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Solution for Convergence Problem in DEMATEL Method: DEMATEL of Finite Sum of Influences

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Abstract: Decision-making trial and evaluation laboratory (DEMATEL) is one of the multicriteria decision-making methods based on asymmetric linguistic comparison matrices that has received a great deal of attention, and it is a widely used method in various fields. One of the drawbacks of DEMATEL is a convergence problem that may occur when the infinite sum of normalized influences does not converge. Based on the observations of some examples, the new concept of DEMATEL, the DEMATEL of a finite sum of influences (FSI DEMATEL), is proposed. Instead of an infinite sum, a finite sum of influences is used in FSI DEMATEL so that the convergence problem is avoided. The advantage is that FSI DEMATEL can handle more decision-making problems than the DEMATEL. It can also be used for fuzzy evaluations. FSI DEMATEL can be used as the multicriteria decision-making method to evaluate the relationships between the factors in many different fields.

Keywords: multicriteria decision-making; DEMATEL of a finite sum of influences; fuzzy numbers; defuzzification; convergence problem

1. Introduction

Nowadays, decision-making in many intelligent systems is a very important process that is complicated due to uncertainty, vagueness, limited knowledge, sources, and time [1]. Multicriteria decision-making (MCDM) is the collective term for mathematical methods for solving decision problems with multiple conflicting criteria [2], which differ in their properties and problem types that they are best suited for solving. A subset of MCDM methods are subjective methods, where experts evaluate objects based on their knowledge and experience [3]. Most of them are weighting methods with the goal of assigning weights to objects. Many methods use pairwise comparisons between objects, of which AHP (analytic hierarchy process) is the most popular [4], while BWM (best–worst method) [5] has also gained popularity in the last decade. Full consistency method (FUCOM) and level-based weight assessment (LBWA) [6] are two of the newer methods based on pairwise comparisons that have been introduced in recent years. TOPSIS (technique for order performance by similarity to ideal solutions) and VIKOR (vise kriterijumska Optimizacija i kompromisno resenje) are two of the best known methods where alternatives are directly evaluated with respect to multiple criteria [4], while CILOS [7] (method of the criterion impact loss) is one such method developed in recent years. The most known outranking methods are PROMETHEE (preference ranking organization method for enrichment evaluation) and ELECTRE (elimination et choix traduisant la relalite) [4]. Methods that focus on evaluating the interdependencies among criteria are DEMATEL (decision-making trial and evaluation laboratory) [8], ANP (analytic network process), and the more recent method WINGS (weighted influence nonlinear gauge system [9]).

This paper focuses on DEMATEL (decision-making trial and evaluation laboratory) [4], one of the most widely used MCDM methods [10], which is the seventh most frequently used MCDM method in applications. It was first developed by the Geneva Research Centre of the Battelle Memorial Institute to visualize the structure of complex causal

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relationships through matrices and digraphs. It is especially useful in analyzing the cause-and-effect relationships between factors of the system and also to find the critical factors of a system [10]. DEMATEL has received a great deal of attention, and it is a widely used method in various fields, such as engineering [11,12], management sciences [13,14], medicine [15], COVID-19 [16–18], energy [19,20], urbanization [21,22], ecology [23,24], and others. It is also one of suitable methods to deal with the degree of importance of evaluation factors and to determine the cause–effect relationships between factors [25]. Compared to other MCDM methods, DEMATEL has some advantages. It effectively analyzes the direct and indirect relationships and influences between different factors and visualizes the relationships. DEMATEL can be used to calculate the weights of factors and determine their ranking, as well as identify critical factors [8].

Depending on the application of the DEMATEL, it can be classified into three types: The first type is just clarifying the correlations between the factors; the second type identifies the key factors based on the causal relationships and the degrees of relationships between them; and the third type determines the factors weights by analyzing the relationships and impact levels of factors [8].

Moreover, many innovations, hybrid methods, and combinations, such as DEMATEL and BMW [26], DEMATEL and TOPSIS [27,28], AHP and DEMATEL [29], DEMATEL and PROMETHEE [16], DEMATEL-ISM [30], DEMATEL and ANP [15], and others, have been explored in the mentioned method [8,25].

In an uncertain environment, the outcome of decision-making is highly influenced by subjective judgments. Decision makers' assessments are in asymmetric and vague information. Fuzzy set theory and grey theory are mathematical tools to represent and manage vagueness and uncertainty in decision-making [31,32]. Therefore, many authors use triangular fuzzy numbers (TFNs) [12], grey numbers [33], hesitant fuzzy evaluation [33], or other fuzzy evaluation [14,21,25,34–36] in DEMATEL to represent decision makers' evaluations.

There are two variants of the fuzzy DEMATEL. The difference between them is in the timing of the defuzzification process. In the first variant, the defuzzification process takes place at the beginning (before the method starts), while in the second variant, defuzzification takes place at the end of the method calculations.

In the first one, the experts estimates are given with TFNs and converted into scalar values, before the method is applied [37]. Its main drawback is that early defuzzification reduces the importance of the TFNs [1,38–40]. In the second variant, the decision makers use the TFNs throughout the DEMATEL, and the defuzzification is performed at the end of the method calculations [1]. Another problem in DEMATEL is a convergence problem. If all row sums of the normalized direct relation matrix are equal to 1, then the matrix is stochastic [41], and the infinite sum of normalized influences does not converge; therefore, the total relation matrix $T = X + X^2 + X^3 + \ldots$ does not exist [42]. Some authors have already tried to solve the convergence problem [38,42–44]. In the literature [45], several other problems in DEMATEL are described, e.g., experts weights of importance, the differences between formulas for calculating the weights of factors, and the problem of normalizing the initial scores [8].

The aim of this paper is to introduce a new concept in DEMATEL that can solve the convergence problem. Based on the observations from some examples, the new concept in DEMATEL, the DEMATEL of a finite sum of influences (FSI DEMATEL), is proposed. DEMATEL uses the infinite sum of influences, while FSI DEMATEL uses the finite sum. By using the new concept in the fuzzy DEMATEL, defuzzification is not required at the beginning and the fuzzy numbers can be used throughout the method. The DEMATEL and FSI DEMATEL are applied in several examples. The comparison between DEMATEL and FSI DEMATEL shows that FSI DEMATEL is suitable for application and can handle more decision problems than DEMATEL. A comparison between FSI DEMATEL and selected other subjective weighting MCDM methods confirms the suitability of FSI DEMATEL, when the analysis of interrelations between objects is the primary goal.

The FSI DEMATEL can be applied as an MCDM method to evaluate the influence of factors. It can be used in many different fields, such as engineering, management, medicine, energy, urbanization, ecology, and others (such as DEMATEL). However, FSI DEMATEL can deal with more decision problems than DEMATEL. When a convergence problem arises, DEMATEL cannot be used, but FSI DEMATEL can. In this paper, the FSI DEMATEL is also applied to two real problems from the literature.

The rest of this paper is organized as follows: In Section 2, we introduce the DEMATEL, fuzzy numbers, and the problems that arise when fuzzy numbers are included in DEMATEL. In Section 3, we propose a new approach, FSI DEMATEL, which is explained with some examples. At the end of the paper, we give a summary of our research and suggestions for future work with FSI DEMATEL.

2. Methods

2.1. DEMATEL

DEMATEL is used for the analysis of relationships between causes and effects of components of the system. DEMATEL is divided into four steps:

Step 1: Generate the direct-influence matrix D.

Select n factors for comparison. Experts are asked to make pairwise comparisons between those factors. They use a scale 0 to 4, where 0 represents no influence and 4 represents very high influence (Table 1). The assessments of m experts are arranged in the direct matrix $D^k = \left[d_{ij}^k\right]$, where D^k is nxn matrix and d_{ij}^k indicates the assessment of expert k in relation to the direct influence of factor i on factor j. D^k is an asymmetric matrix as the influence of factor i on factor j is not necessarily equal to the influence of factor j on factor i. The group direct matrix $D = \left[d_{ij}\right]$ is an average of matrices D^k, where its factors d_{ij} are the arithmetic means of the factors $d_{ij}^k, k = 1, \ldots, m$.

Table 1. Linguistic terms, their corresponding scalar numbers, and their corresponding triangular fuzzy number.

Linguistic Terms	Abbreviation	Corresponding Scalar Number	Corresponding Triangular Fuzzy Number
No influence	NI	0	(0, 0, 0.25)
Very low influence	VLI	1	(0, 0.25, 0.5)
Low influence	LI	2	(0.25, 0.5, 0.75)
High influence	HI	3	(0.5, 0.75, 1)
Very high influence	VHI	4	(0.75, 1, 1)

A diagram, called a map of influence relations between factors, can also be created. It consists of factors presented with circles and connections between factors and presented with arrows. The assessments of the factors are written on the arrows.

Step 2: Derive the normalized direct-relation matrix X.

$X = \left[x_{ij}\right]$ is the normalized direct-relation matrix, and x_{ij} is calculated by dividing d_{ij} by the maximum row sum as follows:

$$x_{ij} = \frac{d_{ij}}{\max\limits_{1 \le i \le n} \sum\limits_{j=1}^{n} d_{ij}}, \ i, j = 1, \ldots, n. \tag{1}$$

Step 3: Derive the total relation matrix T.

Total relation matrix T is an infinitive sum of influences among factors. $T = \left[t_{ij}\right]$ is calculated as follows:

$$T = X + X^2 + \ldots + X^n + \ldots = X(I - X)^{-1} \tag{2}$$

where I is the identity matrix.

Step 4: Sum the rows and columns and construct the causal diagram.

The row sums R_i, $i = 1, \ldots, n$ and the column sums C_j, $j = 1, \ldots\ n$ are calculated as follows;

$$R_i = \sum_{j=1}^{n} t_{ij},\ i = 1, \ldots, n, \tag{3}$$

$$C_j = \sum_{i=1}^{n} t_{ij},\ j = 1, \ldots, n. \tag{4}$$

R_i represents direct and indirect effects of the factor i on other factors. C_j represents direct and indirect effects that the factor j receives from all other factors. $R_i + C_i$ is also called prominence value and represents the importance of factor i. The net effect that factor i contributes to the system represents the difference $R_i - C_i$ or relations value.

When the influences of factors are determined using the DEMATEL, a causal diagram can be constructed for better transparency and easier analysis. It consists of a horizontal axis (prominence), which indicates how important the factor is, and a vertical axis (relations), which classifies the factor in a cause group or an effect group [46]. Absolute and relative values can be studied in the diagram. The absolute values depend on the normalization of assessments. There are few different types of normalization [8], so the same assessments can have different absolute values of the final results. Therefore, the relative values are important, which represent the relationships between the factors.

Step 5: The weights of factors can be calculated using Equation (5). Step 5 is optional.

$$\omega_i = \sqrt{(R_i + C_i)^2 + (R_i - C_i)^2} \tag{5}$$

2.2. Fuzzy Sets

The behavior of decision makers is in the decision process results in asymmetric and uncertain information. Fuzzy sets were first developed by Zadeh in 1965 [47]. Fuzzy sets are used to represent and handle vagueness and uncertainty in decision-making. In fuzzy set, each number between 0 and 1 indicates a partial truth, so we can express and handle vague or imprecise judgments mathematically [46]. Fuzzy set is defined as follows: Let X be a set, A be a subset of X, and $\mu_A : X \to [0, 1]$ be a function. $\mu_A : X \to [0, 1]$ is called the membership function of A. The set $\widetilde{A} = \{(x, \mu_A(x)) : x \in X\}$ is called the fuzzy set.

The membership functions can have different shapes, such as triangular, trapezoidal, or Gaussian. Triangular fuzzy numbers (TFNs) correspond to the case when set A is a set of real numbers. They are commonly used in the fuzzy DEMATEL [1]. They can be used also to express human linguistic evaluations. A TFN is defined as triplet (l, m, u), where $l \leq m \leq u$. l is called the lower bound, u is the upper bound, and m is the center of TFN. The membership function of triplet (l, m, u) is [48]

$$\mu(x) = \begin{cases} 0, & x < l \text{ or } x > u \\ (x-l)/(m-l), & l \leq x \leq m \\ (u-x)/(u-m) & m < x \leq u \end{cases}. \tag{6}$$

2.3. Fuzzy DEMATEL

Fuzzy DEMATEL uses TFN evaluations, which influence the steps of DEMATEL. Here, only the differences of fuzzy DEMATEL are stressed.

Step 1: Fuzzy direct-influence matrix $\widetilde{D}$ is generated, where the linguistic evaluations are converted into corresponding TFNs (Table 1).

$$\widetilde{D} = \begin{pmatrix} (l_{11}, m_{11}, u_{11}) & (l_{12}, m_{12}, u_{12}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (l_{22}, m_{22}, u_{22}) & \cdots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \cdots & (l_{nn}, m_{nn}, u_{nn}) \end{pmatrix}$$

Step 2: Derive the normalized direct-relation matrix $\widetilde{X} = (X_l, X_m, X_u)$ using the normalization formula:

$$x_{ij} = \frac{(l_{ij}, m_{ij}, u_{ij})}{\max\limits_{1 \le i \le n} \sum\limits_{j=1}^{n} u_{ij}},\ i, j = 1, \ldots, n \tag{7}$$

Step 3: Derive the total relation matrix $\widetilde{T} = (T_l, T_m, T_u)$ separately for the lower bounds (T_l), the middle values (T_m), and the upper bounds (T_u).

$$T_l = X_l (I - X_l)^{-1} \tag{8}$$

$$T_m = X_m (I - X_m)^{-1} \tag{9}$$

$$T_u = X_u (I - X_u)^{-1} \tag{10}$$

The graded mean integration representation (GMIR [49]) method is chosen for defuzzification because of its simplicity and accuracy [50]. It has also been used in many applications [51–54]

$$T = \frac{T_l + 4T_m + T_u}{6}. \tag{11}$$

Step 4: Derive the row sums and the column sums and construct the causal diagram.

Step 5: The weights of factors can be calculated using Equation (5).

3. DEMATEL of a Finite Sum of Influences

3.1. Convergence Problem in DEMATEL

When the total relation matrix T is calculated, we may encounter the problem that the infinite sum of terms does not converge:

Let $X = [x_{ij}]_{n \times n}$, $0 \le x_{ij} < 1, 0 < \sum\limits_{j=1}^{n} x_{ij} \le 1, 0 < \sum\limits_{i=1}^{n} x_{ij} \le 1$. Then $\sum\limits_{i=1}^{h} X^i = X + X^2 + X^3 \ldots + X^h = X(I + X + X^2 + X^3 + \ldots + X^{h-1})\left[(I - X)(I - X)^{-1}\right] = X(I - X^h)(I - X)^{-1}$. The total relation matrix T can be obtained by $T = X + X^2 + X^3 + \ldots = \lim\limits_{h \to \infty} \sum\limits_{i=1}^{h} X^i$, when $\lim\limits_{h \to \infty} X^h = [0]_{n \times n}$. If all row sums are not equal to 1, then we can guarantee $\lim\limits_{h \to \infty} X^h = [0]_{n \times n}$ [42]. If all row sums are equal to 1, then $\lim\limits_{h \to \infty} X^h \ne [0]_{n \times n}$, and a convergence problem arises.

3.1.1. Example 1

This is an example where the convergence problem arises in the DEMATEL. In this example, two decision makers made pairwise comparisons between four factors. Figure 1 shows the average assessments of the decision makers. For better transparency, these assessments are then written into the direct-influence matrix D.

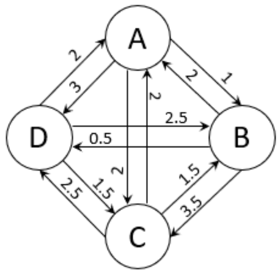

Figure 1. Map of influence relations between factors for Example 1.

$$D = \begin{pmatrix} 0 & 1 & 2 & 3 \\ 2 & 0 & 3.5 & 0.5 \\ 2 & 1.5 & 0 & 2.5 \\ 2 & 2.5 & 1.5 & 0 \end{pmatrix}$$

The normalized direct-relation matrix X is derived by (1) (Table 2).

Table 2. The normalized direct-relation matrix X with row sums.

X	A	B	C	D	Row Sums
A	0.00	0.17	0.33	0.50	1.00
B	0.33	0.00	0.58	0.08	1.00
C	0.33	0.25	0.00	0.42	1.00
D	0.33	0.42	0.25	0.00	1.00

The normalized direct-relation matrix X has all row sums equal to 1. Therefore, the total relation matrix T cannot be determined because $T = X + X^2 + X^3 + \ldots$ does not exist. Therefore, the DEMATEL cannot be used.

3.1.2. Example 2

Here is a fuzzy DEMATEL example. Four factors were evaluated using TFNs. Figure 2 shows the map of influence relations between factors, with the corresponding linguistic evaluations of the decision maker.

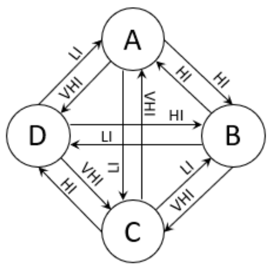

Figure 2. Map of influence relations between factors for Example 2.

The direct-influence matrix D shows assessments written in corresponding TFNs.

$$D = \begin{pmatrix} (0,0,0) & (0.5,0.75,1) & (0.25,0.5,0.75) & (0.75,1,1) \\ (0.5,0.75,1) & (0,0,0) & (0.75,1,1) & (0.25,0.5,0.75) \\ (0.75,1,1) & (0.25,0.5,0.75) & (0,0,0) & (0.5,0.75,1) \\ (0.25,0.5,0.75) & (0.5,0.75,1) & (0.75,1,1) & (0,0,0) \end{pmatrix}$$

Table 3 shows the normalized direct-relation matrix of the upper bounds X_u derived by Equation (6).

Table 3. The normalized direct-relation matrix of the upper bounds X_u with row sums.

X_u	A	B	C	D	Row Sums
A	0.083	0.333	0.250	0.333	1.00
B	0.333	0.083	0.333	0.250	1.00
C	0.333	0.250	0.083	0.333	1.00
D	0.250	0.333	0.333	0.083	1.00

The row sums of the upper bounds are equal to 1, so there is the convergence problem as in Example 1. The fuzzy DEMATEL cannot be used for this problem.

3.2. New Approach—DEMATEL of a Finite Sum of Influences (FSI DEMATEL)

The matrix T represents the sum of all normalized influences of factors. $T = X + X^2 + X^3 + \ldots$, where X represents direct normalized influences, and $X^2, X^3, X^4, \ldots$ represent indirect influences. The different levels of influences are determined. The first level of influences are direct influences collected in matrix X. The second level of influences are indirect influences through one factor, represented in matrix X^2. The third level of influences are indirect influences through two factors gathered in X^3 and so on. The indirect influences of factors on a selected factor are initially large and then decrease with the levels (Example 3). The higher levels of influences are smaller and contribute less to the total influence.

3.2.1. Example 3

An example from the literature [39] comparing the factors of the DPSIR (driver–pressure–state–impact–response) model for forest management is selected. Three experts evaluated five factors of the model (Figure 3).

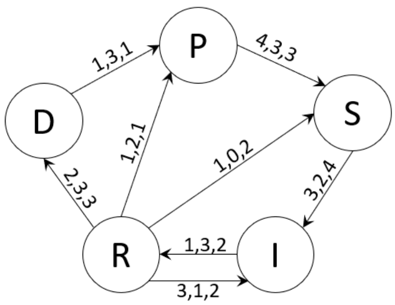

Figure 3. Map of influence relations between factors for Example 3.

The normalized influences between factors are summarized in Table 4; direct influences—level 1 in matrix X, and indirect influences of levels 2 to 5 in matrices X^2, X^3, X^4 and X^5.

This example shows the normalized direct influence of each factor on the other factors, and the first few terms of normalized indirect influences of one factor on others. The results show that the influences at higher levels are smaller. The influences of the fourth-level X^4 are already very small. Considering the influence of factor R on factor P, we find that the normalized direct first-level influence is 0.190, the indirect second-level influence is 0.091, the indirect third-level influence is 0.016, the indirect fourth-level is 0.011, and the indirect fifth-level influence is 0.005. Considering the influence of factor D on factor P, we find that the normalized direct first-level influence is 0.238. There are no indirect second-, third-, and fourth-level influences, because there is no path of length two, three, or four from vertex D to vertex P (Figure 4). The indirect fifth-level influence of factor D on factor P is 0.003 and follows the path $D \to P \to S \to I \to R \to P$.

Table 4. First to fifth levels of influences [55].

X	D	P	S	R	I	X^2	D	P	S	R	I
D	0.000	0.238	0.000	0.000	0.000	D	0.000	0.000	0.113	0.000	0.000
P	0.000	0.000	0.476	0.000	0.000	P	0.000	0.000	0.000	0.000	0.204
S	0.000	0.000	0.000	0.000	0.429	S	0.000	0.000	0.000	0.122	0.000
R	0.381	0.190	0.143	0.000	0.286	R	0.000	0.091	0.091	0.082	0.061
I	0.000	0.000	0.000	0.286	0.000	I	0.109	0.054	0.041	0.000	0.082
X^3	**D**	**P**	**S**	**R**	**I**	**X^4**	**D**	**P**	**S**	**R**	**I**
D	0.000	0.000	0.000	0.000	0.049	D	0.000	0.000	0.000	0.014	0.000
P	0.000	0.000	0.000	0.058	0.000	P	0.022	0.011	0.008	0.000	0.017
S	0.047	0.023	0.017	0.000	0.035	S	0.000	0.011	0.011	0.010	0.007
R	0.031	0.016	0.055	0.017	0.062	R	0.007	0.011	0.010	0.018	0.029
I	0.000	0.026	0.026	0.023	0.017	I	0.009	0.004	0.016	0.005	0.018
X^5	**D**	**P**	**S**	**R**	**I**						
D	0.005	0.003	0.002	0.000	0.004						
P	0.000	0.005	0.005	0.005	0.004						
S	0.004	0.002	0.007	0.002	0.008						
R	0.007	0.005	0.008	0.008	0.009						
I	0.002	0.003	0.003	0.005	0.008						

3.2.2. Example 4

An example with four factors is presented in Figure 4.

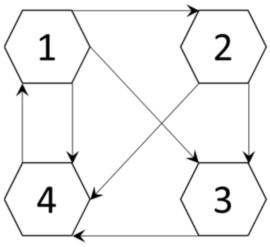

Figure 4. Map of influence relations between factors for Example 4.

Here we focus on the influences of factor 1 on factor 4.

There are only four important direct and indirect influences that should be included in total relation matrix T:

- $1 \rightarrow 4$ (direct first-level influence),
- $1 \rightarrow 2 \rightarrow 4$ (indirect second-level influence of factor 1 through factor 2 on factor 4),
- $1 \rightarrow 3 \rightarrow 4$ (indirect second-level influence of factor 1 through factor 3 on factor 4),
- $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$ (indirect third-level influence of factor 1 through factor 2 and factor 3 on factor 4).

It is pointless to take influence $1 \rightarrow 2 \rightarrow 4 \rightarrow 1 \rightarrow 4$ into account, since that influence has already been included before in influences $1 \rightarrow 4$ and $1 \rightarrow 2 \rightarrow 4$. Similarly, higher levels of influences are already included in lower levels of influences.

Based on observations form Examples 3 and 4, we propose to use a certain number of terms instead of an infinite number of terms when calculating total relation matrix T.

We propose a new approach—DEMATEL of a finite sum of influences (FSI DEMATEL). This method differs from the DEMATEL in Step 3, where the total relation matrix T is calculated. Instead of an infinite sum, a finite sum (a certain number of terms) is used (one term less than the number of factors) (11). Based on the above examples, only $n-1$ terms, where n is the number of factors, are considered.

$$T = X + X^2 + \ldots + X^{n-1} \tag{12}$$

3.3. *Algorithm of FSI DEMATEL*

Step 1: Generate the direct-influence matrix D (Equation (1)).

Step 2: Derive the normalized direct-relation matrix X (Equation (2)).

This step differs in the FSI DEMATEL from the DEMATEL. In FSI DEMATEL, matrix T is a finite sum of influences between factors. T is calculated by Equation (12).

Step 4: Sum the rows and the columns, and then construct the causal diagram (Equations (3) and (4)).

Step 5: The weights of factors are calculated (Equation (5)).

3.4. *Evaluation of FSI DEMATEL*

Three examples follow. The DEMATEL cannot be used for two of them.

3.4.1. Example 5 (Continuation of Example 1)

We showed that the DEMATEL cannot be used for this problem, because all row sums are equal to 1. However, we can use FSI DEMATEL. As this example has four criteria, the total relation matrix is calculated as the sum of the direct first-level influences (X) (Table 2) and the second- and third-level indirect influences (X^2 and X^3):

$$T = X + X^2 + X^3 \tag{13}$$

and shown in Table 5, columns 2–5. The row sums in Equation (3) and column sums (C) in Equation (4) of matrix T are calculated and presented in Table 5, columns 6–7. The prominence values, relation values, and the weights of the factors in Equation (5) are calculated and presented in Table 5, columns 8–10.

Table 5. The results of FSI DEMATEL, row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 5.

T (FSI)	A	B	C	D	R	C	$R_i + C_i$	$R_i - C_i$	Weights
A	0.56	0.63	0.88	0.94	3.00	3.00	6.00	0.00	0.250
B	0.81	0.48	1.03	0.68	3.00	2.58	5.58	0.42	0.233
C	0.81	0.68	0.62	0.88	3.00	3.34	6.34	−0.34	0.264
D	0.81	0.79	0.82	0.57	3.00	3.07	6.07	−0.07	0.253

3.4.2. Example 6 (Continuation of Example 2)

This is a continuation of Example 2. Using the FSI fuzzy DEMATEL, we can obtain the influences of the factors. Using FSI fuzzy DEMATEL, we can solve the problem of non-convergence of the upper bounds. The results are presented in Table 6.

Table 6. The results of FSI DEMATEL, row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 6.

T (FSI)	A	B	C	D	R	C	$R_i + C_i$	$R_i - C_i$	Weights
A	0.57	0.76	0.78	0.88	3	3.01	6.01	−0.01	0.250
B	0.82	0.52	0.92	0.75	3	2.74	5.74	0.26	0.239
C	0.88	0.69	0.61	0.82	3	3.23	6.23	−0.23	0.260
D	0.75	0.76	0.92	0.57	3	3.02	6.02	−0.02	0.251

3.4.3. Example 7

This is an example from the literature [44], where the DEMATEL cannot be used due to convergence problem. Decision makers compared four factors. Figure 5 shows their average assessments.

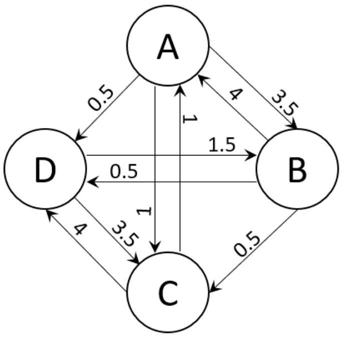

Figure 5. Map of influence relations between factors for Example 7.

Average assessments of decision makers are written in the direct-influence matrix D.

$$D = \begin{pmatrix} 0 & 3.5 & 1 & 0.5 \\ 4 & 0 & 0.5 & 0.5 \\ 1 & 0 & 0 & 4 \\ 0 & 1.5 & 3.5 & 0 \end{pmatrix}$$

Authors proposed the revised DEMATEL, where a small positive number (parameter ε) is added to the sum (13), when the normalized direct-relation matrix X is derived as follows:

$$x_{ij} = \frac{d_{ij}}{\varepsilon + \max\limits_{1 \le i \le n} \sum\limits_{j=1}^{n} d_{ij}},\ i, j = 1, \ldots, n. \quad (14)$$

The problem is that the results of the revised DEMATEL depend on the value of parameter ε. Table 7 ($\varepsilon = 10^{-4}$) and Table 8 ($\varepsilon = 10^{-5}$) show that results differ for different values of parameter ε.

Table 7. T matrix obtained with different values of parameter epsilon (10^{-4}), row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 7.

T	A	B	C	D	R	C	$R_i + C_i$	$R_i - C_i$	Weights
A	12,500.03	12,500.40	12,499.82	12,499.75	50,000	50,000	100,000	0.00	0.250
B	12,500.52	12,500.03	12,499.75	12,499.70	50,000	50,000	100,000	0.00	0.250
C	12,499.73	12,499.72	12,500.03	12,500.52	50,000	50,000	100,000	0.00	0.250
D	12,499.72	12,499.86	12,500.40	12,500.03	50,000	50,000	100,000	0.00	0.250

Table 8. T matrix obtained with different values of parameter epsilon (10^{-5}), row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 7.

T	A	B	C	D	R	C	$R_i + C_i$	$R_i - C_i$	Weights
A	125,000.03	125,000.40	124,999.82	124,999.75	500,000	500,000	1,000,000	0.00	0.250
B	125,000.52	125,000.03	124,999.75	124,999.70	500,000	500,000	1,000,000	0.00	0.250
C	124,999.73	124,999.72	125,000.03	125,000.52	500,000	500,000	1,000,000	0.00	0.250
D	124,999.72	124,999.86	125,000.40	125,000.03	500,000	500,000	1,000,000	0.00	0.250

The other problem of revised DEMATEL is that the results, the sums of all normalized influences, are very high and therefore not realistic. The results of FSI DEMATEL are presented in Table 9. The results (sums of influences) derived with FSI DEMATEL, are more realistic.

Table 9. T matrix obtained with FSI DEMATEL, row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 7.

T	A	B	C	D	R	C	$R_i + C_i$	$R_i - C_i$	Weights
A	0.65	1.22	0.62	0.51	3.00	3.00	6.00	0.00	0.250
B	1.34	0.65	0.51	0.51	3.00	3.00	6.00	0.00	0.250
C	0.62	0.39	0.65	1.34	3.00	3.00	6.00	0.00	0.250
D	0.39	0.74	1.22	0.65	3.00	3.00	6.00	0.00	0.250

3.4.4. Example 8

The aim of this example is to compare the DEMATEL and the FSI DEMATEL, when both methods can be used (there is no convergence problem). For this comparison, a DEMATEL application from the literature [56] was selected. The study was conducted to identify the critical factors of the ice-cream industry supply chain system and the relationships between these factors, and to prioritize the critical factors to help implantation in the Indian ice-cream industry. Three experts evaluated eight critical factors for cold chains.

Matrix D represents assessments of all three experts.

$$D = \begin{pmatrix} 0,0,0 & 2,3,4 & 0,3,2 & 3,2,2 & 4,2,2 & 1,1,2 & 2,2,2 & 3,1,4 \\ 1,3,2 & 0,0,0 & 3,4,3 & 2,3,2 & 3,3,3 & 3,3,3 & 4,3,3 & 4,2,4 \\ 2,2,3 & 2,2,3 & 0,0,0 & 2,3,3 & 3,2,2 & 4,4,3 & 4,2,3 & 2,1,3 \\ 3,1,2 & 4,1,1 & 4,3,3 & 0,0,0 & 2,3,1 & 2,3,1 & 2,4,3 & 2,3,3 \\ 1,2,3 & 3,3,2 & 3,2,2 & 3,2,3 & 0,0,0 & 3,2,2 & 2,2,4 & 3,2,1 \\ 1,4,1 & 2,1,3 & 2,1,2 & 4,2,1 & 2,4,1 & 0,0,0 & 3,3,3 & 2,3,1 \\ 4,3,3 & 3,2,2 & 2,1,3 & 3,1,2 & 2,3,3 & 1,2,2 & 0,0,0 & 3,3,1 \\ 3,2,4 & 2,2,2 & 1,4,4 & 2,3,4 & 3,3,3 & 1,3,3 & 3,3,2 & 0,0,0 \end{pmatrix}$$

Tables 10 and 11 represent the results derived with DEMATEL and with FSI DEMATEL.

Table 10. T matrix obtained with DEMATEL, row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 8.

T	F1	F2	F3	F4	F5	F6	F7	F8	R	C	$R_i + C_i$	$R_i - C_i$	Weights
F1	0.55	0.67	0.64	0.65	0.70	0.60	0.72	0.68	5.20	5.59	10.79	−0.38	0.117
F2	0.79	0.68	0.86	0.81	0.88	0.81	0.95	0.86	6.65	5.45	12.10	1.19	0.132
F3	0.74	0.72	0.65	0.75	0.78	0.77	0.86	0.74	6.00	5.73	11.73	0.26	0.128
F4	0.69	0.67	0.76	0.60	0.73	0.67	0.82	0.73	5.66	5.64	11.31	0.02	0.123
F5	0.68	0.69	0.71	0.71	0.62	0.67	0.79	0.69	5.56	5.95	11.50	−0.39	0.125
F6	0.64	0.63	0.64	0.66	0.69	0.53	0.76	0.67	5.23	5.43	10.66	−0.20	0.116
F7	0.72	0.66	0.68	0.67	0.73	0.63	0.66	0.69	5.44	6.42	11.86	−0.99	0.129
F8	0.78	0.73	0.80	0.79	0.83	0.74	0.87	0.67	6.21	5.73	11.94	0.48	0.130

Table 11. T matrix obtained with FSI DEMATEL, row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 8.

T (FSI)	F1	F2	F3	F4	F5	F6	F7	F8	R	C	$R_i + C_i$	$R_i - C_i$	Weights
F1	0.34	0.46	0.43	0.44	0.48	0.40	0.48	0.47	3.51	3.77	7.28	−0.26	0.117
F2	0.53	0.43	0.59	0.55	0.60	0.56	0.65	0.59	4.49	3.68	8.17	0.81	0.132
F3	0.50	0.49	0.40	0.52	0.52	0.54	0.59	0.50	4.05	3.87	7.93	0.18	0.128
F4	0.47	0.45	0.53	0.38	0.49	0.45	0.56	0.50	3.82	3.81	7.63	0.01	0.123
F5	0.46	0.47	0.48	0.49	0.39	0.46	0.54	0.47	3.75	4.02	7.77	−0.26	0.125
F6	0.44	0.43	0.43	0.45	0.47	0.33	0.53	0.46	3.53	3.67	7.19	−0.14	0.116
F7	0.50	0.45	0.46	0.45	0.50	0.42	0.41	0.47	3.67	4.34	8.01	−0.67	0.129
F8	0.54	0.49	0.55	0.54	0.57	0.50	0.59	0.42	4.20	3.87	8.07	0.33	0.130

The results are presented in the cause-and-effect diagram (Figure 6).

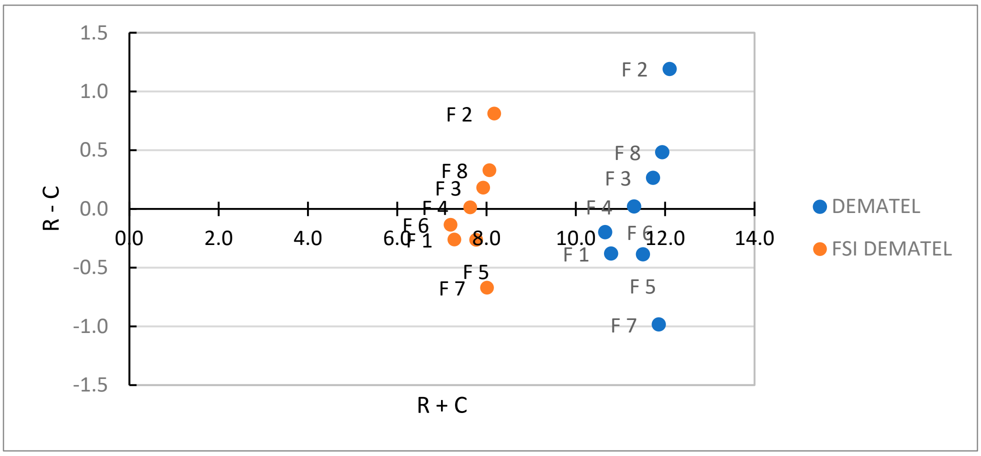

Figure 6. Comparison of cause-and-effect factors calculated by DEMATEL and FSI DEMATEL.

Authors compared eight factors using DEMATEL. Factors in the cause group and factors in the effect group are the same for both methods. We can note that the main difference between FSI DEMATEL and DEMATEL are fewer stretched factors in FSI DEMATEL than in DEMATEL (Figure 6). In the diagram, the absolute values depend on the normalization of assessments. Therefore, the relative values are important, which represent the relationships between the factors. The distribution and the relationships between the factors in this example remain the same for both methods. The weights of the factors in this example are the same for both methods. We see that FSI DEMATEL retains all the advantageous features of DEMATEL and, in addition, has its own advantages in solving the convergence problem. We can conclude that the FSI DEMATEL is suitable because it gives comparable results to the DEMATEL, when both methods can be used.

3.4.5. Example 9

This example compares the fuzzy DEMATEL and the FSI DEMATEL. It is taken from the literature [48]. A company wants to improve the application process of value stream mapping. The main issues obtained from the proposed approach are the evaluation and improvement of the manufacturing processes from the economic and environmental sides. In this case study, three different experts evaluated five factors, using TFNs and the fuzzy DEMATEL.

Matrices D_1, D_2, and D_3 represent individual TFN assessments of tree experts.

$$D_1 = \begin{pmatrix} (0,0,0.25) & (0.25,0.5,0.75) & (0,0.25,0.5) & (0.5,0.75,1) & (0.25,0.5,0.75) \\ (0.5,0.75,1) & (0,0,0.25) & (0,0.25,0.5) & (0.5,0.75,1) & (0.25,0.5,0.75) \\ (0.5,0.75,1) & (0.5,0.75,1) & (0,0,0.25) & (0.5,0.75,1) & (0.25,0.5,0.75) \\ (0,0.25,0.5) & (0.25,0.5,0.75) & (0.25,0.5,0.75) & (0,0,0.25) & (0,0,0.25) \\ (0.75,1,1) & (0.75,1,1) & (0.25,0.5,0.75) & (0.75,1,1) & (0,0,0.25) \end{pmatrix}$$

$$D_2 = \begin{pmatrix} (0,0,0.25) & (0.5,0.75,1) & (0,0.25,0.5) & (0.5,0.75,1) & (0.25,0.5,0.75) \\ (0.25,0.5,0.75) & (0,0,0.25) & (0.25,0.5,0.75) & (0.25,0.5,0.75) & (0,0.25,0.5) \\ (0.25,0.5,0.75) & (0.5,0.75,1) & (0,0,0.25) & (0.25,0.5,0.75) & (0.25,0.5,0.75) \\ (0,0.25,0.5) & (0.25,0.5,0.75) & (0,0.25,0.5) & (0,0,0.25) & (0,0,0.25) \\ (0.25,0.5,0.75) & (0.75,1,1) & (0.25,0.5,0.75) & (0.75,1,1) & (0,0,0.25) \end{pmatrix}$$

$$D_3 = \begin{pmatrix} (0,0,0.25) & (0.25,0.5,0.75) & (0.25,0.5,0.75) & (0.75,1,1) & (0,0.25,0.5) \\ (0,0.25,0.5) & (0,0,0.25) & (0.25,0.5,0.75) & (0.5,0.75,1) & (0,0,0.25) \\ (0.25,0.5,0.75) & (0.25,0.5,0.75) & (0,0,0.25) & (0.5,0.75,1) & (0.5,0.75,1) \\ (0,0.25,0.5) & (0,0.25,0.5) & (0,0.25,0.5) & (0,0,0.25) & (0,0.25,0.5) \\ (0.25,0.5,0.75) & (0.75,1,1) & (0.5,0.75,1) & (0.75,1,1) & (0,0,0.25) \end{pmatrix}$$

We made two calculations. In the first one, we calculated the matrix T separately for the upper value (7), middle value (8), and lower bounds (9), which the results are presented in Table 12, and in the second calculation, we used the FSI DEMATEL (12), which the results are presented in Table 13.

Table 12. T matrix obtained with fuzzy DEMATEL, row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 9.

T	C1	C2	C3	C4	C5	R	C	$R_i + C_i$	$R_i - C_i$	Weights
C1	0.21	0.38	0.27	0.46	0.25	1.57	1.49	3.06	0.08	0.189
C2	0.30	0.23	0.26	0.40	0.21	1.40	1.83	3.23	−0.42	0.202
C3	0.37	0.44	0.23	0.48	0.31	1.83	1.33	3.15	0.50	0.198
C4	0.19	0.25	0.20	0.19	0.13	0.97	2.12	3.09	−1.14	0.204
C5	0.41	0.53	0.37	0.58	0.21	2.09	1.11	3.20	0.98	0.207

Table 13. T matrix obtained with FSI DEMATEL, row sums (R), column sums (C), prominence values ($Ri + Ci$), relations values ($Ri - Ci$), and weights of factors for Example 9.

T (FSI)	C1	C2	C3	C4	C5	R	C	$R_i + C_i$	$R_i - C_i$	Weights
C1	0.17	0.37	0.24	0.47	0.23	1.48	1.39	2.88	0.09	0.184
C2	0.28	0.20	0.24	0.40	0.18	1.30	1.80	3.10	−0.50	0.201
C3	0.36	0.44	0.19	0.49	0.30	1.78	1.21	2.99	0.58	0.195
C4	0.16	0.23	0.17	0.15	0.10	0.81	2.15	2.96	−1.34	0.208
C5	0.42	0.56	0.37	0.63	0.18	2.15	0.98	3.13	1.17	0.213

The results are presented in the cause-and-effect diagram Figure 7.

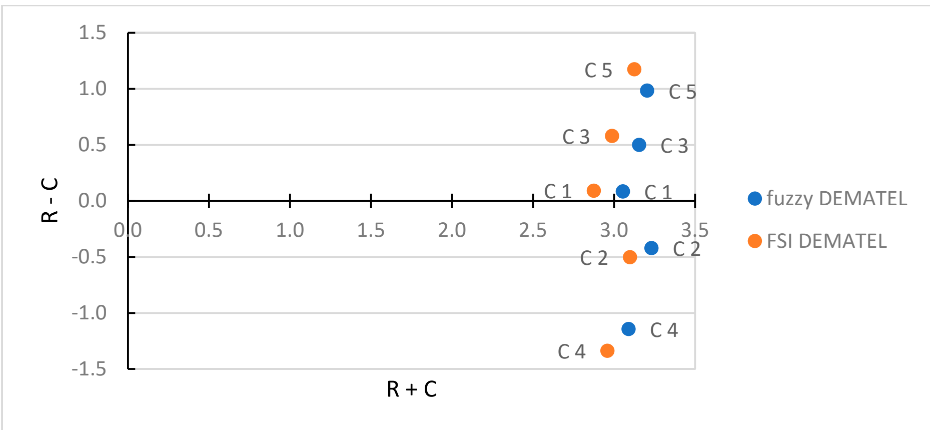

Figure 7. Cause-and-effect factors calculated with FSI DEMATEL and fuzzy DEMATEL.

The authors compared five criteria using fuzzy DEMATEL. We compared their results with those calculated using the FSI DEMATEL. The distribution and relationships between the factors of both methods are similar, as can be seen from the diagram (Figure 7). The factors in the cause group and the factors in the effect group are the same for both methods. The absolute values of the factors differ, while the relative values remain similar, regardless of the method used. If we compare the weights of criteria, we see that the weights differ slightly, while the ranking of the criteria remains the same. FSI DEMATEL has emphasized the two most important criteria somewhat more and given them slightly higher weights. The results show that the FSI DEMATEL is suitable for use because it gives comparable results to the fuzzy DEMATEL.

4. Discussion

4.1. Comparison of DEMATEL and FSI DEMATEL

Table 14 shows which examples can be solved with DEMATEL and which with FSI DEMATEL.

Table 14. Comparison of the solvability of examples with DEMATEL, fuzzy DEMATEL, and FSI DEMATEL.

	DEMATEL	Fuzzy DEMATEL	FSI DEMATEL
Example 1	X	NA	√
Example 2	NA	X	√
Example 3	√	NA	√
Example 7	X	NA	√
Example 8	√	NA	√
Example 9	NA	√	√

NA—not applicable, X—can not be used, √—can be used.

In Example 1, all row sums of the normalized direct-relation matrix X are equal to 1, and in Example 2, all rows of the upper bounds of the normalized direct-relation matrix X are equal to 1. Therefore, the total relation matrix T cannot be determined in either example, and DEMATEL (Example 1) or fuzzy DEMATEL (Example 2) cannot be used for these two problems. Using FSI DEMATEL, the convergence problem is solved, and the results for both problems can be computed.

Example 7 is from the literature, where DEMATEL cannot be used due to the convergence problem. The authors [44] have proposed a revised DEMATEL as a solution to the convergence problem, but the sums of all the influences in the total relation matrix are very high and therefore not realistic. The results derived by FSI DEMATEL are smaller and more realistic, suggesting that FSI DEMATEL is more suitable than the revised DEMATEL. The results derived by revised DEMATEL depend on the value of parameter ε, while FSI DEMATEL is independent.

While FSI DEMATEL uses the direct influences and up to $n-1$ levels of indirect influences between factors, where n is the number of factors, DEMATEL uses all levels from one to infinity. Example 3 shows that the normalized indirect influences decrease with the level of influences, suggesting that higher levels of influences are irrelevant and need not be used in the calculation of the total relation matrix T, thus highlighting one of the advantages of FSI DEMATEL.

Examples 8 and 9 are real problems from the literature, where the convergence problem did not occur. Example 8 uses numerical evaluations, while Example 9 uses fuzzy evaluations. Both examples can be solved using FSI DEMATEL as well as DEMATEL (Example 8) or fuzzy DEMATEL (Example 9). The comparison shows that the distribution of the factors in the cause-and-effect diagram and the weights of the factors of FSI DEMATEL are similar to those of DEMATEL (or fuzzy DEMATEL), which confirms the suitability of FSI DEMATEL.

We can conclude that the FSI DEMATEL can deal with problems that DEMATEL cannot. The new method can be used in more cases, while this is not possible with the DEMATEL due to the convergence problem. The results obtained with DEMATEL and FSI DEMATEL are comparable, and the relationships between the factors remain similar.

4.2. Comparison of FSI DEMATEL with Other MCDM Methods

We selected different subjective MCDM methods to compare their properties with those of FSI DEMATEL. Besides DEMATEL, we selected WINGS as an extension of DEMATEL. Then, we selected AHP and TOPSIS as two well-known and most commonly used MCDM methods in applications [4]. We also selected ANP as one of the best-known methods that considers interactions between factors. Finally, we selected two newer MCDM methods [6]: FUCOM [57] and LBWA [58]. The results of the comparison are summarized in Table 15.

Table 15. Comparison of FSI DEMATEL and other MCDM methods.

	FSI DEMATEL	Revised DEMATEL	DEMATEL	WINGS	AHP	TOPSIS	ANP	FUCOM	LBWA
Pairwise comparisons	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Weights calculation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fuzzy extension	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Easy to use	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes
Influences between criteria	Yes	Yes	Yes	Yes	No	No	Yes	No	No
Consistency measure	No	No	No	No	Yes	No	Yes	Yes	No
Without convergence problem	Yes	Yes	No	No	NA	NA	NA	NA	NA

NA—not applicable.

All methods listed in Table 15 have their advantages and disadvantages. With the exception of TOPSIS, all methods use pairwise comparisons. The weights of criteria or alternatives can be calculated by all methods. All methods also have fuzzy extensions. While most methods are easy to use, ANP is known for its more complicated model and the many pairwise comparisons required. Among other methods, FUCOM uses a nonlinear optimization model. While FSI DEMATEL, DEMATEL, WINGS, and ANP are the methods used when evaluating the interactions between factors is the primary objective of the problem, the main objective of the other methods (AHP, TOPSIS, FUCOM, and LBWA) is to calculate the weights of criteria or alternatives. With the exception of LBWA, all of these methods allow a consistency measurement, which is one of the main drawbacks of all other methods, except ANP. The main advantage of FSI DEMATEL compared to DEMATEL and WINGS is the nonexistent convergence problem. Revised DEMATEL was proposed to solve the convergence problem as the FSI DEMATEL. However, the FSI DEMATEL has more advantages. Results derived by FSI DEMATEL are not dependant on the value of parameter ε, and also, the results are more suitable because the sums of all the influences in the total relation matrix are smaller and more realistic. In summary, FSI DEMATEL is easy to use, pairwise comparisons are used to evaluate the influences between pairs of factors, factor weights can be calculated, and it has a fuzzy extension. Its main disadvantage compared to other subjective weighting MCDM methods is the lack of a consistency measure, but this is also the case with all other methods for assessing influences between factors, except ANP, which is not easy to use.

5. Conclusions

In this paper, we discussed the convergence problem in DEMATEL. The convergence problem can occur when the infinite sum of normalized influences does not converge. Since the indirect influences of factors on a selected factor are initially large and then decrease with the level of influence, we proposed a new method, FSI DEMATEL. Instead of an infinite sum, a finite sum (a certain number of terms) of influences is used in FSI DEMATEL. To validate and verify the proposed method, it was compared with similar methods from the literature (DEMATEL and fuzzy DEMATEL).

This study shows that FSI DEMATEL has successfully solved the problem of convergence. Six examples using the DEMATEL and the FSI DEMATEL were presented. The results show that the FSI DEMATEL is suitable for the application.

The FSI DEMATEL is also comparable with the established fuzzy DEMATEL because the relationships between the factors are similar in both methods. Likewise, the FSI DEMATEL can be used with other types of fuzzy numbers (neutrosophic, intuitionistic).

In summary, the FSI DEMATEL gives comparable results to the DEMATEL. The advantage of the FSI DEMATEL is that it can be used even if the DEMATEL cannot be used due to the convergence problem. Therefore, the proposed method—FSI DEMATEL—can be applied as an MCDM method to evaluate the influence of factors in many different fields.

In the future, we plan to adapt the FSI DEMATEL for the WINGS. The WINGS is similar to the DEMATEL. It considers not only the influence of one factor on another but also the importance (strength) of each factor itself [56].

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Abbreviations

A list of acronyms used in the paper

DEMATEL	Decision-making Trial and Evaluation Laboratory
FSI DEMATEL	DEMATEL of a finite sum of influences
MCDM	Multicriteria decision-making
AHP	Analytic Hierarchical Process
TOPSIS	Technique for Order Performance by Similarity to Ideal Solutions
VIKOR	VIse Kriterijumska Optimizacija I Kompromisno Resenje
ELECTRE	Elimination Et Choix Traduisant la REIalite
TFNs	Triangular fuzzy numbers
DPSIR	Driver–Pressure–State–Impact–Response model
WINGS method	Weighted Influence Nonlinear Gauge System

A list of variables used in the paper

T	Total relation matrix
D	Direct-influence matrix
X	Normalized direct-relation matrix
I	Identity matrix
R_i	Sum of row i
C_j	Sum of column j
$R_i + C_i$	Prominence value of factor i
$R_i - C_i$	Relations value of factor i
T_l	The total relation matrix for the lower bounds
T_m	The total relation matrix for the middle values
T_u	The total relation matrix for the upper bounds

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