
C_1	0.0000	0.0935	0.0382	...	0.0377	0.1030	0.0382
C_2	0.1043	0.0000	0.0524	...	0.0379	0.0847	0.0950
C_3	0.1246	0.1297	0.0000	...	0.0943	0.0703	0.1090
C_4	0.0703	0.1187	0.0297	...	0.0848	0.1081	0.0377
C_5	0.0747	0.1163	0.0523	...	0.1227	0.0976	0.0852
C_6	0.1261	0.1225	0.0855	...	0.0796	0.0602	0.0786
C_7	0.1110	0.1078	0.1113	...	0.0786	0.0819	0.0878
C_8	0.1007	0.1098	0.0739	...	0.0000	0.0395	0.0674
C_9	0.0714	0.0936	0.0672	...	0.0365	0.0000	0.0621
C_{10}	0.1050	0.1081	0.1232	...	0.0580	0.0667	0.0000

For example, total-relation matrix can be found by multiplying X with $(I - X)^{-1}$.

$$\begin{aligned}
 a_{11} &= 0.0000(1.2174) + 0.0935(0.3262) \\
 &\quad + 0.0382(0.1934) + 0.1032(0.2559) \\
 &\quad + 0.0667(0.2172) + 0.1246(0.2854) \\
 &\quad + 0.0584(0.2620) + 0.0377(0.1899) \\
 &\quad + 0.1030(0.2751) + 0.0382(0.2020) \\
 &= 0.2174.
 \end{aligned}
 \tag{14}$$

Table 10 shows the TRM.

Step 7: plot causal diagram

Cause-and-effect diagram is obtained by calculating the sum of rows, R , and the sum of columns, D . These two sums are used to compute $R + D$ and $R - D$ values.

We have the following example.

Summation of rows:

$$\begin{aligned}
 C_1 &= 0.2174 + 0.3262 + 0.1934 + 0.2559 + 0.2172 \\
 &\quad + 0.2854 + 0.2620 + 0.1899 + 0.2751 + 0.2020 \\
 &= 2.4247.
 \end{aligned}
 \tag{15}$$

Summation of columns:

$$\begin{aligned}
 C_1 &= 0.2174 + 0.3147 + 0.4201 + 0.2660 + 0.3248 \\
 &\quad + 0.3954 + 0.3646 + 0.3402 + 0.2512 + 0.3548 \\
 &= 3.2492.
 \end{aligned}
 \tag{16}$$

Table 11 presents these values according to criteria.

The results can be obtained by mapping the data set of $(R + D, R - D)$ into Cartesian plane, in which the

TABLE 10: TRM.

Criteria	C_1	C_2	C_3	...	C_8	C_9	C_{10}
C_1	0.2174	0.3262	0.1934	...	0.1899	0.2751	0.2020
C_2	0.3147	0.2411	0.2108	...	0.1897	0.2588	0.2531
C_3	0.4201	0.4540	0.2236	...	0.3014	0.3180	0.3324
C_4	0.2660	0.3276	0.1751	...	0.2164	0.2645	0.1896
C_5	0.3248	0.3843	0.2372	...	0.2886	0.2963	0.2733
C_6	0.3954	0.4205	0.2819	...	0.2712	0.2905	0.2862
C_7	0.3646	0.3885	0.2918	...	0.2582	0.2934	0.2820
C_8	0.3402	0.3718	0.2483	...	0.1746	0.2427	0.2522
C_9	0.2512	0.2886	0.1964	...	0.1646	0.1526	0.1995
C_{10}	0.3548	0.3823	0.2988	...	0.2365	0.2751	0.1979

TABLE 11: R , D , $R + D$, and $R - D$ for criteria.

Criteria	R	D	$R + D$	$R - D$
C_1	2.4247	3.2492	5.6739	-0.8245
C_2	2.4327	3.5848	6.0176	-1.1521
C_3	3.4056	2.3573	5.7628	1.0483
C_4	2.2383	2.3834	4.6218	-0.1451
C_5	2.8249	2.3416	5.1665	0.4833
C_6	3.1288	2.5993	5.7281	0.5295
C_7	2.9301	3.0943	6.0244	-0.1642
C_8	2.7429	2.2910	5.0339	0.4519
C_9	2.0477	2.6672	4.7149	-0.6195
C_{10}	2.8608	2.4683	5.3291	0.3925

performance of each criterion of the entire subcontractors' selection system can be measured or interpreted.

5. Results

The $(R + D)$ and $(R - D)$ values are translated into a causal diagram. Figure 2 shows the causal diagram where cause group and effect group of criteria are separated by $R + D$ axis.

The above causal diagram visualises the cause criteria and the effect criteria. The cause criteria are Experience, Quality, Length of Time in Industry, Compliance with Regulations, and Safety Management as their values of $(R - D)$ are positives. On the other hand, the effect criteria are Financial Stability, Performance History, Timely Payment to Labour, Price, and Completing on Time as their values of $(R - D)$ are negatives. It is suggested that the criteria in cause group ought to be given priority as these criteria influence other criteria in suggesting the best subcontractors. This result also indicates that "Experience" is the most influential factor in subcontractors' selection owing to the largest value of $(R - D)$.

Step 8: identify types of criteria

The interpretation of this diagram can be further made based on the coordinates of $(R + D, R - D)$. Tsai et al. [45] suggest that criteria can be divided into four types. In this analysis, all criteria are mapped into four quadrants based on the coordinates of $(R + D, R - D)$. The first type is ensued when $(R - D)$ is positive and $(R + D)$ is large. This indicates that the criteria are the cause criteria which are also driving

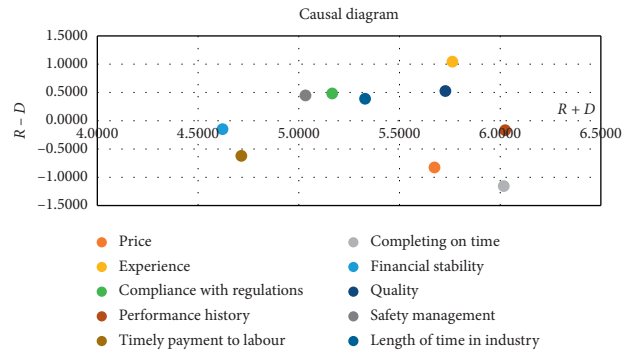


FIGURE 2: Causal diagram of criteria.

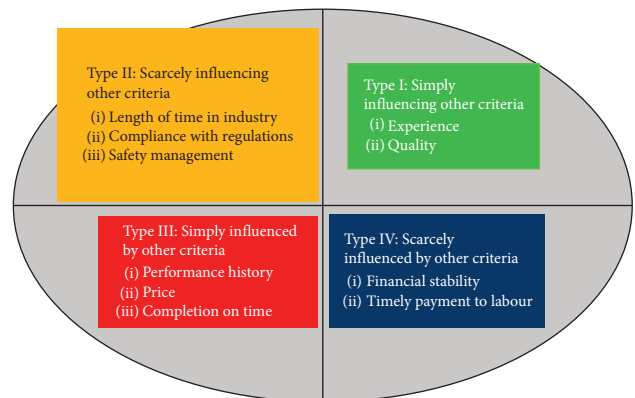


FIGURE 3: Quadrant analysis.

cause for solving problems. Therefore, the criterion "Experience" is the most important cause in influencing subcontractors' selection. The second type happens when $(R - D)$ is positive and $(R + D)$ is small. This indicates that the criteria are independent and can influence only a few other criteria. In this subcontractors' selection, the criterion "Safety Management" is an independent criterion and does not influence other criteria much. The third type is ensued when $(R - D)$ is negative and $(R + D)$ is large. This indicates that the criteria are effect-type in which can be directly improved. The criterion "Completing on Time" is an effect criterion, where it depends heavily on other criteria. Finally, the interpretation can be made when $(R - D)$ is negative and $(R + D)$ is small. This indicates that the criteria are independent and hardly influenced by other criteria. In the case of subcontractors' selection, the criterion "Financial Stability" is seen as an independent criterion. Summarily, these types of criteria and their respective criteria of subcontractors' selectors are divided into four quadrants.

Figure 3 depicts the quadrant analysis in which four types of criteria are identified.

Looking at the results from the two figures, it is shown that "Experience" and "Quality" are the driving factors of influencing the selection of subcontractors. Therefore, subcontractors who had vast experience and produced quality works would have an advantage to be chosen as subcontractors. This result is different from that of [46] which suggested that "on-time delivery of materials,"

“failure to complete contract,” and “reputation” are the most influencing criteria. Perhaps the different research frameworks used in these studies contributed to the different results.

6. Conclusions

Multicriteria decision-making methods under neutrosophic environment are an active research area and many relevant integration methods have been investigated over the years. However, real applicability of the decision-making methods can be achieved when the detailed integration of the decision-making method and neutrosophic sets is well understood. In this paper, an extended neutrosophic set is integrated with a decision-making method to gain better understanding about the use of neutrosophic sets in decision-making. The SVNS was proposed to substitute the neutrosophic sets due to its complexity in computations, particularly in real scientific and engineering case applications. The SVNS also has no direct integration with causal analysis decision-making methods such as DEMATEL despite the advantages of its three memberships in dealing with indeterminacy information. This paper proposed the SVNS-DEMATEL method, where the real numbers in DEMATEL are substituted with SVNN. This proposed method is applied to subcontractors' selection, where ten criteria are evaluated. The aim of the proposed method is a plot of causal diagram. In this paper, we identified the cause criteria and the effect criteria that could be used in subcontractors' selection. Truth membership, indeterminacy membership, and falsity membership of SVNS provide a comprehensive evaluation of criteria, in which all criteria are successfully separated into two groups. The proposed SVN-DEMATEL method is a valuable instrument to decide the key criteria that could become cause criteria and effect criteria. The experimental results show that the proposed method can successfully capture the important result of decision-making, where the criteria “Experience” and “Quality” are the main causes that need to be highly considered in subcontractors' selection, while “Completing on Time” is a criterion that has no effect in subcontractors' selection. Differentiating the important criteria while choosing subcontractors would really help the main contractor in ensuring the success of construction projects.

The contributions of this paper are fivefold:

- (1) We propose using relative weights of decision-makers based on three memberships of SVNS instead of considering equal weights among the five decision-makers. The proposed method uses a proportion equation that makes the weights of decision-makers more suitable for real-life application.
- (2) We propose using a weighted averaging operator to find aggregated direct relation matrix, where a series of multiplications of assessment scales and relative weights of decision-makers are accounted.
- (3) We propose introducing a transformation equation instead of typical averaged defuzzification method to transform three memberships of SVNS to single real numbers.

- (4) We propose an extension to the computational procedures of DEMATEL, where all criteria under investigation are segregated into four types based on degree of influence.
- (5) We extend the analysis in the application part with quadrant analysis, where all criteria are mapped onto one of the four quadrants. This analysis is in addition to the causal diagram, which is typically used in the analysis of DEMATEL. These five contributions are embedded in the proposed SVNS-DEMATEL, in which ten criteria of subcontractors' selection are segregated into four types. In future studies, we would like to extend the SVN-DEMATEL beyond the scope of causal diagram. As the SVN-DEMATEL can effectively identify the criteria, the two obtained groups of criteria contain useful information about which criteria specifically influenced other criteria. These unidirectional relationships can be explored as part of future research direction.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed equally to the writing of this manuscript and read and approved the final manuscript.

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