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# Sustainable supply chain management using approximate fuzzy DEMATEL method

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ABSTRACT

This study develops the approximate fuzzy Decision Making Trial and Evaluation Laboratory (AFDEMATEL) to analyze uncertain influential factors. The approximate fuzzy arithmetic operations under the weakest *t*-norm ($T_\omega$) arithmetic operations to evaluate sustainable supply chain management based on AFDEMATEL. The fuzzy DEMATEL is one of important decision-making method under uncertain environment. The fuzzy DEMATEL had to be developed for clearly display expert's options with linguistic variables. The fuzzy operations usually adopt α-cut arithmetic in fuzzy DEMATEL. In this research, the fuzzy DEMATEL technology is substituted with the AFDEMATEL technology. In the sustainable supply chain management example, the AFDEMATEL is employed to find fuzzy cause and effect relationships among criteria. Particular note should be made of the following: [1] the fuzzy DEMATEL with α-cut arithmetic model cannot exactly handle fuzzy cause and effect relationships under uncertain environment, and the fuzziness accumulation phenomenon of the α-cut arithmetic may influence final fuzzy cause and effect relationships; and [2] the approximate fuzzy arithmetic operations gives a justifiable fuzziness spread to analyze fuzzy cause and effect relationships. In the case of selection of cans suppliers, the AFDEMATEL examines the influential factors. Proposed method provides justifiable fuzzy cause and effect relationships with approximate fuzzy arithmetic and can analyze across quadrants phenomenon under uncertain environment, since decision-makers usually want to accurately estimate uncertain influential factors.



## 1. Introduction

Since environmental awareness affects almost all parts of society and is a special concern for industry, companies and decision-makers must consider environmental issues in all administrative activities (Marcus and Fremeth, 2009). Sustainable supply chain management has attracted great interest from practitioners and supply chain managers such as the studies of Mirzapour Al-e-hashem et al. (2013), Govindan et al. (2014) and Kannan et al. (2014). Integrating environmental factors into supply chain management, product design, supply network design, and material purchasing has become an essential part of critical thinking (Green et al., 1996; Hervani et al., 2005; Sarkis, 2005; Srivastava, 2007; Ren et al., 2015a, 2015b, 2016). Analyzing factors influencing sustainable supply chain management is always objective, and thus the decision making model for selecting sustainable suppliers is crucial in supply chain management (An et al., 2015). Kuo et al. (2010) proposed the hybrid decision model, which integrates the artificial neural network (ANN) and two multi-attribute decision analysis methods for green supplier selection.

Dobos and Vörösmarty (2014) utilized data envelopment analysis (DEA) with the common weights analysis (CWA) method to determine green suppliers. While the previous literature has looked at the importance of sustainable supplier selection, some vague or ambiguous information exists in sustainable supply chain management. Thus, the fuzzy set theory could be one possible way to evaluate the selection of green suppliers. Some studies used fuzzy decision models to facilitate evaluating the performance of sustainable supply chain management (Tseng, 2011; Tseng and Chiu, 2013; Kannan et al., 2013; Tseng et al., 2014; Wu et al., 2015; Su et al., 2016). These fuzzy decision models have been proven highly effective in aggregating the views of experts and thereby providing information of greater credibility.

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Decision Making Trial and Evaluation Laboratory (DEMATEL) (Gabus and Fontela, 1973; Fontela and Gabus, 1976) has been widely applied in decision-making method with the aim of investigating complex and intertwined problematic group. (Fontela and Gabus, 1976). The DEMATEL method adopts mathematical techniques to obtain analysis of logical relationships and direct impact relations between systematic criteria. This method can enhance understanding of the specific experts' viewpoints of interacted factors, and criteria and provide a feasible solution by applying a visualization structure model (He and Cheng, 2012). The DEMATEL technique is widely used in solving complex problems, such as control systems (Hori and Shimizu, 1999), e-learning evaluation (Tzeng et al., 2007), strategy or policy analysis (Huang et al., 2007; Hsu et al., 2007; Wei et al., 2010), measurement evaluating(Liou et al., 2007, 2008), hospital service quality (Jiunn-I et al., 2010), decision making (Michnik, 2013), sustainable supply chain management (Ren et al., 2013; Liang et al., 2016).

Because of the uncertain or vague environment, DEMATEL method also should be extended to analyze criteria under uncertain environment which considers the fuzzy or linguistic variables in DEMATEL method. Table 1 summarizes some developments of fuzzy DEMATEL. Wu and Lee (2007) combined DEMATEL method with fuzzy logic, and applied in high-tech Company. The results presented the cause group and the effect group of competencies. For the R&D project selection of a Taiwanese company, fuzzy DEMATEL also has adopted to solve group decision-making under uncertain environment (Lin and Wu, 2008). Tseng (2009) developed grey-fuzzy DEMATEL to estimate real estate agent service quality expectation ranking. Chang et al. (2011) analyzed key influence factor using fuzzy DEMATEL method for supplier selection in the electronics industry. Chou et al. (2012) proposed a hybrid model, which combines fuzzy Analytic Hierarchy Process (AHP) with fuzzy DEMATEL method, to evaluate human resources for science and technology (HRST). The results showed that improving infrastructure may be a better long-term choice in HRST. Lin (2013) adopted the fuzzy DEMATEL in green supply chain management (GSCM). The cause and the effect criteria in GSCM were investigated and discussed. Horng et al. (2013) proposed a new model for creativity assessment within the context of the DEMATEL method application. This study uses multiple stages of sample selection and data collection, including qualitative and quantitative surveys. The DEMATEL method was used to conduct a relationship analysis of creativity for future restaurant space design. Yeh and Huang (2014) used the hybrid approach, which combined fuzzy DEMATEL with Analytic Network Process (ANP) approaches, to find correlations among the dimensions and the relative weights of criteria, respectively, in determining wind farm locations. Lin et al. (2014) proposed the weakest $t$-norm ($T_\omega$) fuzzy GERT and applied the method to GSCM. Govindan et al. (2015) proposed intuitionistic fuzzy based DEMATEL method which adopted the intuitionistic fuzzy sets to DEMATEL, and applied to evaluate GSCM. Jeng (2015) used fuzzy DEMATEL to supply chain collaboration. This study adopted Taiwanese manufacturing firms as an example case, and provides discussion and insights for supply chain practitioners.

In the fuzzy DEMATEL mechanism, total relation fuzzy matrix is calculated by using fuzzy arithmetic. The α-cut arithmetic is popularly employed to calculate total relation fuzzy matrix in past researches. However, Chang et al. (2006) mentioned that α-cut arithmetic was fuzzier because of the fuzziness accumulation phenomenon. Lin et al. (2011) and Garg (2014) also employed the weakest t-norm based method to decrease the phenomenon of fuzziness accumulation. Therefore, fuzzy DEMATEL with α-cut arithmetic can not effectively analyze fuzzy interval of result.

This study proposes the AFDEMATEL which adopts approximate fuzzy arithmetic operations under the weakest $t$-norm ($T_\omega$) arithmetic operations. The purpose is to improve on the traditional fuzzy DEMATEL, and extends $T_\omega$ fuzzy DEMATEL method (Lin et al., 2014) to overcome the accumulating phenomenon of fuzziness or credibly reduce fuzzy spreads. The proposed model will help to accurately evaluate cause and effect relationships while the fuzzy intervals may across quadrants. Furthermore, selection of cans suppliers (Dalalah et al., 2011) was examined and compared it with the traditional fuzzy DEMATEL (Lin and Wu, 2004). The rest of this paper is organized as follows. Section 2 introduces the α-cut and the approximate fuzzy arithmetic operations. In Section 3, the traditional fuzzy DEMATEL is describes. In Section 4, proposed approximate fuzzy Decision Making Trial and Evaluation Laboratory (AFDEMATEL) are described. Section 5 presents a sustainable SCM example to examine the AFDEMATEL model. Section 6 provided concluding remarks.

## 2. The basic of fuzzy arithmetic

The fuzzy arithmetic is one of main technique in fuzzy DEMATEL technology. In this section, some basic definitions of fuzzy arithmetic are presented.

**Definition 1.** Let $\tilde{M}$ be a fuzzy number (FN) on $\Re$. A triangular fuzzy number $\tilde{M}$ can be defined as a triplet $(m_1, m_2, m_3)$. The *membership function* $\tilde{M}(x)$ that defines the membership grades of elements $x \in \Re$ to $\tilde{M}$:

$$\tilde{M}(x) = \begin{cases} 0, & x < m_1, \\ (m - a_1)/(m_2 - m_1), & m_1 \le x \le m_2, \\ (m_3 - x)/(m_3 - m_2), & m_2 \le x \le m_3, \\ 0, & x > m_3, \end{cases}$$

where $m_2$ is the *center* and $m_1$ and $m_3$ denote the *left and right bounds* of $\tilde{M}$ respectively, with

**Definition 2.** A TFN is characterized by its membership function $\tilde{P}$ or, alternatively, by its α-cuts $A_\alpha$ which can be defined as following:

$$P_\alpha = \left\{ x | \tilde{P}(x) \ge \alpha \right\}, \tag{1}$$

or given for a TFN

$$P_\alpha = [p_1^{(\alpha)}, p_2^{(\alpha)}] = [p_1 + \alpha(p_2 - p_1), p_3 - \alpha(p_3 - p_2)], \tag{2}$$

where $p_1^{(\alpha)}$ and $p_2^{(\alpha)}$ respectively denote the *left* and *right bounds* of $P_\alpha$.

According to the characteristics of TFN and the Zadeh's sup-min operator (Zadeh, 1965) can be stated as

$$(\tilde{P} \circ \tilde{Q})(z) = \sup_{x \circ y = z} \min(\tilde{P}(x), \tilde{Q}(y)), \tag{3}$$

where ∘ denotes any arithmetic operation.

The α-cuts of fuzzy numbers, $\tilde{P} = (a_1, a_2, a_3)$ and $\tilde{Q} = (b_1, b_2, b_3)$ $\forall \tilde{P}, \tilde{Q} \in \Re$, are as follows:

(1) Addition of two fuzzy numbers:

$$\tilde{P} + \tilde{Q} = (p_1 + q_1, p_2 + q_2, p_3 + q_3) \tag{4}$$

(2) Subtraction of two fuzzy numbers:

$$\tilde{P} - \tilde{Q} = (p_1 - q_3, p_2 - q_2, p_3 - q_1) \tag{5}$$

(3) Multiplication of two fuzzy numbers:

$$\tilde{P} \times \tilde{Q} \cong (p_1 \times q_1, p_2 \times q_2, p_3 \times q_3) \tag{6}$$

(4) Division of two fuzzy numbers:

$$\tilde{P} / \tilde{Q} \cong (p_1/q_3, p_2/q_2, p_3/q_1) \tag{7}$$

**Table 1**
Some developments of fuzzy DEMATEL.

| Author(s) | year | methods | Applied fields |
|---|---|---|---|
| Wu & Lee | 2007 | Fuzzy DEMATEL | Global managers' competencies |
| Lin & Wu | 2008 | Fuzzy DEMATEL | R&D project |
| Tseng | 2009 | Grey-fuzzy DEMATEL | Customer expectation |
| Chang et al. | 2011 | Fuzzy DEMATEL | Supplier selection |
| Chou et al. | 2012 | Fuzzy AHP+ fuzzy DEMATEL | HRST |
| Lin et al. | 2013 | Fuzzy DEMATEL | Green supply chain management |
| Horng et al. | 2013 | Fuzzy Delphi + DEMATEL | Restaurant space design |
| Yeh & Huang | 2014 | Fuzzy DEMATEL + ANP | Wind farm location |
| Lin et al. | 2014 | $T_\omega$ Fuzzy DEMATEL | Green supply chain management |
| Govindan et al. | 2015 | Intuitionistic fuzzy DEMATEL | Green supply chain management |
| Jeng | 2015 | Fuzzy DEMATEL | Supply chain management |

In Zadeh's extension principle (Zadeh, 1965), the original 'min' is replaced by $t$-norm on the interval [0,1]. Then the basic concepts and definition of the weakest $t$-norm arithmetic operations is as follows:

$$(\tilde{P} \circ \tilde{Q})(z) = \sup_{x \circ y = z} T(\tilde{P}(x), \tilde{Q}(y)), \tag{8}$$

**Definition 3.** Each $t$-norm may be shown to satisfy the following inequalities:

$$T_\omega(p_2, q_2) \le T(p_2, q_2) \le T_M(p_2, q_2) = \min(p_2, q_2),$$

where

$$T_\omega(p_2, q_2) = \begin{cases} p_2, & \text{if } q_2 = 1, \\ p_2, & \text{if } q_2 = 1, \\ 0, & \text{otherwise}, \end{cases}$$

$T_\omega$ is the weakest $t$-norm. The operations of $T_\omega$ fuzzy arithmetic can be seen in the research of Chang et al. (2006), Hong (2001a, 2001b), Hong (2006), Kolesárová (1995) and Mesiar (1997). Lin et al. (2011) proposed approximate fuzzy arithmetic operations under the weakest $t$-norm ($T_\omega$) arithmetic operations. The approximate fuzzy arithmetic extended the $T_\omega$ fuzzy arithmetic, and obtained the advantages of approximate fuzzy arithmetic. The approximate fuzzy arithmetic can obtain fitter decision values, which have smaller fuzziness accumulating, under vague environment. The approximate fuzzy arithmetic operations under the weakest $t$-norm ($T_\omega$) arithmetic operations are as follows:

(1) Addition:

$$\tilde{P}(+_{T_\omega})^\alpha \tilde{Q} = [p_1{}^{(\alpha=1)} + q_1^{(\alpha=1)} - \max((p_1{}^{(\alpha=1)} - a_1{}^{(\alpha)}), (q_1^{(\alpha=1)} - q_1^{(\alpha)})), \; p_2{}^{(\alpha=1)} + p_2^{(\alpha=1)} + \max((p_2{}^{(\alpha)} - p_2{}^{(\alpha=1)}), (q_2^{(\alpha)} - q_2^{(\alpha=1)}))] \tag{9}$$

(2) Subtraction

$$\tilde{P}(-_{T_\omega})^\alpha \tilde{Q} = [p_1{}^{(\alpha=1)} - q_1^{(\alpha=1)} - \max((p_1{}^{(\alpha=1)} - p_1{}^{(\alpha)}), (q_2^{(\alpha)} - q_2^{(\alpha=1)})), \; p_2{}^{(\alpha=1)} - p_2^{(\alpha=1)} + \max((q_1^{(\alpha=1)} - q_1^{(\alpha)}), (p_2{}^{(\alpha)} - p_2{}^{(\alpha=1)}))] \tag{10}$$

(3) Multiplication

$$\tilde{P}(\times_{T_\omega})^\alpha \tilde{Q} = [p_2 q_2 - \max((p_1^{(\alpha=1)} - p_1^{(\alpha)})q_2, (q_1^{(\alpha=1)} - q_1^{(\alpha)})p_2)), \; p_2 q_2 + \max((p_2^{(\alpha)} - p_2^{(\alpha=1)})q_2, (q_2^{(\alpha)} - q_2^{(\alpha=1)})p_2))] \tag{11}$$

(4) Division

$$\tilde{P}(\div_{T_\omega})^\alpha \tilde{Q} = [(p_2/q_2 - \max((p_1^{(\alpha=1)} - p_1^{(\alpha)})/q_2, p_2(1/q_2^{(\alpha=1)} - 1/q_2^{(\alpha)})), \; p_2/q_2 + \max((p_2^{(\alpha)} - p_2^{(\alpha=1)})/q_2, p_2(1/q_1^{(\alpha)} - 1/q_1^{(\alpha=1)}))] \tag{12}$$

## 3. Traditional fuzzy DEMATEL method

In decision-making systems, people usually make judgments according to their experience and expertise. This is human centric activity processed in uncertain environments. Traditional or crisp DEMATEL may not be effective or suitable for solving group or multi-criteria decision-making in uncertain environments. Therefore, it is necessary to build an extended DEMATEL method by applying fuzzy theory. To deal with human assessments, the preferences of decision-makers are employed to fuzzy numbers by adopting fuzzy linguistic scale. In this section, the fuzzy DEMATEL (Lin and Wu, 2004) will be briefly introduced.

**Step 1**: Design the fuzzy linguistic scale and average the assessment. To deal with the ambiguities of human assessments, the linguistic variable should be determined. Moreover, in order to form expert committees for group knowledge required to achieve the goals. It must acquire and average the assessment of experts' preferences using Lin and Wu (2004).

**Step 2**: Initial direct-relation fuzzy matrix. The fuzzy DEMATEL turn fuzzy matrix $\tilde{Z}$ into normalized initial direct-relation matrix which is called fuzzy matrix $\tilde{X}$ is produced as follows:

$$\tilde{Z} = \begin{bmatrix} 0 & \tilde{z_{12}} & \cdots & \tilde{z_{1n}} \\ \tilde{z_{21}} & 0 & \cdots & \tilde{z_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z_{n1}} & \tilde{z_{n2}} & \cdots & 0 \end{bmatrix} \tag{13}$$

In the matrix, $\tilde{z_{ij}} = (\underline{z}_{ij}, z_{ij}, \bar{z}_{ij}) \forall i = 1, \ldots, n. j = 1, \ldots, n.$ and $\tilde{z_{ij}} = (0, 0, 0) \forall i = j$.

By normalizing the initial direct-relation fuzzy matrix, the normalizing direct-relation fuzzy matrix $\tilde{X}$can be obtained as follows:

$$\tilde{X}^{\alpha=0} = \begin{bmatrix} \tilde{x_{11}} & \tilde{x_{nn}} & \cdots & \tilde{x_{1n}} \\ \tilde{x_{21}} & \tilde{x_{22}} & \cdots & \tilde{x_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x_{n1}} & \tilde{x_{n2}} & \cdots & \tilde{x_{nn}} \end{bmatrix}^{\alpha=0} \tag{14}$$

where

$$\tilde{x_{ij}} = \frac{\tilde{z_{ij}}}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} \tilde{z_{ij}}} = \left( \frac{\underline{z}_{ij}}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} \tilde{z_{ij}}}, \frac{z_{ij}}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} \tilde{z_{ij}}}, \frac{\bar{z}_{ij}}{\max\limits_{1 \le i \le n} \sum_{j=1}^{n} \tilde{z_{ij}}} \right) \tag{15}$$

**Step 3**: Attain the fuzzy total-influence matrix. The fuzzy total-influence matrix $\tilde{T}$ can be computed (Lin and Wu, 2004):

$$\tilde{T}^{\alpha=0} = \lim_{k \to \infty} (\tilde{X_1} + \tilde{X_2} + \cdots + \tilde{X_k}) = [X \times (I - X)]^{\alpha=0} \tag{16}$$

**Step 4**: Defuzzify into the crisp values. The sum of rows and the sum of columns are respectively denoted as vectors $\tilde{D}$ and $\tilde{R}$ within the total relation fuzzy matrix.

$$\tilde{D} = \left[\sum_{i=1}^{n} \tilde{t_{ij}}\right]_{1\times n}^{\alpha=0} \quad (17)$$

$$\tilde{R} = \left[\sum_{j=1}^{n} \tilde{t_{ij}}\right]_{1\times n}^{\alpha=0} \quad (18)$$

Using traditional α-cut arithmetic the $\tilde{D}_i + \tilde{R}_i$ and $\tilde{D}_i - \tilde{R}_i$ are calculated. Then $\tilde{D}_i + \tilde{R}_i$ and $\tilde{D}_i - \tilde{R}_i$are defuzzified into crisp values and map into the total influence matrix. $(\tilde{D}_i + \tilde{R}_i)^{def}$ provides an index of the strength of the influences dispatched and received is positive, then the criterion affects others. If $(\tilde{D}_i - \tilde{R}_i)^{def}$ is positive that the criterion affects others, and $(\tilde{D}_i - \tilde{R}_i)^{def}$ is negative that criterion is influenced by others.

**Step 5**: Establish and analyze the structural model. The causal relation map can be drawn.

## 4. Approximate fuzzy DEMATEL

This study extends $T_\omega$ fuzzy DEMATEL (Lin et al., 2014) to AFDEMATEL for sustainable supply chain management. Because the approximate fuzzy arithmetic operations under the weakest $t$-norm $(T_\omega)$ can effectively reduce the fuzziness accumulation phenomenon (Lin et al., 2011), this study adopts the approximate fuzzy arithmetic operations to substitute traditional α-cut arithmetic. The AFDEMATEL can be as an alternative for decision making. The procedures of the AFDEMATEL are shown in Fig. 1.

**Step 1**: Design the fuzzy linguistic scale and average the assessment. The step is the same as in traditional fuzzy DEMATEL.

**Step 2**: Initial $(T_\omega)^\alpha$ direct-relation fuzzy matrix. In this step, the approximate fuzzy arithmetic operations normalizing direct-relation fuzzy matrix $\tilde{X}^{(T_\omega)^\alpha}$ can be computed through Eqs. (9)–(12).

$$\tilde{X}^{(T_w)^a} = \begin{bmatrix} \tilde{X_{11}} & \tilde{X_{12}} & \dots & \tilde{X_{1n}} \\ \tilde{X_{21}} & \tilde{X_{22}} & \dots & \tilde{X_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{X_{n1}} & \tilde{X_{n2}} & \dots & \tilde{X_{nn}} \end{bmatrix}^{(T_w)^a} \quad (19)$$

$$(\tilde{x_{ij}})^{(T_\omega)^\alpha} = (\underline{x}_{ij}, x_{ij}, \bar{x}_{ij})^{(T_\omega)^\alpha} \quad (20)$$

where

$$(\underline{x}_{ij})^{(T_\omega)^\alpha} = \frac{z_{ij}}{\max\limits_{1\le i\le n}\sum_{j=1}^{n}\tilde{z_{ij}}} - \frac{z_{ij}-\underline{z}_{ij}}{\max\limits_{1\le i\le n}\sum_{j=1}^{n}\tilde{z_{ij}}},\ (x_{ij})^{(T_\omega)^\alpha} = \frac{z_{ij}}{\max\limits_{1\le i\le n}\sum_{j=1}^{n}\tilde{z_{ij}}},\ (\bar{x}_{ij})^{(T_\omega)^\alpha} = \frac{z_{ij}}{\max\limits_{1\le i\le n}\sum_{j=1}^{n}\tilde{z_{ij}}} + \frac{\bar{z}_{ij}-z_{ij}}{\max\limits_{1\le i\le n}\sum_{j=1}^{n}\tilde{z_{ij}}}.$$

**Step 3**: Attain the $(T_\omega)^\alpha$ fuzzy total-influence matrix. The total $(T_\omega)^\alpha$ relation fuzzy matrix can be defined and computed using $(T_\omega)^\alpha$ operations as follows:

$$\tilde{T}^{(T_\omega)^\alpha} = \lim_{k\to\infty}(\tilde{X}_1(+_{T_\omega})^\alpha\tilde{X}_2(+_{T_\omega})^\alpha\cdots(+_{T_\omega})^\alpha\tilde{X}_k) = \left[X(\times_{T_\omega})^\alpha(I(-_{T_\omega})^\alpha X)\right] \quad (21)$$

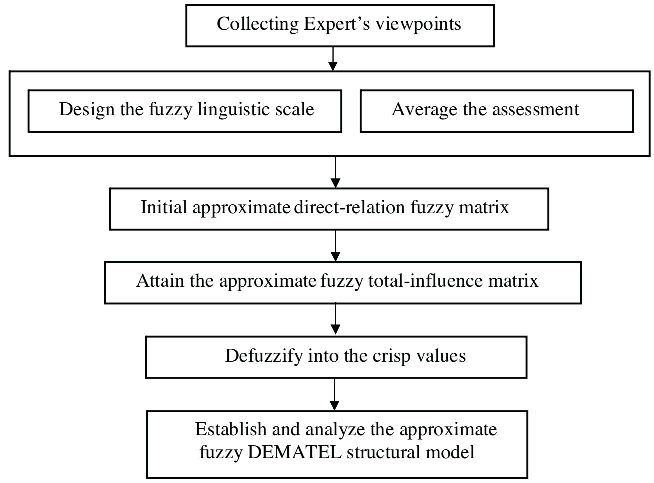


**Fig. 1.** Procedures of AFDEMATEL.

**Step 4**: Defuzzify into the crisp values. The sum of rows and the sum of columns are respectively denoted as vectors $\tilde{D}$ and $\tilde{R}$ within the total $(T_\omega)^\alpha$ relation fuzzy matrix.

$$\tilde{D} = \tilde{t_{1j}}(+_{T_\omega})^\alpha\tilde{t_{2j}}(+_{T_\omega})^\alpha\cdots(+_{T_\omega})^\alpha\tilde{t_{nj}} = \left[\sum_{i=1}^{n}\tilde{t_{ij}}\right]_{1\times n}^{(T_\omega)^\alpha} \quad (22)$$

$$\tilde{R} = \tilde{t_{i1}}(+_{T_\omega})^\alpha\tilde{t_{i2}}(+_{T_\omega})^\alpha\cdots(+_{T_\omega})^\alpha\tilde{t_{in}} = \left[\sum_{j=1}^{n}\tilde{t_{ij}}\right]_{1\times n}^{(T_\omega)^\alpha} \quad (23)$$

Using $T_\omega$ operations the $\tilde{D}_i(+_{T_\omega})^\alpha\tilde{R}_i$ and $\tilde{D}_i(-_{T_\omega})^\alpha\tilde{R}_i$ are calculated. Then $\tilde{D}_i(+_{T_\omega})^\alpha\tilde{R}_i$ and $\tilde{D}_i(-_{T_\omega})^\alpha\tilde{R}_i$are defuzzified into crisp values and map into the total influence matrix.

**Step 5**: Establish and analyze the AFDEMATEL structural model. The AFDEMATEL causal relation map can be drawn. The AFDEMATEL can obtain more objective $\tilde{D}_i(+_{T_\omega})^\alpha\tilde{R}_i$ and $\tilde{D}_i(-_{T_\omega})^\alpha\tilde{R}_i$. This is because that AFDEMATEL can analyze fuzzy interval crosses different quadrants. The fuzzy DEMATEL with α-cut arithmetic could not achieve this due to the fuzziness accumulation phenomenon.

## 5. Numerical example

This study applies the AFDEMATEL for sustainable supply chain management. The selection of cans suppliers are examined in this study.

### 5.1. The case: the selection of cans suppliers

This proposed AFDEMATEL will apply on an industry case study for the selection of cans suppliers at Nutridar Factory in Amman-Jordan (Dalalah et al., 2011) to demonstrate the proposed model. Table 2 shows the criteria of cans suppliers, which include seventeen influence factors. By adopting a fuzzy triangular number, a fuzzy DEMATEL exertion will be put in place by expressing different degrees of influence or causality in crisp DEMATEL, with five

**Table 2**
The list of critical criteria of cans suppliers (Dalalah et al., 2011).

| Critical criteria | |
|---|---|
| $C_1$: Unit price and payment terms | $C_{10}$: Compensation for waste |
| $C_2$: Delivery terms | $C_{11}$: Printing complies to design and color |
| $C_3$: Supplier factory capacity | $C_{12}$: Easy open and spoon leveling |
| $C_4$: Shipping method | $C_{13}$: Testing methods for packaging materials and available tests from supplier |
| $C_5$: Lead time | $C_{14}$: Variation of dimensions |
| $C_6$: Location of can supplier | $C_{15}$: Stretch wrapping and clean separators, pallet size and height |
| $C_7$: Technical specifications | $C_{16}$: Major customers with the same business |
| $C_8$: Certifications | $C_{17}$: Certificate of supplier materials |
| $C_9$: Services and communications with the supplier | |

**Table 3**
Corresponding relation between linguistic variable and fuzzy number in example 2 (Dalalah et al., 2011).

| Linguistic variable | Corresponding TFNs |
|---|---|
| No Influence (NO) | (0, 0, 0.25) |
| Very Low Influence (VL) | (0, 0.25, 0.25) |
| Low Influence (L) | (0.25, 0.5, 0.75) |
| High Influence (H) | (0.5, 0.75, 1.0) |
| Very High Influence (VH) | (0.75, 1.0, 1.0) |

linguistic terms as {NO, VL, L, H, VH} and their corresponding positive triangular fuzzy numbers. These linguistic terms are shown in Table 3. This example was experimented to help identify the best supplier among a set of suppliers. This group includes the production manager, the quality manager, the material manager, the maintenance manager, the research and development manager and the planning manager which has six working experts. The initial-direct fuzzy matrix from the assessment data of experts is depicted in Table 4.

In order to access the casual relationships between strategic objectives, this study examines$\tilde{D}_i + \tilde{R}_i$,$\tilde{D}_i - \tilde{R}_i$, $(\tilde{D}_i + \tilde{R}_i)^{def}$, and $(\tilde{D}_i - \tilde{R}_i)^{def}$ with two fuzzy operations (α-cut and $(T_\omega)^\alpha$). $\tilde{D}_i$ is re the sum of rows total-relation fuzzy matrix and $\tilde{R}_i$ is sum of columns of the total-relation fuzzy matrix. In this study, the defuzzification procedure uses COG (center of gravity) defuzzification method. The results are shown in Table 5. This yields two sets of numbers: $(\tilde{D}_i + \tilde{R}_i)^{def}$, which shows the importance of all strategic objectives by aggregating all expert preferences, and $(\tilde{D}_i - \tilde{R}_i)^{def}$, which assigns strategic objectives into cause and effect groups. Moreover, the fuzzy spreads of $\tilde{D}_i + \tilde{R}_i$ and $\tilde{D}_i - \tilde{R}_i$ are shown in Table 5. In Table 5, the phenomena can be observed that AFDEMATEL method can obtain smaller fuzzy spreads which means the AFDEMATEL can credibly reduce fuzzy spreads.

Fig. 2 shows the cause and effect diagram with different fuzzy arithmetic. Quadrant I contains the core factors ($C_1$, $C_7$, $C_8$, $C_{16}$) should be considered. These criteria are the important in selection of cans suppliers. Quadrant II contains driving criteria ($C_3$, $C_4$, $C_6$, $C_{12}$, $C_{14}$) only affects a few other criteria. Quadrant III contains independent criteria ($C_5$, $C_9$, $C_{11}$, $C_{13}$, $C_{15}$) can be individually handled because they may not affect other criteria. Quadrant IV contains affected criteria ($C_2$, $C_{10}$, $C_{17}$) should be indirectly considered. Furthermore, from observing Fig. 2(b)–(d) also shows AFDEMATEL method with different α values can obtain the reasonable fuzzy bound. The fuzzy bounds of criteria ($C_1$, $C_2$, $C_4$, $C_5$, $C_{11}$, $C_{12}$, $C_{14}$, $C_{15}$, $C_{16}$, $C_{17}$) cross different quadrants, which should give a more credible analysis. In AFDEMATEL method, the cross different quadrants phenomenon also may be changed with different α values. This phenomenon can not be observed in fuzzy DEMATEL method or $T_\omega$ fuzzy DEMATEL.

Fig. 3 AFDEMATEL shows a causal relation map with the AFDEMATEL method, and displays results of defuzzified and fuzzy bounds values. Again, AFDEMATEL may change the decision-making process in that more accurate evaluations are possible in uncertain environments.

### 5.2. Theoretical and managerial implications

An effective decision model for supplier selection is essential in sustainable supply chain management. Theoretically, the fuzzy set theory can be employed to design an AFDEMATEL model for supplier selection in sustainable supply chain management systems. The AFDEMATEL model utilizes fuzzy bounds with various α values to prioritize decisions. The method proposed in this study is better than the conventional fuzzy DEMATEL. In real-world practice, the AFDEMATEL model employs fuzzy numbers or linguistic variables to deal with complicated trade-offs in sustainable supply chain management systems.

**Table 4**
The assessment data fuzzy matrix of a general manager (Dalalah et al., 2011).

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ | $C_{16}$ | $C_{17}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_1$ | – | VH | L | H | H | NO | VH | L | H | H | H | VH | L | L | H | H | H |
| $C_2$ | H | – | H | H | H | NO | NO | L | L | H | NO | L | NO | NO | NO | NO | NO |
| $C_3$ | H | VH | – | L | VH | L | NO | NO | H | H | NO | NO | NO | NO | NO | H | NO |
| $C_4$ | VH | H | NO | – | NO | NO | NO | L | L | H | NO | NO | NO | NO | H | H | NO |
| $C_5$ | H | H | L | NO | – | NO | L | NO | L | NO | NO | L | NO | NO | L | VH | NO |
| $C_6$ | H | H | NO | H | H | – | NO | L | L | H | NO | L | NO | NO | NO | VH | L |
| $C_7$ | VH | NO | NO | NO | H | NO | – | H | NO | VH | H | NO | L | H | H | H | L |
| $C_8$ | L | L | L | H | NO | NO | H | – | H | H | H | NO | H | VH | NO | H | H |
| $C_9$ | NO | NO | NO | NO | L | NO | NO | L | – | NO | NO | NO | NO | NO | NO | H | NO |
| $C_{10}$ | H | H | NO | VH | NO | NO | H | NO | L | – | H | L | H | H | H | H | H |
| $C_{11}$ | H | L | NO | NO | L | NO | NO | NO | NO | H | – | NO | L | NO | NO | H | VH |
| $C_{12}$ | VH | H | NO | NO | H | NO | NO | NO | NO | H | NO | – | NO | NO | NO | L | H |
| $C_{13}$ | NO | NO | NO | NO | NO | NO | H | NO | H | NO | NO | NO | – | H | NO | H | H |
| $C_{14}$ | H | L | NO | NO | NO | NO | VH | H | VH | VH | H | NO | L | – | NO | H | NO |
| $C_{15}$ | H | NO | NO | H | L | NO | NO | NO | L | VH | NO | NO | NO | NO | – | H | L |
| $C_{16}$ | H | H | H | NO | H | H | H | VH | H | H | H | L | H | VH | H | – | H |
| $C_{17}$ | L | NO | NO | NO | L | NO | H | H | H | H | H | L | NO | NO | L | H | – |

−: means triangular fuzzy number [0, 0, 0].

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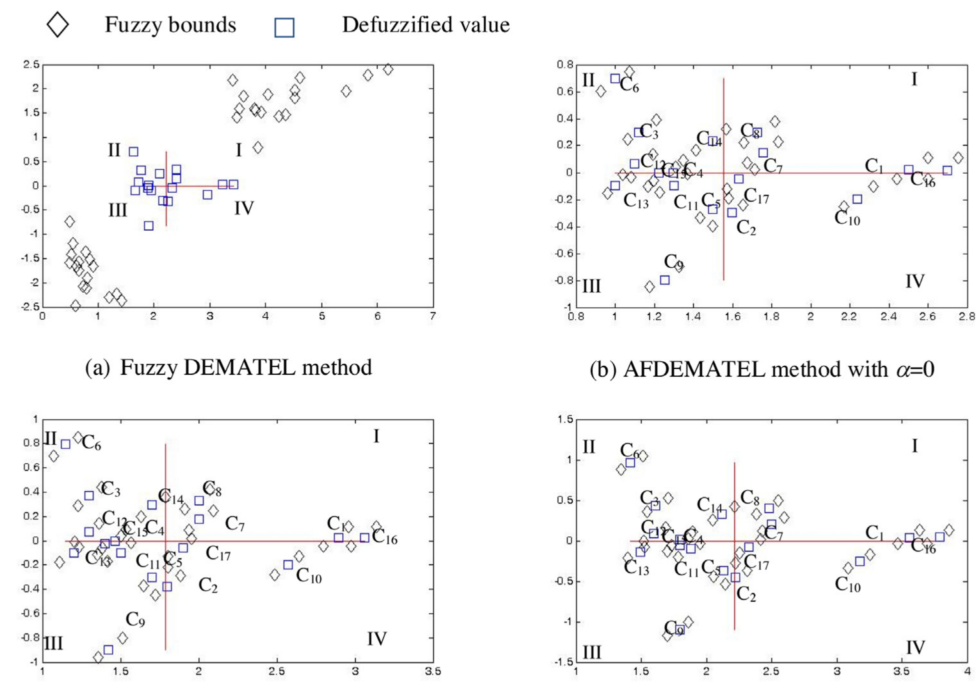
**Table 5**
The values of $\tilde{D}_i+\tilde{R}_i$, $\tilde{D}_i-\tilde{R}_i$, $(\tilde{D}_i+\tilde{R}_i)^{def}$, and $(\tilde{D}_i-\tilde{R}_i)^{def}$ with different fuzzy DEMATEL methods.

| | Fuzzy DEMATEL method | | | | | AFDEMATEL method with α=0 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\tilde{D}_i+\tilde{R}_i$ | $\tilde{D}_i-\tilde{R}_i$ | Fuzzy spread | $(\tilde{D}_i+\tilde{R}_i)^{def}$ | $(\tilde{D}_i-\tilde{R}_i)^{def}$ | $\tilde{D}_i(+_{T_\omega})^\alpha\tilde{R}_i$ | $\tilde{D}_i(-_{T_\omega})^\alpha\tilde{R}_i$ | Fuzzy spread | $(\tilde{D}_i(+_{T_\omega})^\alpha\tilde{R}_i)^{def}$ | $(\tilde{D}_i(-_{T_\omega})^\alpha\tilde{R}_i)^{def}$ |
| $C_1$ | (1.33, 2.52, 5.83) | (−2.23, 0.03, 2.28) | 4.50 | 3.22 | 0.02 | (2.44, 2.52, 2.60) | (−0.04, 0.03, 0.11) | 0.16 | 2.50 | 0.02 |
| $C_2$ | (0.80. 1.57, 4.36) | (−2.10, −0.32, 1.46) | 3.56 | 2.24 | −0.32 | (1.50, 1.57, 1.65) | (−0.40, −0.32, −0.24) | 0.16 | 1.60 | −0.30 |
| $C_3$ | (0.56, 1.14, 3.60) | (−1.19, 0.32, 1.86) | 3.04 | 1.76 | 0.32 | (1.06, 1.14, 1.21) | (0.25, 0.32, 0.39) | 0.15 | 1.12 | 0.30 |
| $C_4$ | (0.65, 1.27, 3.81) | (−1.57, 0.01, 1.58) | 3.15 | 1.90 | 0.00 | (1.20, 1.27, 1.35) | (−0.06, 0.01, 0.09) | 0.15 | 1.30 | 0.00 |
| $C_5$ | (0.73, 1.51, 4.24) | (−2.07, −0.26, 1.44) | 3.50 | 2.15 | −0.29 | (1.43, 1.51, 1.58) | (−0.33, −0.26, −0.19) | 0.15 | 1.50 | −0.27 |
| $C_6$ | (0.49, 1.00, 3.40) | (−0.74, 0.67, 2.18) | 2.91 | 1.62 | 0.70 | (0.93, 1.00, 1.07) | (0.60, 0.67, 0.75) | 0.15 | 1.00 | 0.70 |
| $C_7$ | (0.91, 1.75, 4.53) | (−1.65, 0.15, 1.97) | 3.61 | 2.39 | 0.15 | (1.68, 1.75, 1.83) | (0.07, 0.15, 0.23) | 0.16 | 1.76 | 0.14 |
| $C_8$ | (0.86, 1.73, 4.62) | (−1.53, 0.30, 2.24) | 3.76 | 2.40 | 0.33 | (1.66, 1.73, 1.82) | (0.22, 0.30, 0.38) | 0.16 | 1.73 | 0.30 |
| $C_9$ | (0.59, 1.25, 3.85) | (−2.47, −0.77, 0.79) | 3.26 | 1.90 | −0.82 | (1.18, 1.25, 1.33) | (−0.85, −0.77, −0.70) | 0.15 | 1.25 | −0.80 |
| $C_{10}$ | (1.20, 2.24, 5.44) | (−2.29, −0.18, 1.95) | 4.24 | 2.96 | −0.17 | (2.17, 2.24, 2.32) | (−0.26, −0.18, −0.10) | 0.15 | 2.24 | −0.20 |
| $C_{11}$ | (0.65, 1.30, 3.92) | (−1.75, −0.08, 1.52) | 3.27 | 1.95 | −0.10 | (1.23, 1.30, 1.37) | (−0.15, −0.08, −0.01) | 0.14 | 1.30 | −0.10 |
| $C_{12}$ | (0.53, 1.11, 3.53) | (−1.42, 0.05, 1.58) | 3.00 | 1.72 | 0.07 | (1.04, 1.11, 1.19) | (−0.02, 0.05, 0.14) | 0.15 | 1.10 | 0.06 |
| $C_{13}$ | (0.49, 1.02, 3.48) | (−1.59, −0.10, 1.41) | 2.99 | 1.66 | −0.09 | (0.96, 1.02, 1.08) | (−0.15, −0.10, −0.03) | 0.12 | 1.00 | −0.10 |
| $C_{14}$ | (0.78, 1.49, 4.04) | (−1.37, 0.24, 1.89) | 3.25 | 2.10 | 0.25 | (1.41, 1.49, 1.57) | (0.17, 0.24, 0.32) | 0.15 | 1.50 | 0.24 |
| $C_{15}$ | (0.60, 1.24, 3.81) | (−1.66, −0.03, 1.55) | 3.20 | 1.88 | −0.04 | (1.17, 1.24, 1.31) | (−0.10, −0.03, 0.04) | 0.14 | 1.22 | 0.00 |
| $C_{16}$ | (1.42, 2.67, 6.19) | (−2.37, 0.03, 2.40) | 4.76 | 3.42 | 0.02 | (2.60, 2.67, 2.75) | (0.05, 0.03, 0.11) | 0.16 | 2.70 | 0.01 |
| $C_{17}$ | (0.81, 1.64, 4.53) | (−1.90, −0.05, 1.82) | 3.72 | 2.32 | −0.04 | (1.57, 1.64, 1.71) | (−0.12, −0.05, 0.02) | 0.14 | 1.63 | −0.05 |




(a) Fuzzy DEMATEL method

(b) AFDEMATEL method with $\alpha$=0

(c) AFDEMATEL method with $\alpha$=0.3

(d) AFDEMATEL method with $\alpha$=0.7

**Fig. 2.** Comparison of cause and effect diagram in the selection of cans supplier.

The AFDEMATEL model utilizes defuzzified values, unit price and payment terms ($C_1$), technical specifications ($C_7$), certifications ($C_8$), and major customers with the same business ($C_{16}$) as those factors measured by firms. Certifications are also included by the International Organization for Standardization (ISO) 14000 Environmental management. In the fuzzy right bound, the variation of dimensions ($C_{14}$) and certificate of supplier materials ($C_{17}$) should be considered. In the example herein, the certificate of supplier materials should satisfy the ISO 14000 when the decision-maker adopts the results of the fuzzy right bound. In the fuzzy left bound, only certifications ($C_8$) and technical specifications ($C_7$) are considered. In an uncertain environment, the important criteria of cans suppliers are $C_8$ and $C_7$, which are related to environmental issues. In sustainable supply chain management, the proposed AFDEMATEL model offers guidelines for management to allocate resources. In addition, the AFDEMATEL model can divide the criteria of cans suppliers into four quadrants with fuzzy bounds and α values.

This study improves the traditional fuzzy DEMATEL method and extends the $T_\omega$ fuzzy DEMATEL method (Lin et al., 2014) by decreasing the phenomenon of fuzziness accumulation. The AFDEMATEL model is able to accurately evaluate the cause and effect relationships when the fuzzy intervals are across quadrants with different α values for decision makers. In the example of cans suppliers selection, the AFDEMATEL model suggests that decision makers in

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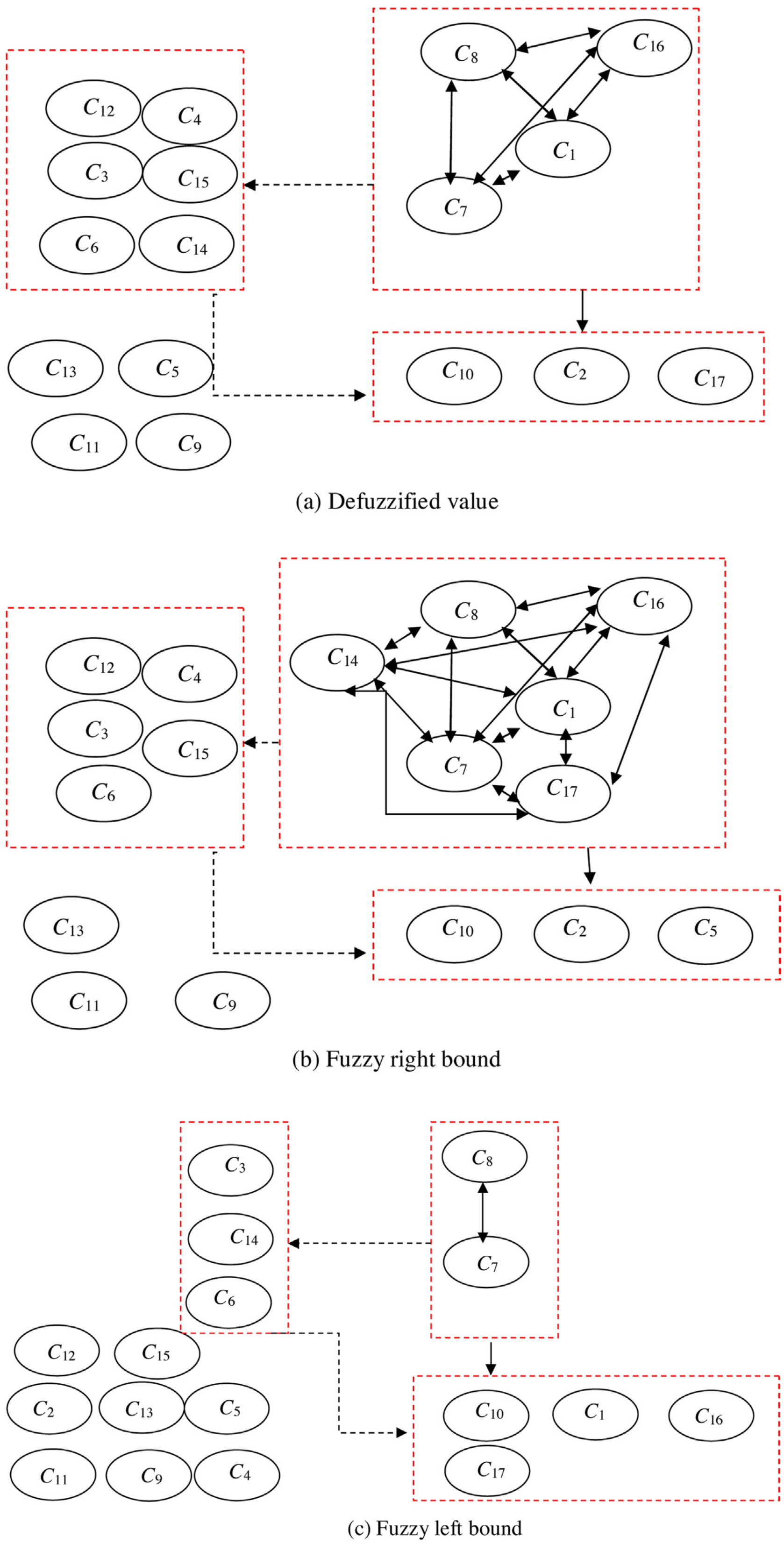


**Fig. 3.** The causal relation map with AFDEMATEL with $\alpha$=0 method.

supply chain networks can target the ISO 14000 and the technical specifications.

## 6. Conclusions

Fuzzy DEMATEL is one of important method in evaluating cause and effect relationships. Thus, this paper extended Lin et al. (2014) $T_\omega$ fuzzy GERT method to AFDEMATEL which improve on fuzzy DEMATEL. The proposed AFDEMATEL was successfully applied to sustainable supply chain management, with useful and more credible results obtained.

In numerical example, the fuzzy DEMATEL model cannot really handle fuzzy cause and effect relationships while the fuzzy interval crosses different quadrants. The proposed AFDEMATEL shows provided more credible results to the amount of fuzziness. Moreover, AFDEMATEL can observe the change of cross different quadrants phenomenon with different $\alpha$ values. This is better than $T_\omega$ fuzzy GERT method (Lin et al., 2014). Further research may investigate a number of remaining issues, which may extend the realizable application of AFDEMATEL. AFDEMATEL can also integrate other evaluation methods or implement to purchase system.

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