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ORIGINAL ARTICLE

A new DEMATEL method based on interval type-2 fuzzy sets for developing causal relationship of knowledge management criteria

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Abstract

The fuzzy decision-making trial and evaluation laboratory (fuzzy DEMATEL) has been used to solve various multi-criteria group decision-making problems where triangular type-1 fuzzy sets are utilized in defining decision makers' linguistic evaluation. Most of the fuzzy DEMATEL modifications are built from linguistic variables based on type-1 fuzzy sets (T1FS). Previous literature suggests that interval type-2 fuzzy sets (IT2FS) can offer an alternative that can handle vagueness and uncertainty. This paper proposes a modification fuzzy DEMATEL characterized by IT2FS for linguistic variables. Differently from the typical fuzzy DEMATEL which directly utilizes triangular type-1 fuzzy numbers, this modification introduces trapezoidal IT2 fuzzy numbers to enhance evaluation in the group decision-making environment. This new modification includes linguistic variables expressed by IT2FS and an expected value method for normalizing upper and lower memberships of IT2FS to crisp numbers. The proposed modification is applied to a case of knowledge management (KM) where eleven criteria are considered. Three experts in KM were invited to provide linguistic judgments with respect to the criteria, and the eight-step computational procedure of the proposed modification was implemented without losing the originality of the DEMATEL method. The results unveiled that 'trust' is the most influential criteria in KM. Therefore, trust is a phenomenon that impacts on the success of KM. Comparable results are also presented to check the feasibility of the proposed method. It is shown that the criteria weight and the causal relationship of criteria using the proposed method are consistent with the other two methods.

Keywords Interval type-2 fuzzy sets · Causal relationship · DEMATEL · Knowledge management

1 Introduction

Multi-criteria decision-making (MCDM) has been widely recognized as one of the most important methods in group decision-making. MCDM methods are used to compare, rank and order several alternatives and criteria based on linguistic evaluation provided by decision makers (DMs). A typical MCDM problem may involve a group of DMs to provide qualitative and quantitative evaluation for determining the performance of each alternative with respect to criteria and the relative importance of criteria with respect to overall judgments [2]. There have been many MCDM methods available in the literature such as analytic hierarchy process (AHP), simple additive weighting (SAW), analytic network process (ANP) and technique for order preference by similarity to ideal solution (TOPSIS). One of the MCDM methods that is specifically tailored for searching causal relationships among criteria and dimensions in decision problems is the decision-making trial and evaluation laboratory (DEMATEL). The DEMATEL method has been developed initially to visualize the causal relationship of sub-systems through a causal diagram [12]. It has been proven as a useful method to solve complicated problems and has many advantages in explaining the interconnected relationships among criteria and dimensions. The final analysis of DEMATEL is a causal diagram, which can separate numbers of criteria into cause group and effect group. The causal group has an influence on the

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effect group where such influence is used to estimate the criteria weights [10]. In other words, the causal diagram represents a communication network or a domination relationship between entities and their groupings [16]. This method can verify the interdependence among the criteria and confirm the relationship that reflects an essential system [9, 16, 37]. The DEMATEL method is a practical and useful tool, especially in visualizing the structure of complex causal relationships with matrices or diagrams. The causal relationship shows a contextual link between the elements of the system in which a numeral represents the strength of influence of each element [19]. The DEMATEL method has several advantages; these include revealing the relationships among factors, for prioritizing the criteria based on the nature of the relationship and for representing the severity of the effect on each other criteria [23]. The DEMATEL also has been successfully integrated with other MCDM approaches. The integration of DEMATEL with two other MCDM methods has been used to assist corporate financing group DMs for obtaining a satisfactory group solution [39]. The group of DMs can systemically structure a relationship among a criteria network and derive priority weights of criteria using the integrated method. The DEMATEL system was also integrated with ANP, GRA and VIKOR for selecting and reconfiguring global manufacturing and logistics system [40]. The DEMATEL combined with VIKOR and ANP was proposed to solve the problem of conflicting criteria in information security risk control [45]. Recently, fuzzy integral was used to aggregate performance values using the weights obtained from the combined DEMATEL and ANP [24].

It has been demonstrated that numerous studies of MCDM methods apply fuzzy sets to deal with uncertainty in alternative selections and to overcome the vagueness limitations of MCDM methods. As a result, fuzzy DEMATEL was introduced to deal with the uncertainty in linguistic evaluations. One of the advantages of fuzzy DEMATEL is the consideration given to the condition of fuzziness and handle with flexibility in fuzziness situations [45]. The evaluation of criteria and alternatives in fuzzy DEMATEL is typically given in linguistic variables. A linguistic variable is a variable whose values form the phrases or sentences in a natural language [42]. The linguistic variables are used as variables whose values are not numbers but linguistic terms [46] and can effectively describe quantitative expressions [3]. Most of the existing fuzzy DEMATEL modifications use linguistic variables based on type-1 fuzzy sets (T1FS). For example, the T1FS and DEMATEL were utilized to construct a structural model [23]. The DEMATEL was based on T1FS with two other decision-making methods and was integrated in evaluating knowledge transfer effectiveness, with reference to green supply chain project outcomes [36]. The balanced scorecard was the basis for a strategic management system, and a fuzzy DEMATEL method based on T1FS was applied to visualize the structure of complicated causal relationships with matrices or digraphs [18]. The fuzzy DEMATEL method has been used to identify the influential factors when selecting suppliers using T1FS [7, 26, 41].

With the latest development of type-2 fuzzy sets (T2FS) and the concept of interval type-2 fuzzy sets (IT2FS), the causal diagram in DEMATEL deserves a more comprehensive evaluation because it represents uncertainties better than the T1FS does. T2FS is characterized by a fuzzy membership function, as each element of this set is a fuzzy set in the closed interval [0, 1], unlike a T1FS where the membership grade is a crisp number in the closed interval [0, 1] [28]. The membership functions of T2FS are three-dimensional and include a footprint of uncertainty (FOU) which is the new third dimension of T2FS and provides additional degrees of freedom for directly modelling and handling uncertainties [29, 38]. IT2FS has been spread widely, thus far, and has been successfully applied to perceptual computing [31, 32], control systems [13, 17, 44] and transportation problems [21, 25]. A variation in human decision-making was modelled using the shape of type-2 fuzzy membership functions [33]. Very recently Kilic and Kaya [20] have evaluated an investment project that used T2FS and crisp values simultaneously. In short, IT2FS has provided extra flexibility in capturing uncertainties in the real world owing to the fact that it is described by primary and secondary membership [15]. Moreover, T2FS can provide us with more of a degree of freedom to represent the uncertainty and the vagueness of the real world [47].

Recent developments in IT2FS and the advantages of fuzzy DEMATEL have led to a renewed interest in exploration for a possible merger of these two entities into one integrated method. However, until now, there has been very little discussion about this integration. There was a discussion made by Hosseini and Tarokh [14] that proposed T2FS as an extension of DEMATEL and its application to perceptual computing for decision-making. However, the study fails to consider the superiority of trapezoidal fuzzy numbers and concept of fuzzy intervals in defining linguistic variables. Furthermore, the perceptual computing they used in decision-making is conceptually similar to linguistic evaluation in fuzzy DEMATEL. In contrast to this method, this paper proposes the new fuzzy DEMATEL where the DEMATEL is combined with trapezoidal IT2 fuzzy numbers. The framework of the proposed modification is a new IT2 fuzzy DEMATEL without loss of generality of the fuzzy DEMATEL. Instead of triangular fuzzy numbers, the proposed modification fully utilizes trapezoidal IT2 fuzzy numbers in linguistic scales where other computational implications would be emerging out of this integration. There are several key features which arise from our proposed modifications. The introduction of IT2FS in DEMATEL provides more room for improvement with the use of IT2 trapezoidal fuzzy numbers compared to triangular IT2 fuzzy numbers. Most of the descriptions of IT2FS in decision-making used trapezoidal fuzzy numbers thanks to its non-single maximum membership property which further enhances the group decision ability of the fuzzy environment. Instead of using the interval approach provided by Wu and Mendel [43] to obtain the linguistic scale, the proposed modification uses the IT2FS preference scale proposed by Abdullah and Najib [1] in defining the linguistic variables. This preference scale avoids the computation of mean and standard deviation where these statistical measures would undermine the expert knowledge in providing evaluations. This preference scale offers comprehensive evaluation thanks to the property of IT2FS where it can deal with more room of uncertainty. The last feature is the normalization method used. In this step, IT2FS is normalized to crisp numbers using an expected value method. The proposed modification uses the concept of expected values as proposed by Hu et al. [15] instead of the Jaccard similarity measure or the min-max normalization method. The Jaccard similarity measure and min-max normalization method need a higher computational effort as compared to the expected value method. Furthermore, it has been proven that the expected value method is more reasonable compared to the approaches proposed by Baas and Kwakernaak [4], and Lee and Li [22]. They analysed thirteen sets of fuzzy numbers provided by Bortolan and Degani [6] to verify the veracity of the expected value method. It is shown that the results calculated using the expected value were consistent with those obtained by the ranking method [8]. We also used the expected value instead of the ranking method as it fit well with $n \times n$ matrices, sum of columns and sum of rows within the fuzzy DEMATEL. Based on these arguments, we propose a new IT2 fuzzy DEMATEL by integrating with the comprehensive features of the IT2 fuzzy numbers and DEMATEL. This new approach combines the advantages of IT2FS and the interconnected features of DEMATEL, which can showcase the relationship among the criteria network in the framework of group decision-making. The newly proposed modification is applied to a multi-criteria problem of knowledge management (KM). This is typically referred as a process of managing knowledge and information where multiple criteria of KM can be used for measuring KM performance, but most importantly, these criteria need to be considered concurrently. Therefore, in order to deal with uncertainty in the assessment of multi-criteria KM and also to overcome the vagueness in DMs' judgment, the case of KM was applied to our proposed modification. Besides the benefits the proposed modification offers the relationships among the criteria of KM, it also allows the prioritizing of criteria based on the cause–effect group through a causal diagram. The rest of this paper was organized as follows. The methodology used for the development of the newly proposed modification IT2 fuzzy DEMATEL framework is outlined in Sect. 2. In Sect. 3, an experiment using the KM criteria with a group of DMs is presented to demonstrate the feasibility and consistency of the new IT2 fuzzy DEMATEL. Section 4 concludes the results and how the newly proposed method performed against the existing methods.

2 Proposed method

This study proposes a new IT2 fuzzy DEMATEL with the purpose to obtain comprehensive evaluation, using the new advantages of IT2FS linguistic variables. The new modification uses IT2 trapezoidal fuzzy numbers and the concept of expected value to obtain crisp values. The new modification could effectively avoid vague and imprecise evaluations. Furthermore, it also provides straightforward calculations because of the simplicity of expected value. More information on IT2FSs and operations with them can be found in Appendix 1. The new IT2 fuzzy DEMATEL is proposed without losing the general structure of traditional DEMATEL [11] and fuzzy DEMATEL [18]. To better conceptualize the new IT2 fuzzy DEMATEL, the following procedures were proposed.

Table 1 Linguistic variables

Linguistic variables	IT2 FN
Very high influence	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
High influence	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
Low influence	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))
Very low influence	((0.2,0.3,0.3,0.4;1,1), (0.25,0.3,0.3,0.35;0.9,0.9))
No influence	((0,0.1,0.1,0.1;1,1), (0,0.1,0.1,0.05;0.9,0.9))

Step 1 Linguistic data collection
In MCDM problems, responses from groups of decision makers (DMs) are mainly focused on the opinions regarding a rating of criteria for the problems identified. The DMs were asked to specify a rating using five DEMATEL linguistic levels varying from 'no influence' to 'very high influence' with respect to the criteria. The new linguistic variables with IT2 FN are shown in Table 1.

Step 2 Generate the initial direct-relation matrix, A.
The IT2 FN score x_{ij}^k was given by the kth DM and indicated the influential level that criteria i has on criteria j. The $n \times n$ matrix A was calculated using the next equation by averaging the individual DMs' scores.

$$A_{ij} = \frac{1}{H}\sum_{k=1}^{H} x_{ij}^k \tag{1}$$

where H is the total number of DMs and

$$\begin{aligned} x_{ij}^k &= \left(\tilde{A}_{ij}^U, \tilde{A}_{ij}^L\right) \\ &= \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right),\right. \\ &\quad \left.\left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right) \end{aligned}$$

A_{ij} shows the initial direct relation that a criterion exerts on and received from other criteria.

Step 3 Calculate the normalized initial direct-relation matrix, D
On the basis of the initial direct-relation matrix A_{ij}, the normalized initial direct-relation matrix, D, can be obtained using the following equations.

$$s = \max\left(\max_{1 \le i \le n}\sum_{j=1}^{n} A_{ij}, \max_{1 \le j \le n}\sum_{i=1}^{n} A_{ij}\right), \tag{2}$$

and

$$D = \frac{A}{s} \tag{3}$$

where $\max_{1 \le i \le n}\sum_{j=1}^{n} A_{ij}$ and $\max_{1 \le j \le n}\sum_{i=1}^{n} A_{ij}$ are the upper and lower IT2 FN of A_{ij}. All A_{ij} are typical IT2 FS; therefore, the fourth element of UMF entails the greatest value in A_{ij}.
The sum of each row i of matrix A represented the total direct effects the criterion i gave to the other criteria, and the sum of each column j of matrix A_{ij} represented the total direct effects received to other criteria by criterion i.

Step 4 Construct the $n \times n$ matrix, Z
Matrix Z is constructed by arranging matrix D according to the upper IT2FN and the lower IT2FN

$$Z_x = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & 0 \end{bmatrix} \tag{4}$$

where

$$x = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) = \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right), \left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right)$$

Therefore, there are eight $n \times n$ matrices. The construction of the $n \times n$ matrix is needed for the calculation in the next step since it involves multiplication of matrices between matrix Z and identity matrix I. According to the matrix multiplication definition, the number of elements in a row of matrix Z must be equal with the number of element of column in identity matrix I.

Step 5 Attain the total-influence matrix, T
The total-influence matrix, T, can be acquired using next equation in which I was denoted as identity matrix.

$$T_x = Z_x(I - Z_x)^{-1} \tag{5}$$

Step 6 Structural correlation analysis
The sum of rows and the sum of columns was separately denoted as vector r and c through next equations. $D_i + R_i$ is constructed by adding r to c, and $D_i - R_i$ is constructed by subtracting r from c.

$$T_x = \left[t_{ij}\right]_{n \times n}, \quad i,j = 1,2,\ldots,n \quad \text{and} \tag{6}$$

$$r_x = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1 = [t_i] n \times 1} \tag{7}$$

$$c_x = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n = [t_i] 1 \times n} \tag{8}$$

where

$$\begin{aligned} x &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \\ &= \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right),\right. \\ &\quad \left.\left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right). \end{aligned}$$

Step 7 Calculate expected value, $E(W)$
The expected values of $E(D_i + R_i)$ and $E(D_i - R_i)$ are calculated using Eq. (9).

$$E(D_i \pm R_i) = \frac{1}{2}\left(\frac{1}{4}\sum_{i=1}^{4}\left((D_i \pm R_i)^L + (D_i \pm R_i)^U\right)\right) \times \frac{1}{4}\left(\sum_{i=1}^{2}\left(H_i(A_i^L) + H_i(A_i^U)\right)\right), \quad (9)$$

This step is called as normalization. It is a process where IT2 FN is normalized to a crisp number.

Step 8 Construct causal diagram
The horizontal axis vector,$D_i + R_i$ is named "Prominence" and shows the degree of importance the criterion i plays in the system. The vertical axis $D_i - R_i$ is named "Relation" and shows the net effect the criterion i contributed to the system. When $D_i - R_i$ is positive, criterion i is a net causer, and when $D_i - R_i$ is negative, criterion i is a net receiver [11, 12].

In this IT2 fuzzy DEMATEL, we introduce new linguistic variables using trapezoidal IT2 fuzzy numbers instead of triangular fuzzy numbers. Besides, we also utilize a new method to calculate the weight of the criteria by applying the expected value. The newly proposed modification is applied to develop a causal relationship among criteria of KM.

3 A case of knowledge management

Knowledge management (KM) is one of the key processes in managing organizational knowledge. The ultimate aim of KM is to ensure organizational objectives are achieved. In this case study, eleven criteria of KM are employed, in which most of these criteria are mainly based on the works of Martensson [27] and Bixler [5]. The eleven criteria are top management support (C1), communication (C2), culture and people (C3), sharing knowledge (C4), incentives (C5), time (C6), trust (C7), cost (C8), performance measurements (C9), information technology (C10) and security (C11). The KM case is considered to test the procedures and the feasibility of the new IT2 fuzzy DEMATEL framework. The computations of this case are implemented in the following steps.

Step 1 Linguistic data collection
Three experts in the field of KM were voluntarily agreed to form a group of DMs. Two professors attached with Master of Business Administration program and one senior assistant registrar at the registrar office of a public university in Malaysia were invited to make evaluation. They were asked to provide rating of degree of influence among criteria using the five linguistic variables based on IT2FN (see Table 1). For example, DMs ratings with respect to criteria C1 are shown in Appendix 2.

Step 2 Generate the initial direct-relation matrix, A
Using the decision goals in step 1, the average of DMs' opinions was calculated using Eq. (1) to obtain matrix A.

$$A = \begin{bmatrix} 0 & A_{1,2} & \cdots & A_{1,11} \\ A_{2,1} & 0 & \cdots & A_{2,11} \\ \vdots & \vdots & \vdots & \vdots \\ A_{11,1} & A_{11,2} & \cdots & 0 \end{bmatrix}$$

With reference to the three matrices in Appendix 2, the element of $A_{2,1}$, of matrix A for example is generated as follows:

$$A_{2,1} = \frac{1}{3}\begin{pmatrix} ((0.8,0.9,0.9,1.0;1,1),(0.85,0.9,0.9,0.95;0.9,0.9)) \\ +((0.6,0.7,0.7,0.8;1,1),(0.65,0.7,0.7,0.75;0.9,0.9)) \\ +((0.6,0.7,0.7,0.8;1,1),(0.65,0.7,0.7,0.75;0.9,0.9)) \end{pmatrix}$$

$$A_{2,1} = ((0.67, 0.77, 0.77, 0.87{:}1, 1)(0.72, 0.77, 0.77, 0.62{:}0.9, 0.9))$$

The full elements of matrix A are presented in Appendix 3.

Step 3 Calculating the normalized initial direct-relation matrix, D
The normalized direct-relation matrix can be obtained using Eqs. (2) and (3)

$$D = \begin{bmatrix} 0 & D_{1,2} & \cdots & D_{1,11} \\ D_{2,1} & 0 & \cdots & D_{2,11} \\ \vdots & \vdots & \vdots & \vdots \\ D_{11,1} & D_{11,2} & \cdots & 0 \end{bmatrix}$$

where $D_{i,j} = \left(\frac{A_{i,j}^U}{7.93}, \frac{A_{i,j}^L}{7.93}\right)$. Matrix D can be referred to in Appendix 4.

Step 4 Construct the $n \times n$ matrix, Z_x
Matrix Z_x are arranged according to the membership functions using Eq. (4). There are eight $n \times n$ matrices:
$Z_{a_{11}^U}, Z_{a_{12}^U}, Z_{a_{13}^U}, Z_{a_{14}^U}, Z_{a_{11}^L}, Z_{a_{12}^L}, Z_{a_{13}^L}$ and $Z_{a_{14}^L}$.
As an example, the matrix of $Z_{a_{11}^U}$ is given as

$$
Z_{a_{11}^U} = \begin{vmatrix}
0 & 0.067 & 0.067 & 0.067 & 0.085 & 0.076 & 0.092 & 0.085 & 0.085 & 0.059 & 0.067 \\
0.085 & 0 & 0.076 & 0.101 & 0.059 & 0.051 & 0.076 & 0.042 & 0.076 & 0.042 & 0.042 \\
0.042 & 0.076 & 0 & 0.051 & 0.042 & 0.051 & 0.076 & 0.034 & 0.059 & 0.042 & 0.067 \\
0.059 & 0.085 & 0.059 & 0 & 0.051 & 0.051 & 0.051 & 0.051 & 0.085 & 0.085 & 0.059 \\
0.0845 & 0.067 & 0.050 & 0.042 & 0 & 0.059 & 0.076 & 0.067 & 0.067 & 0.050 & 0.050 \\
0.067 & 0.067 & 0.050 & 0.085 & 0.042 & 0 & 0.059 & 0.076 & 0.076 & 0.067 & 0.059 \\
0.101 & 0.085 & 0.085 & 0.076 & 0.085 & 0.059 & 0 & 0.050 & 0.076 & 0.059 & 0.101 \\
0.085 & 0.042 & 0.042 & 0.076 & 0.092 & 0.076 & 0.067 & 0 & 0.076 & 0.067 & 0.067 \\
0.092 & 0.067 & 0.050 & 0.085 & 0.067 & 0.050 & 0.085 & 0.059 & 0 & 0.042 & 0.042 \\
0.050 & 0.059 & 0.059 & 0.085 & 0.034 & 0.076 & 0.059 & 0.076 & 0.067 & 0 & 0.076 \\
0.059 & 0.059 & 0.067 & 0.051 & 0.051 & 0.042 & 0.101 & 0.067 & 0.059 & 0.067 & 0
\end{vmatrix}
$$

Step 5 Attain the total-influence matrix, T_x

Total-influence matrix can be obtained using Eq. (5). In this case study, we used 11 × 11 identity matrix since we had eleven criteria. The total-influence matrix should be positive values, so the concept of absolute value is needed to ensure the total-influence matrix is always in positive values.

Computation of $T_{a_{11}^U}$:

$T_{a_{11}^U} = Z_{a_{11}^U}(I - Z_{a_{11}^U})^{-1}$ where I is 11 × 11 identity matrix. Then, we get, matrix

The computation of $T_{a_{11}^U}, T_{a_{12}^U}, T_{a_{13}^U}, T_{a_{14}^U}, T_{a_{11}^L}, T_{a_{12}^L}, T_{a_{13}^L}$ and $T_{a_{14}^L}$ is similar to the computation of $T_{a_{11}^U}$.

Step 6 Structural correlation analysis

The sum of rows and the sum of columns are calculated to obtain structural correlation analysis. Equations (6) to (8) are used to obtain $D_i + R_i$. Table 2 and Table 3 show values of $D_i + R_i$ and $D_i - R_i$, respectively.

$$
T_{a_{11}^U} = \begin{bmatrix}
0.148 & 0.199 & 0.187 & 0207 & 0.204 & 0.190 & 0.234 & 0.201 & 0.225 & 0.174 & 0.191 \\
0.206 & 0.121 & 0.179 & 0.218 & 0.165 & 0.152 & 0.200 & 0.147 & 0.199 & 0.143 & 0.152 \\
0.148 & 0.171 & 0.092 & 0.154 & 0.131 & 0.135 & 0.180 & 0.122 & 0.163 & 0.126 & 0.156 \\
0.181 & 0.194 & 0.162 & 0.124 & 0.153 & 0.150 & 0.175 & 0.152 & 0.203 & 0.178 & 0.164 \\
0.202 & 0.177 & 0.152 & 0.161 & 0.105 & 0.156 & 0.196 & 0.166 & 0.185 & 0.146 & 0.155 \\
0.191 & 0.182 & 0.156 & 0.205 & 0.149 & 0.105 & 0.186 & 0.178 & 0.199 & 0.166 & 0.167 \\
0.243 & 0.220 & 0.207 & 0.218 & 0.206 & 0.179 & 0.155 & 0.175 & 0.221 & 0.177 & 0.224 \\
0.215 & 0.167 & 0.154 & 0.203 & 0.201 & 0.182 & 0.201 & 0.115 & 0.206 & 0.173 & 0.181 \\
0.213 & 0.182 & 0.156 & 0.204 & 0.172 & 0.152 & 0.208 & 0.163 & 0.128 & 0.143 & 0.152 \\
0.174 & 0.174 & 0.162 & 0.203 & 0.140 & 0.173 & 0.184 & 0.176 & 0.189 & 0.103 & 0.181 \\
0.181 & 0.172 & 0.168 & 0.170 & 0.154 & 0.142 & 0.219 & 0.166 & 0.179 & 0.162 & 0.110
\end{bmatrix}
$$

Table 2 Values of $D_i + R_i$

Criteria	$D + R$ (upper)				$D + R$ (lower)			
C1	(4.262	7.867	7.867	20.121)	(5.653	7.874	7.874	11.836)
C2	(3.840	7.209	7.209	18.877)	(5.148	7.216	7.216	10.930)
C3	(3.354	6.451	6.451	16.941)	(4.553	6.459	6.459	9.8695)
C4	(3.905	7.310	7.310	19.105)	(5.213	7.317	7.317	11.050)
C5	(3.583	6.807	6.807	17.975)	(4.832	6.816	6.816	10.367)
C6	(3.600	6.834	6.834	17.774)	(4.851	6.841	6.841	10.402)
C7	(4.362	8.022	8.022	20.680)	(5.770	8.023	8.028	12.046)
C8	(3.758	7.081	7.081	18.584)	(5.049	7.089	7.089	10.756)
C9	(3.968	7.407	7.407	19.320)	(5.296	7.413	7.413	11.196)
C10	(3.552	6.760	6.760	17.867)	(4.791	6.765	6.765	10.295)
C11	(3.654	6.919	6.919	18.012)	(4.923	6.925	6.925	10.530)

Table 3 Values of $D_i - R_i$

Criteria	$D - R$ (upper)				$D - R$ (lower)			
C1	(0.058	0.091	0.091	0.421)	(0.0732	0.0894	0.089	0.131)
C2	(− 0.076	− 0.118	− 0.118	− 0.254)	(− 0.094	− 0.120	− 0.120	− 0.165)
C3	(− 0.197	− 0.306	− 0.306	− 0.447)	(− 0.235	− 0.306	− 0.306	− 0.420)
C4	(− 0.233	− 0.363	− 0.363	− 0.811)	(− 0.288	− 0.365	− 0.365	− 0.515)
C5	(0.020	0.032	0.032	0.074)	(0.028	0.032	0.032	0.050)
C6	(0.168	0.261	0.261	0.324)	(0.206	0.263	0.263	0.368)
C7	(0.088	0.138	0.138	0.311)	(0.102	0.138	0.138	0.183)
C8	(0.237	0.369	0.369	0.820)	(0.294	0.372	0.372	0.526)
C9	(− 0.223	− 0.347	− 0.347	− 0.767)	(− 0.266	− 0.347	− 0.347	− 0.478)
C10	(0.168	0.261	0.261	0.574)	(0.195	0.261	0.261	0.349)
C11	(− 0.011	− 0.017	− 0.017	− 0.246)	(− 0.016	− 0.017	− 0.017	− 0.029)

Step 7 Calculate expected value, $E(W)$

Expected values convert the IT2 trapezoidal fuzzy numbers of $D_i + R_i$ and $D_i - R_i$ into crisp values using Eq. (9). The crisp values are presented in Table 4.

It can be seen in that C7 has the highest value of $D_i + R_i$ so it has the strongest relationship with the other criteria in the index of the strength of relationship among the criteria. On the other hand, C3 has the weakest relationship with the other criteria since it has the lowest value of $D_i + R_i$. The criteria are ranked as C7 ≻ C1 ≻ C9 ≻ C4 ≻ C2 ≻ C8 ≻ C11 ≻ C5 ≻ C6 ≻ C10 ≻ C3. The ranking order of the criteria is made based on the values of $D_i + R_i$.

Step 8 Construct a causal diagram

The causal diagram is developed with the vertical axis $D_i - R_i$ and the horizontal axis $D_i + R_i$ as shown in Fig. 1.

The criteria assessed on the graph are top management support (C1), communication (C2), culture and people (C3), sharing knowledge (C4), incentives (C5), time (C6), trust (C7), cost (C8), performance measurements (C9), information technology (C10) and security (C11). The horizontal axis shows the importance of each criterion, whereas the vertical axis divides criteria into the cause and effect groupings. These types of causal diagrams can help to visualize the complicated causal relationships of criteria into a visible structural model. Furthermore, with the visualization of a causal diagram, we can make decisions by recognizing the cause and effect criteria. The criteria C1, C5, C6, C7, C8 and C10 are grouped as the cause criteria which are called net causers, while effect criteria group comprises C2, C3, C4, C9 and C11. These latter criteria are also known as net receivers. The causal diagram indicates that C7 receives the highest score of importance among the criteria. Thus, in the case of KM, the new modification IT2 fuzzy DEMATEL recognizes ‘trust’ as the most influential criteria. Trust in KM is described as the belief that another party will not act in a way that is harmful to the trusting firm, will act in such a way that it is beneficial to the trusting firm, will act reliably, and finally will behave or respond in a predictable and mutually acceptable manner [34]. Based on these definitions, there is

Table 4 Crisp values of $D_i + R_i$ and $D_i - R_i$

Criteria	$D + R$	$D - R$
C1	8.711	0.124
C2	8.033	− 0.127
C3	7.189	− 0.300
C4	8.138	− 0.392
C5	7.600	0.035
C6	7.597	0.251
C7	8.901	0.147
C8	7.896	0.399
C9	8.244	− 0.371
C10	7.547	0.277
C11	7.696	− 0.044

no doubt that the invisible criteria trust is essential for the effectiveness of KM. These results are in agreement with research by Politis [35] which also concluded that 'trust' is positively related to KM.

The results of this KM case study indicate the importance of the eleven criteria in fulfilling organizational objectives. Out of the eleven criteria, the criteria 'trust' was considered as the most important criteria followed by 'top management support'. It is somewhat surprising that the criteria 'culture and people' was the least important criteria in KM. This implies that organizations could be succeeded without so much depending on its employees and their culture. Despite the order of importance of the criteria, it is interesting to note that there was no clear indication on the weight of importance of one criterion to another.

For the purpose of comparative analysis, the problem of KM is also applied to traditional DEMATEL [11] and fuzzy DEMATEL [18] to observe the consistency of the modification. Traditional DEMATEL uses a crisp number, while fuzzy DEMATEL uses type-1 triangular fuzzy numbers in defining linguistic variables. The ranking of the same criteria and causal relationships using the other two methods is presented in Table 5.

Table 5 shows comparative analysis of KM applied to traditional DEMATEL [11] and fuzzy DEMATEL [18] to observe the consistency of the modification. The criteria assessed were top management support (C1), communication (C2), culture and people (C3), sharing knowledge (C4), incentives (C5), time (C6), trust (C7), cost (C8), performance measurements (C9), information technology (C10) and security (C11). Interestingly, the results of the ranked criteria and causal relationship using the proposed IT2 fuzzy DEMATEL are consistent with the result of traditional DEMATEL [11] and also fuzzy DEMATEL [18]. The results support the notion that the proposed modification is not sensitive to the type of fuzzy numbers used in defining linguistic variables.

4 Conclusion

A new IT2 fuzzy DEMATEL modification has been proposed with two main innovations. Firstly, we used trapezoidal IT2 fuzzy numbers to replace the triangular IT1 fuzzy numbers. We applied trapezoidal IT2FS proposed by [1] since this preference scale offers a more comprehensive judgment. Secondly, we used the concept of the expected value proposed by [15] in order to overcome the computationally expense of the Jaccard similarity measure with min-max normalization and the ranking method in obtaining the crisp values. The proposed modification is able to handle fuzzy MCDM problems with a more comprehensive approach thanks to the extra properties of IT2FS and successfully established criteria weights with causal relationships. A case of KM with eleven criteria was implemented using the proposed modification to manage the organization knowledge. IT2 fuzzy DEMATEL

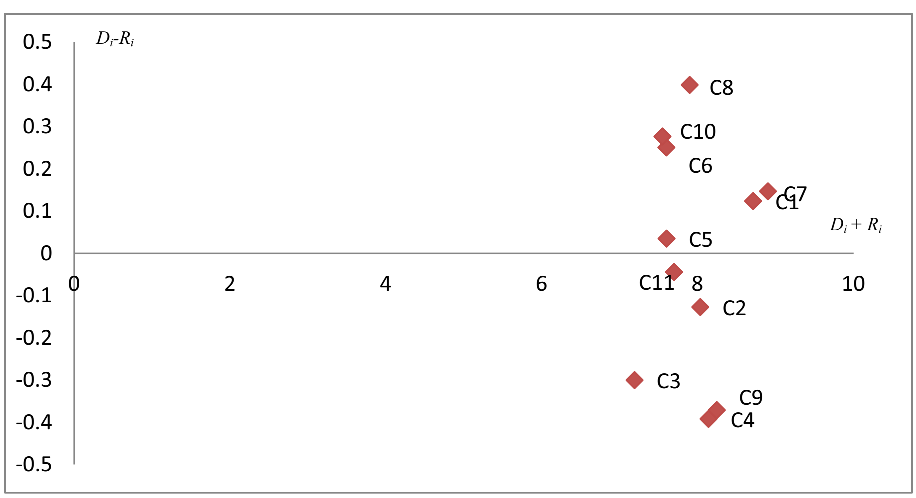

Fig. 1 Causal diagram developed with the vertical axis $D_i - R_i$ and the horizontal axis $D_i + R_i$

Table 5 Comparative analysis

Evaluation method	$D + R$	$D - R$
Traditional DEMATEL [11]	C7 ≻ C1 ≻ C9 ≻ C4 ≻ C2 ≻ C8 ≻ C11 ≻ C5 ≻ C6 ≻ C10 ≻ C3	Net causer: C1, C5, C6, C7, C8, C10 Net receiver: C2, C3, C4, C9, C11
Fuzzy DEMATEL [18]	C7 ≻ C1 ≻ C9 ≻ C4 ≻ C2 ≻ C8 ≻ C11 ≻ C5 ≻ C6 ≻ C10 ≻ C3	Net causer: C1, C5, C6, C7, C8, C10 Net receiver: C2, C3, C4, C9, C11
Modification of IT2-DEMATEL	C7 ≻ C1 ≻ C9 ≻ C4 ≻ C2 ≻ C8 ≻ C11 ≻ C5 ≻ C6 ≻ C10 ≻ C3	Net causer: C1, C5, C6, C7, C8, C10 Net receiver: C2, C3, C4, C9, C11

effectively avoids inadequate vagueness in KM criteria selection. The results identified 'trust' as the most influential criteria in KM and as the criteria that should be given extra attention from management. The new modification also successfully classified the criteria of KM into two groups. The criteria that caused decisions: top management support, incentives, time, trust, cost and information technology. The second group of criteria is known as the effects or the net receiver criteria. In this group, the criteria were communication, culture and people, sharing knowledge, performance measurements and security. A comparative analysis of causal relationships between the proposed modification and the other existing methods was performed, and the findings show that the proposed modification is consistent with the other two DEMATEL-based methods. Thus, it can be concluded that the proposed IT2 fuzzy DEMATEL is comparable with the other methods. The proposed modification managed to offer the criteria weight and a causal diagram by applying trapezoidal IT2 fuzzy numbers and the concept of expected value. Hence, it can effectively avoid inadequate reflection of the vagueness in the MCDM problems. Nonetheless, this study has some limitations. The optimum number of DMs and reliability of the results are always the main issue in decision-making. However, there are several computational methods that could be used in ensuring the reliability of the results. One of the possible methods that could be explored in future research is sensitivity analysis. The analysis could be used to check the sensitivity of the results in the causal diagram owing to different sources of uncertainty in linguistic judgement.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix 1

Trapezoidal fuzzy numbers

A trapezoidal fuzzy number can be defined as $\tilde{m} = (a, b, c, d)$ where the membership functions $\mu_{\tilde{m}}$ of $\tilde{m}$ is given by:

$$\mu_{\tilde{m}} = \begin{cases} \dfrac{x-a}{b-a} & (a \le x \le b) \\ 1 & (b \le x \le c) \\ \dfrac{d-x}{d-c} & (c \le x \le d) \end{cases} \tag{10}$$

where b and c are called a mode interval of $\tilde{m}$, a and d are called lower and upper limits of $\tilde{m}$, respectively [35].

Let $\tilde{A}$ and $\tilde{B}$ be two positive trapezoidal fuzzy numbers parameterized by (a_1, a_2, a_3, a_4) and (b_1, b_2, b_3, b_4), then the arithmetic operations of these two trapezoidal fuzzy numbers are given as follows [6].

$$\tilde{A} \oplus \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4) \tag{11}$$

$$\tilde{A} - \tilde{B} = (a_1 - b_1, a_2 - b_2, a_3 - b_3, a_4 - b_4) \tag{12}$$

$$\tilde{A} \otimes \tilde{B} = (a_1 \times b_1, a_2 \times b_2, a_3 \otimes b_3, a_4 \times b_4) \tag{13}$$

$$\left(\tilde{A}\right)^{-1} = \left(\frac{1}{a_4}, \frac{1}{a_3}, \frac{1}{a_2}, \frac{1}{a_1}\right) \tag{14}$$

Type-1 fuzzy set

Let $\tilde{A}$ be a type-1 trapezoidal fuzzy set, $\tilde{A} = (a_1, a_2, a_3, a_4; H_1(A), H_2(A))$. Figure 2 shows the $\tilde{A}$ where $H_1(\tilde{A})$ denotes the membership value of the element $a_2, H_2(\tilde{A})$ denotes the membership value of the element $a_3, 0 \le H_1(A) \le 1$ and $0 \le H_2(A) \le 1$. If $a_2 = a_3$, then the type-1 fuzzy set $\tilde{A}$ becomes a triangular T1FS.

Interval type-2 fuzzy set

We briefly present some definitions of T2FS and IT2 FS. Mendel et al. [30] proposed the following definitions of T2FS.

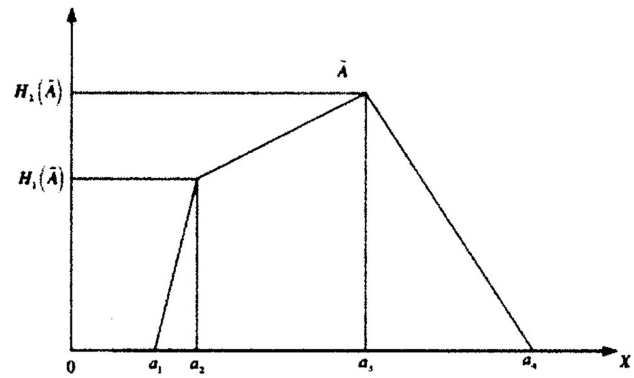

Fig. 2 A type-1 trapezoidal fuzzy set

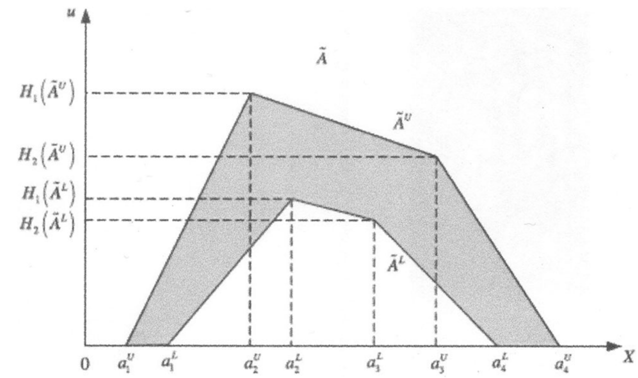

Fig. 3 An interval type-2 trapezoidal fuzzy set

Definition 1.1 A type-2 fuzzy set $\tilde{\tilde{A}}$ in the universe of discourse X can be represented by a type-2 membership function $\mu_{\tilde{\tilde{A}}}$ shown as follows:

$$\tilde{\tilde{A}} = \left\{(x,u), \mu_{\tilde{\tilde{A}}}(x,u) \middle| \forall x \in X, \forall u \in J_x \subseteq [0,1], 0 \leq \mu_{\tilde{\tilde{A}}}(x,u) \leq 1\right\} \tag{15}$$

where J_x denotes an interval in [0, 1].

The type-2 fuzzy set $\tilde{\tilde{A}}$ also can be written as follows.

Definition 1.2 A type-2 fuzzy set $\tilde{\tilde{A}}$ in the universe of discourse X can be represented by a type-2 membership function $\mu_{\tilde{\tilde{A}}}$.

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_x} \mu_{\tilde{\tilde{A}}}(x,u)/(x,u) \tag{16}$$

where $J_x \subseteq [0,1]$ and $\int\int$ denotes the union over all admissible x and u.

For simplicity, the T2FS $\tilde{\tilde{A}}$ may be written as interval membership.

Definition 1.3 Let $\tilde{\tilde{A}}$ be a T2FS in the universe of discourse X represented by the type-2 membership function $\mu_{\tilde{\tilde{A}}}$. If all $\mu_{\tilde{\tilde{A}}}(x,u) = 1$, then $\tilde{\tilde{A}}$ is called IT2 FS. An IT2 FS $\tilde{\tilde{A}}$ can be regarded as a special case of T2FS, shown as follows:

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_x} 1/(x,u), \tag{17}$$

where $J_x \subseteq [0,1]$.

The property of interval in defining the T2FS paves a way to introduce boundary membership of upper and lower. The upper and lower memberships are defined as follows.

Definition 1.4 The upper membership function (UMF) and lower membership function (LMF) of $\approx\!\!\text{A}$ are two type-1 membership functions.

The heights of the UMF and LMF of IT2 FS are also defined to characterize IT2 FS. Figure 3 shows trapezoidal IT2 FS where upper and lower fuzzy numbers are drawn as reference points.

Figure 2 shows the upper trapezoidal membership function $\tilde{A}_i^U$ and the lower trapezoidal membership function $\tilde{A}_i^L$ of IT2 FS $\tilde{A}_i$.

Arithmetic operations of trapezoidal interval type-2 fuzzy sets

Arithmetic operations of trapezoidal IT2FSs are described by [42]. It is recalled as follows.

Definition 1.5 The addition operation between the trapezoidal IT2FS

$$\begin{aligned}\tilde{\tilde{A}}_1 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \\ &= \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right),\right. \\ &\quad \left.\left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right)\end{aligned}$$

and

$$\begin{aligned}\tilde{\tilde{A}}_2 &= \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \left(\left(a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1\left(\tilde{A}_2^U\right), H_2\left(\tilde{A}_2^U\right)\right),\right. \\ &\quad \left.\left(a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1\left(\tilde{A}_2^L\right), H_2\left(\tilde{A}_2^L\right)\right)\right)\end{aligned}$$

is defined as follows:

$$\begin{aligned}\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \oplus \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \Big(\big(a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U + a_{24}^U; \\ &\quad \min\big(H_1(\tilde{A}_1^U), H_2(\tilde{A}_2^U)\big), \min\big(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)\big)\big)\Big), \\ &\quad \big(a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L, a_{13}^L + a_{23}^L, a_{14}^L + a_{24}^L; \\ &\quad \min\big(H_1(\tilde{A}_1^L), H_2(\tilde{A}_2^L)\big), \min\big(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)\big)\big)\Big)\end{aligned} \tag{18}$$

Definition 1.6 The subtraction operation between the trapezoidal IT2FS

$$\begin{aligned}\tilde{\tilde{A}}_1 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \\ &= \Big(\big(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)\big), \\ &\quad \big(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)\big)\Big)\end{aligned}$$

and

$$\begin{aligned}\tilde{\tilde{A}}_2 &= \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \Big(\big(a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)\big), \\ &\quad \big(a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)\big)\Big)\end{aligned}$$

is defined as follows:

$$\begin{aligned}\tilde{\tilde{A}}_1 - \tilde{\tilde{A}}_2 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) - \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \Big(\big(a_{11}^U - a_{24}^U, a_{12}^U - a_{23}^U, a_{13}^U - a_{22}^U, a_{14}^U - a_{21}^U; \\ &\quad \min\big(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)\big), \min\big(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)\big)\big), \\ &\quad \big(a_{11}^L - a_{24}^L, a_{12}^L - a_{23}^L, a_{13}^L - a_{22}^L, a_{14}^L - a_{21}^L; \\ &\quad \min\big(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)\big), \min\big(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)\big)\big)\Big)\end{aligned} \tag{19}$$

Definition 1.7 The multiplication operation between the trapezoidal IT2FS

$$\begin{aligned}\tilde{\tilde{A}}_1 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \\ &= \Big(\big(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)\big), \\ &\quad \big(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)\big)\Big)\end{aligned}$$

and

$$\begin{aligned}\tilde{\tilde{A}}_2 &= \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \Big(\big(a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)\big), \\ &\quad \big(a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)\big)\Big)\end{aligned}$$

is defined as follows:

$$\begin{aligned}\tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 &= \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \otimes \left(\tilde{A}_2^U, \tilde{A}_2^L\right) \\ &= \Big(\big(a_{11}^U \times a_{21}^U, a_{12}^U \times a_{22}^U, a_{13}^U \times a_{23}^U, a_{14}^U \times a_{24}^U; \\ &\quad \min\big(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)\big), \min\big(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)\big)\big), \\ &\quad \big(a_{11}^L \times a_{21}^L, a_{12}^L \times a_{22}^L, a_{13}^L \times a_{23}^L, a_{14}^L \times a_{24}^L; \\ &\quad \min\big(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)\big), \min\big(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)\big)\big)\Big)\end{aligned} \tag{20}$$

The above definitions and arithmetic operations are prevalently employed in the proposed IT2 fuzzy DEMATEL.

Appendix 2

Appendix 2.1

Evaluation of C1 by DM1

DM1	C1
C1	0
C2	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C3	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))
C4	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))
C5	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C6	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C7	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C8	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C9	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C10	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C11	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))

Appendix 2.2

Evaluation of C1 by DM2

DM2	C1
C1	0
C2	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C3	((0.2,0.3,0.3,0.4;1,1), (0.25,0.3,0.3,0.35;0.9,0.9))
C4	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))
C5	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C6	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))
C7	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C8	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C9	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C10	((0.2,0.3,0.3,0.4;1,1), (0.25,0.3,0.3,0.35;0.9,0.9))
C11	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))

Appendix 2.3

Evaluation of C1 by DM3

DM3	C1
C1	0
C2	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C3	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))
C4	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C5	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C6	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C7	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C8	((0.6,0.7,0.7,0.8;1,1), (0.65,0.7,0.7,0.75;0.9,0.9))
C9	((0.8,0.9,0.9,1.0;1,1), (0.85,0.9,0.9,0.95;0.9,0.9))
C10	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))
C11	((0.4,0.5,0.5,0.6;1,1), (0.45,0.5,0.5,0.55;0.9,0.9))

Appendix 3

Initial direct-relation matrix, *A*

	C1								C2								C3							
C1	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))
C2	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.6	0.7	0.7	0.8)	(0.65	0.7	0.7	0.75))
C3	((0.33	0.43	0.43	0.53)	(0.38	0.433	0.433	0.48))	((0.6	0.7	0.7	0.8)	(0.65	0.7	0.7	0.75))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))
C4	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.47	0.57	0.57	0.67)	(0.517	0.57	0.57	0.62))
C5	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.4	0.5	0.5	0.6)	(0.45	0.5	0.5	0.55))
C6	((0.53	0.63	0.63	0.53)	(0.58	0.63	0.63	0.68))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.4	0.5	0.5	0.6)	(0.45	0.5	0.5	0.55))
C7	((0.8	0.9	0.9	1)	(0.85	0.9	0.9	0.95))	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.67	0.77	0.77	0.87)	(0.716	0.77	0.77	0.82))
C8	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.33	0.43	0.43	0.53)	(0.38	0.433	0.433	0.48))	((0.33	0.43	0.43	0.53)	(0.383	0.433	0.433	0.48)0
C9	((0.73	0.83	0.83	0.93)	(0.78	0.83	0.83	0.88))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.4	0.5	0.5	0.6)	(0.45	0.5	0.5	0.55))
C10	((0.4	0.5	0.5	0.6)	(0.45	0.5	0.5	0.55))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.47	0.57	0.57	0.67)	(0.517	0.57	0.57	0.62))
C11	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.53	0.63	0.63	0.53)	(0.583	0.63	0.63	0.68))

	C4								C5								C6							
C1	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.60	0.70	0.70	0.80)	((0.65	0.70	0.70	0.75))
C2	((0.80	0.90	0.90	1.00)	(0.85	0.90	0.90	0.95))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.40	0.50	0.50	0.60)	((0.45	0.50	0.50	0.55))
C3	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))	((0.40	0.50	0.50	0.60)	((0.45	0.50	0.50	0.55))
C4	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.40	0.50	0.50	0.60)	((0.45	0.50	0.50	0.55))
C5	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.47	0.57	0.57	0.67)	((0.52	0.57	0.57	0.62))
C6	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))
C7	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.47	0.57	0.57	0.67)	((0.52	0.57	0.57	0.62))
C8	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))	((0.73	0.83	0.83	0.93)	(0.78	0.83	0.83	0.88))	((0.60	0.70	0.70	0.80)	((0.65	0.70	0.70	0.75))
C9	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.40	0.50	0.50	0.60)	((0.45	0.50	0.50	0.55))
C10	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.27	0.37	0.37	0.47)	(0.32	0.37	0.37	0.42))	((0.60	0.70	0.70	0.80)	((0.65	0.70	0.70	0.75))
C11	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.33	0.43	0.43	0.53)	((0.38	0.43	0.43	0.48))

	C7								C8								C9							
C1	((0.73	0.83	0.83	0.93)	(0.78	0.83	0.83	0.88))	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))
C2	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))
C3	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))	((0.27	0.37	0.37	0.47)	(0.32	0.37	0.37	0.42))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))
C4	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))
C5	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))
C6	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))
C7	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))
C8	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))
C9	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))
C10	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))
C11	((0.80	0.90	0.90	1.00)	(0.85	0.90	0.90	0.95))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))

	C10								C11							
C1	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))
C2	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))
C3	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))
C4	((0.67	0.77	0.77	0.87)	(0.72	0.77	0.77	0.82))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))
C5	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))	((0.40	0.50	0.50	0.60)	(0.45	0.50	0.50	0.55))
C6	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))
C7	((0.47	0.57	0.57	0.67)	(0.52	0.57	0.57	0.62))	((0.80	0.90	0.90	1.00)	(0.85	0.90	0.90	0.95))
C8	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))
C9	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))	((0.33	0.43	0.43	0.53)	(0.38	0.43	0.43	0.48))
C10	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.60	0.70	0.70	0.80)	(0.65	0.70	0.70	0.75))
C11	((0.53	0.63	0.63	0.73)	(0.58	0.63	0.63	0.68))	((0‘00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))

Appendix 4

Normalized initial direct-relation matrix, D

	C1								C2								C3							
C1	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))
C2	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C3	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))
C4	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))
C5	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C6	((0.07	0.08	0.08	0.07)	(0.07	0.08	0.08	0.09))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C7	((0.10	0.11	0.11	0.13)	(0.11	0.11	0.11	0.12))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))
C8	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))
C9	((0.09	0.10	0.10	0.12)	(0.10	0.10	0.10	0.11))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C10	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))
C11	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.07	0.08	0.08	0.07)	(0.07	0.08	0.08	0.09))

	C4								C5								C6							
C1	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C2	((0.10	0.11	0.11	0.13)	(0.11	0.11	0.11	0.12))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C3	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C4	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C5	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))
C6	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))
C7	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))
C8	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.09	0.10	0.10	0.12)	(0.10	0.10	0.10	0.11))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C9	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C10	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.03	0.05	0.05	0.06)	(0.04	0.05	0.05	0.05))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C11	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))

	C7								C8								C9							
C1	((0.09	0.10	0.10	0.12)	(0.10	0.10	0.10	0.11))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))
C2	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C3	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.03	0.05	0.05	0.06)	(0.04	0.05	0.05	0.05))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))
C4	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))
C5	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))
C6	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C7	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C8	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C9	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))
C10	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))
C11	((0.10	0.11	0.11	0.13)	(0.11	0.11	0.11	0.12))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))

	C10								C11							
C1	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))
C2	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))
C3	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))
C4	((0.08	0.10	0.10	0.11)	(0.09	0.10	0.10	0.10))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))
C5	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))	((0.05	0.06	0.06	0.08)	(0.06	0.06	0.06	0.07))
C6	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))
C7	((0.06	0.07	0.07	0.08)	(0.07	0.07	0.07	0.08))	((0.10	0.11	0.11	0.13)	(0.11	0.11	0.11	0.12))
C8	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))
C9	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))	((0.04	0.05	0.05	0.07)	(0.05	0.05	0.05	0.06))
C10	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))	((0.08	0.09	0.09	0.10)	(0.08	0.09	0.09	0.09))
C11	((0.07	0.08	0.08	0.09)	(0.07	0.08	0.08	0.09))	((0.00	0.00	0.00	0.00)	(0.00	0.00	0.00	0.00))

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