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Research Article

An Intelligent Complex Event Processing with D Numbers under Fuzzy Environment

Fuyuan Xiao

School of Computer and Information Science, Southwest University, Chongqing 400715, China

Correspondence should be addressed to Fuyuan Xiao; xiaofuyuan@swu.edu.cn

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Efficient matching of incoming mass events to persistent queries is fundamental to complex event processing systems. Event matching based on pattern rule is an important feature of complex event processing engine. However, the intrinsic uncertainty in pattern rules which are predecided by experts increases the difficulties of effective complex event processing. It inevitably involves various types of the intrinsic uncertainty, such as imprecision, fuzziness, and incompleteness, due to the inability of human beings subjective judgment. Nevertheless, D numbers is a new mathematic tool to model uncertainty, since it ignores the condition that elements on the frame must be mutually exclusive. To address the above issues, an intelligent complex event processing method with D numbers under fuzzy environment is proposed based on the Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS) method. The novel method can fully support decision making in complex event processing systems. Finally, a numerical example is provided to evaluate the efficiency of the proposed method.

1. Introduction

Nowadays, there has been increasing interest in distributed applications which require processing continuously flowing data from geographically distributed sources to obtain timely responses to complex queries, such as data stream processing (DSP) systems [1–8] and complex event processing (CEP) systems [9–16]. In principle, DSP systems differ from CEP systems as the DSP systems focus on transforming the incoming flow of information, while the CEP systems focus on detecting patterns of information that represent the higher-level events [17, 18]. Because of the advantages such as expressive rule language and efficient event detection model, CEP systems have been highly concerned in academic circles and industry recently [19–25].

In CEP systems, event streams are processed in or near real time for a variety of purposes, from wireless sensor networks to financial tickers and from traffic management to click-stream inspection [17, 18, 26–28]. In those application domains, accurate and effective complex event processing is critical for dealing with real-world events, whereas there are two possible origins for uncertainty which increases the difficulties of accurate and effective complex event processing, such as uncertainty originating at the event source and uncertainty resulting from event inference [29]. For uncertainty originating at the event source (i.e., raw event), there may be uncertainty associated with either the event occurrence itself or the event's attributes, due to a feature of the event source. For uncertainty resulting from event inference (i.e., derived events), they are based on other events and uncertainty can propagate to the derived events. Nevertheless, in DSP systems, many kinds of strategies have been developed to handle the above two types of uncertainty [29–33].

However, most of the CEP systems are dealing with the flow of events where the basic premise underlying the design of the CEP queries proposed is that the associated pattern rules of events are predefined. Moreover, many of predefined pattern rules are based on human beings subjective experience so that it is not necessarily accurate in practice. While rule based reasoning system structure looks simple, the acquisition of knowledge is a big bottleneck in the system. Because the rules come from experts, there are no self-learning functions. Such a behavior gives rise to poor quality of query results. Furthermore, in conventional CEP systems, it inevitably involves various types of the intrinsic uncertainty, such as imprecision, fuzziness, and incompleteness, due to the inability of human beings subjective judgment. In these cases, it seems more reasonable to consider fuzzy situation in the CEP systems.

Due to the efficiency to handle uncertainty and fuse data, some math tools such as fuzzy sets, evidence theory, and probability method are widely used in decision making [34–42], risk analysis [43], diagnosis [44], and optimization problem [45]. Needless to say, fuzzy sets theory introduced by Zadeh is a good approach to settle with the uncertain information [35, 46–50]. The Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS) [51] method proposed by Hwang and Yoon (1981) is widely used in decision making [52]. Moreover, the extension of the TOPSIS [51] method was developed to handle fuzzy data [53, 54]. The TOPSIS method is applied widely in MCDM field. And many applications have proved its effectiveness,whereas there still exist some shortcomings. One of the open questions is that current MCDM based on the TOPSIS method cannot adequately handle these types of uncertainties, such as imprecision, fuzziness, and incompleteness, due to the inability of experts' subjective judgment. *D* numbers proposed by Deng [55] is a new mathematic tool to model uncertainty, since it ignores the condition that elements on the frame must be mutually exclusive. Compared with existing methods, *D* numbers can efficiently represent uncertain information and are more tallied with the actual situation. There is an increasing number of applications about *D* numbers, such as FEMA analysis [56], failure mode analysis [57], environment assessment [58–60], supplier selection [61], and product engineering [62].

To address these issues, we propose an intelligent complex event processing strategy with *D* numbers under fuzzy environment based on the TOPSIS method. The novel method can deal with pattern-rule based uncertainty under fuzzy environment to realize accurate and effective event stream processing. Effectiveness of the proposed method is evaluated through a numerical experiment.

The rest of this paper is organized as follows. Section 2 briefly introduces the preliminaries of this paper. After that, Section 3 proposes an intelligent complex event processing strategy with *D* numbers under fuzzy environment. Section 4 gives a numerical example to show the effectiveness of the proposed method. Finally, Section 5 gives a conclusion.

2. Preliminaries

2.1. Dempster-Shafer Evidence Theory. Dempster-Shafer evident theory [63, 64], also known as evidence theory, is used to handle uncertain information, belonging to the category of artificial intelligence. As a theory reasoning under the uncertain environment, it needs weaker conditions than the Bayesian theory of probability. When the probability is confirmed, Dempster-Shafer theory could convert into Bayesian theory, so it is often regarded as an extension of the Bayesian theory. Dempster-Shafer theory has the advantage of directly expressing the "uncertainty" by assigning the probability to the subsets of the set composed of multiple objects, rather than to an individual object. Besides, it has the ability to combine pairs of bodies of evidence or belief functions to derive a new evidence or belief function. Based on the Dempster-Shafer evident theory, Deng proposed the generalized evidence theory to extend the classical evidence theory [34]. For completeness of the explanation, some basic concepts are introduced as follows.

Definition 1 (frame of discernment). Let U be a set of mutually exclusive and collectively exhaustive, indicated by

$$U = \{E_1, E_2, \ldots, E_i, \ldots, E_N\}. \tag{1}$$

The set U is called frame of discernment. The power set of U is indicated by 2^U, where

$$2^U = \{\emptyset, \{E_1\}, \ldots, \{E_N\}, \{E_1, E_2\}, \ldots, \{E_1, E_2, \ldots, E_i\}, \ldots, U\}, \tag{2}$$

and $\emptyset$ is an empty set. If $A \in 2^U$, A is called a proposition.

Definition 2 (mass function). For a frame of discernment U, a mass function is a mapping m from 2^U to $[0,1]$, formally defined by

$$m := 2^U \longrightarrow [0,1] \tag{3}$$

which satisfies the following condition:

$$\begin{gathered} m(\emptyset) = 0, \\ \sum_{A \in 2^U} m(A) = 1. \end{gathered} \tag{4}$$

In the Dempster-Shafer evident theory, a mass function is also called a basic probability assignment (BPA). If $m(A) > 0$, A is called a focal element; the union of all focal elements is called the core of the mass function.

Definition 3 (Dempster's rule of combination). Dempster's rule of combination, also called orthogonal sum, denoted by $m = m_1 \oplus m_2$, is defined as follows:

$$m(A) = \begin{cases} \dfrac{1}{1-K} \displaystyle\sum_{B \cap C = A} m_1(B)\, m_2(C), & A \neq \emptyset; \\ 0, & A = \emptyset, \end{cases} \tag{5}$$

with

$$K = \sum_{B \cap C = \emptyset} m_1(B)\, m_2(C), \tag{6}$$

where B and C are also elements of 2^U and K is a constant to show the conflict between the two BPAs. Note that Dempster's rule of combination is only applicable to such two BPAs which satisfy the condition $K < 1$.

2.2. D Number Theory. D number theory is a generalization of Dempster-Shafer evidence theory proposed by Deng [55]. In the classical Dempster-Shafer theory, there are several strong hypotheses on the frame of discernment and basic probability assignment and still some shortcomings, which limit the ability of Dempster-Shafer theory to represent some types of information and restrict the application in practice. D number theory, as an extension and development method, is defined as follows.

Definition 4 (D number). Let Ω be a finite nonempty set; a D number is a mapping formulated by

$$D : \Omega \longrightarrow [0,1] \tag{7}$$

with

$$\begin{gathered} \sum_{B \subseteq \Omega} D(B) \le 1, \\ D(\emptyset) = 0, \end{gathered} \tag{8}$$

where B is a subset of Ω.

It seems that the definition of D numbers is similar to the definition of BPA. However, in D number theory, the elements of Ω do not require to be mutually exclusive. In addition, being contrary of the frame of discernment U containing overall events, Ω is acceptable to incomplete information by $\sum_{B \subseteq \Omega} D(B) \le 1$.

Furthermore, for a discrete set $\Omega = \{b_1, b_2, \dots, b_i, \dots, b_n\}$, where $b_i \in R$ and when $i \ne j$, $b_i \ne b_j$. A special form of D numbers can be expressed by

$$\begin{gathered} D(\{b_1\}) = v_1 \\ D(\{b_2\}) = v_2 \\ \vdots \\ D(\{b_i\}) = v_i \\ \vdots \\ D(\{b_n\}) = v_n \end{gathered} \tag{9}$$

or simply denoted as $D = \{(b_1, v_1), (b_2, v_2), \dots, (b_i, v_i), \dots, (b_n, v_n)\}$, where $v_i > 0$ and $\sum_{i=1}^{n} v_i \le 1$.

Definition 5 (two D numbers' rule of combination). Let $D_1 = \{(b_1^1, v_1^1), \dots, (b_i^1, v_i^1), \dots, (b_n^1, v_n^1)\}$, $D_2 = \{(b_1^2, v_1^2), \dots, (b_j^2, v_j^2), \dots, (b_n^2, v_n^2)\}$ be two D numbers; the combination of D_1 and D_2, indicated by $D = D_1 \oplus D_2$, is defined by

$$D(b) = v \tag{10}$$

with

$$\begin{gathered} b = \frac{b_i^1 + b_j^2}{2}, \\ v = \frac{\left(v_i^1 + v_j^2\right)/2}{C}, \\ C = \begin{cases} \displaystyle\sum_{j=1}^{m}\sum_{i=1}^{n}\left(\frac{v_i^1 + v_j^2}{2}\right), & \displaystyle\sum_{i=1}^{n} v_i^1 = 1,\ \sum_{j=1}^{m} v_j^2 = 1; \\ \displaystyle\sum_{j=1}^{m}\sum_{i=1}^{n}\left(\frac{v_i^1 + v_j^2}{2}\right) + \sum_{j=1}^{m}\left(\frac{v_c^1 + v_j^2}{2}\right), & \displaystyle\sum_{i=1}^{n} v_i^1 < 1,\ \sum_{j=1}^{m} v_j^2 = 1; \\ \displaystyle\sum_{j=1}^{m}\sum_{i=1}^{n}\left(\frac{v_i^1 + v_j^2}{2}\right) + \sum_{i=1}^{n}\left(\frac{v_i^1 + v_c^2}{2}\right), & \displaystyle\sum_{i=1}^{n} v_i^1 = 1,\ \sum_{j=1}^{m} v_j^2 < 1; \\ \displaystyle\sum_{j=1}^{m}\sum_{i=1}^{n}\left(\frac{v_i^1 + v_j^2}{2}\right) + \sum_{j=1}^{m}\left(\frac{v_c^1 + v_j^2}{2}\right) + \sum_{i=1}^{n}\left(\frac{v_i^1 + v_c^2}{2}\right) + \frac{v_c^1 + v_c^2}{2}, & \displaystyle\sum_{i=1}^{n} v_i^1 < 1,\ \sum_{j=1}^{m} v_j^2 < 1, \end{cases} \end{gathered} \tag{11}$$

where $v_c^1 = 1 - \sum_{i=1}^{n} v_i^1$ and $v_c^2 = 1 - \sum_{j=1}^{m} v_j^2$.

In the meanwhile, an aggregation operator is proposed on this special D number; it is defined as below.

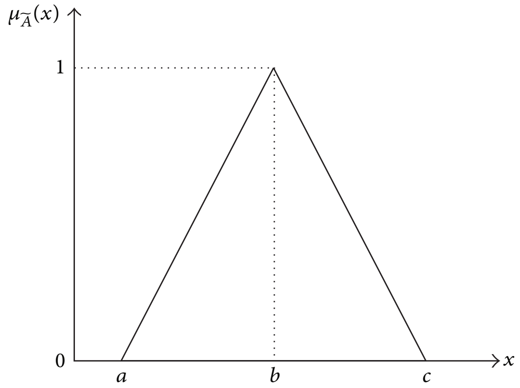

FIGURE 1: A triangular fuzzy number.

Definition 6 (D numbers' integration). For $D = \{(b_1, v_1), (b_2, v_2), \ldots, (b_i, v_i), \ldots, (b_n, v_n)\}$, the integrating representation of D is defined as

$$I(D) = \sum_{i=1}^{n} b_i v_i. \tag{12}$$

2.3. TOPSIS Method with Fuzzy Data. Fuzzy set theory [65] provide an alternative and convenient framework for modeling of real-world fuzzy decision systems mathematically [66–68]. A fuzzy set is any set that allows its members to have different grades of membership in the interval $[0, 1]$. It consists of two components: a set and a membership function associated with it.

Definition 7 (fuzzy set [69]). Let X be a collection of objects denoted generally by x; a fuzzy subset of X, $\tilde{a}$, is a set of ordered pairs:

$$\tilde{a} = \{(x, \mu_{\tilde{a}}(x) \mid x \in X)\}, \tag{13}$$

where $\mu_{\tilde{a}}(x) : X \to [0, 1]$ is called the membership function (generalized characteristic function) which maps X to the membership space M. Its range is the subset of nonnegative real members whose supremum is finite.

Definition 8 (triangular fuzzy number [66]). A fuzzy number is a fuzzy subset of X. And a triangular fuzzy number $\widetilde{A}$ can be defined by a triplet (a, b, c) shown in Figure 1, in which a, b, and c are real numbers with $a < b < c$. Its membership function is defined as

$$\mu_{\widetilde{A}}(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \\ 0, & x > c. \end{cases} \tag{14}$$

Definition 9 (distance between two triangular fuzzy numbers [53]). Let $\widetilde{A} = (a, b, c)$ and $\widetilde{M} = (m, s, n)$ be two triangular fuzzy numbers; then the vertex method is defined to calculate the distance between them as

$$d(\widetilde{A}, \widetilde{M}) = \sqrt{\frac{1}{3}\left[(a-m)^2 + (b-s)^2 + (c-n)^2\right]}. \tag{15}$$

The main idea of TOPSIS is that the best compromise solution should have the shortest Euclidean distance from the positive ideal solution and the farthest Euclidean distance from the negative ideal solution.

The procedures of TOPSIS method with fuzzy data can be described as follows. Let $A = \{A_k \mid k = 1, 2, \ldots, m\}$ be the set of alternatives, $C = \{\widetilde{C}_s \mid s = 1, 2, \ldots, n\}$ be the set of criteria, and $R = \{\tilde{r}_{ks} \mid k = 1, 2, \ldots, m;\ s = 1, 2, \ldots, n\}$ be the performance ratings with the criteria weight vector $W = \{\widetilde{w}_s \mid s = 1, 2, \ldots, n\}$.

Step 1 (calculate normalized ratings). Let B and C be the set of benefit criteria and cost criteria, respectively. The normalized value $\tilde{r}_{ks}$ is calculated by

$$\begin{aligned} \tilde{r}_{ks} &= \left(\frac{a_{ks}}{c_s^+}, \frac{b_{ks}}{c_s^+}, \frac{c_{ks}}{c_s^+}\right), \\ &\qquad \text{where } c_s^+ = \max_k (c_{ks}),\ s \in B, \\ \tilde{r}_{ks} &= \left(\frac{a_s^-}{c_{ks}}, \frac{a_s^-}{b_{ks}}, \frac{a_s^-}{a_{ks}}\right), \\ &\qquad \text{where } a_s^- = \min_k (a_{ks}),\ s \in C. \end{aligned} \tag{16}$$

Step 2 (calculate weighted normalized ratings). In the weighted normalized decision matrix, the modified ratings are calculated by

$$\tilde{v}_{ks} = \widetilde{w}_s \times \tilde{r}_{ks} \quad \text{for } k = 1, 2, \ldots, m,\ s = 1, 2, \ldots, n, \tag{17}$$

where $\widetilde{w}_s$ is the weight of the sth criteria.

Step 3 (determine the fuzzy positive and negative ideal solutions). The elements $\tilde{v}_{ij}$, $\forall i, j$ are normalized positive triangular fuzzy numbers and their ranges belong to the closed interval $[0, 1]$. Then, the fuzzy positive ideal solution (FPIS, A^+) and the fuzzy negative ideal solution (FNIS, A^-) are derived as follows:

$$\begin{aligned} A^+ &= \{\tilde{v}_1^+, \tilde{v}_2^+, \ldots, \tilde{v}_n^+\}, \\ A^- &= \{\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-\}, \end{aligned} \tag{18}$$

where $\tilde{v}_s^+ = (1, 1, 1)$ and $\tilde{v}_s^- = (0, 0, 0)$, $s = 1, 2, \ldots, n$.

Table 1: Linguistic variables for the importance weight of each criterion.

Very poor (VP)	(0, 0, 1)
Poor (P)	(0, 1, 3)
Medium poor (MP)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Medium good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very good (VG)	(9, 10, 10)

Table 2: The importance weight of the criteria.

		Expert$_1$	Expert$_2$	Expert$_3$
Accuracy	(C_1)	0.3069	0.2632	0.1478
Response time	(C_2)	0.2255	0.4358	0.3222
Cost	(C_3)	0.2663	0.0971	0.1269
Operability	(C_4)	0.2013	0.2039	0.4031

Step 4 (calculate the distance of each alternative from the FPIS and the FNIS). The distance of each alternative from A^+ and A^- can be currently calculated as

$$d_k^+ = \sum_{s=1}^{n} d\left(\tilde{v}_{ks}, \tilde{v}_s^+\right), \quad k = 1, 2, \ldots, m,$$
$$d_k^- = \sum_{s=1}^{n} d\left(\tilde{v}_{ks}, \tilde{v}_s^-\right), \quad k = 1, 2, \ldots, m, \tag{19}$$

where $d(\cdot, \cdot)$ is the distance measurement between two fuzzy numbers.

Step 5 (calculate the relative closeness coefficient to the positive ideal solution). The relative closeness coefficient for the alternative A_k with respect to A^+ is

$$C_k = \frac{d_k^-}{d_k^+ + d_k^-}, \quad k = 1, 2, \ldots, m. \tag{20}$$

Step 6 (rank the alternatives). Obviously, an alternative A_k is closer to the FPIS (A^+) and farther from FNIS (A^-) as C_k approaches 1. Therefore according to relative closeness coefficient to the ideal alternative, larger value of C_k indicates the better alternative A_k.

3. The Proposed Method

Before introducing the system architecture of intelligent CEP, we first have a clear understanding of the definition of an event [10, 11]. An event that represents an atomic instance is an occurrence that is of interest at a point in time. Basically, events can be classified into primitive events and composite events. A primitive event instance is predefined as a single occurrence of interest that cannot be split into any small events. A composite event instance that occurs over an interval is created by composing primitive or composite events. A pattern rule is a template, specifying one or more combinations of events by the nesting of sequences (SEQ) and conjunctions (AND), which can have negative event type(s), and their combination. In the following, E_i denotes an event type which can be either primitive or composite. Some details were presented in [70].

Definition 10. A SEQ operator [13] specifies a specific order according to the start time-stamps in which the event must occur, to match the pattern, and thus form a composite event.

$$\begin{aligned} \text{SEQ}\left(E_1, \ldots, E_i, \ldots, E_n\right) = \{&\langle e_1, \ldots, e_i, \ldots, e_n \rangle \mid \\ &\left(e_1 \cdot st < \cdots < e_i \cdot st < \cdots < e_n \cdot st\right) \wedge \left(e_1 \cdot t = E_1\right) \\ &\wedge \cdots \wedge \left(e_i \cdot t = E_i\right) \wedge \cdots \wedge \left(e_n \cdot t = E_n\right)\}. \end{aligned} \tag{21}$$

For example, SEQ (*History_taking*, *Physical_examination*, *Laboratory_examination*) consists of SEQ operator that can be used to monitor the patients who have completed medical diagnosis.

Definition 11. An AND operator [13] takes a set of event types as input, and events occur within a specified time window without a specified time order.

$$\begin{aligned} &\text{AND}\left(E_i, \ldots, E_k, \ldots, E_j\right) \\ &\quad = \left\{\left\langle e_i, \ldots, e_k, \ldots, e_j \right\rangle \mid \left(e_i \cdot t = E_i\right) \wedge \cdots \right. \\ &\quad \left. \wedge \left(e_k \cdot t = E_k\right) \wedge \cdots \wedge \left(e_j \cdot t = E_j\right)\right\}. \end{aligned} \tag{22}$$

For example, AND (*Laboratory_examination*, *Surgery*) consists of AND operator that can be used to monitor the patients' preoperative and postoperative situations.

Currently, the pattern-rule base of CEP systems consisting of a set of pattern rules is predefined where it is based on human beings subjective experience so that it is not necessarily accurate in practice, whereas the acquisition of knowledge is a big bottleneck in the system and most researches on CEP systems seldom discuss how to handle such kinds of problems. As we discussed in Section 1, because the rules come from experts, there is no self-learning function. The CEP engine based on the inaccurate predefined pattern-rule base will generate poor quality of query results. Furthermore, in conventional CEP systems, it inevitably involves various types of the intrinsic uncertainty, such as imprecision, fuzziness, and incompleteness, due to the inability of human beings subjective judgment.

In this section, a novel intelligent complex event processing strategy with D numbers under fuzzy environment is proposed based on the Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS) method. The proposed method can fully support decision making in CEP systems.

The proposed system architecture of intelligent CEP is shown in Figure 2; it mainly involves two components: event collector engine and CEP engine under D number theory

Table 3: The ratings of the three candidates by experts under all criteria.

Alternative	Expert$_1$				Expert$_2$				Expert$_3$			
	C_1	C_2	C_3	C_4	C_1	C_2	C_3	C_4	C_1	C_2	C_3	C_4
PRA$_1$	MG	F	G	G	VG	F	G	G	F	G	F	G
PRA$_2$	F	MG	F	MG	VG	MG	VG	F	MG	MG	G	F
PRA$_3$	G	F	G	MG	VG	MG	VG	G	MG	G	F	VG

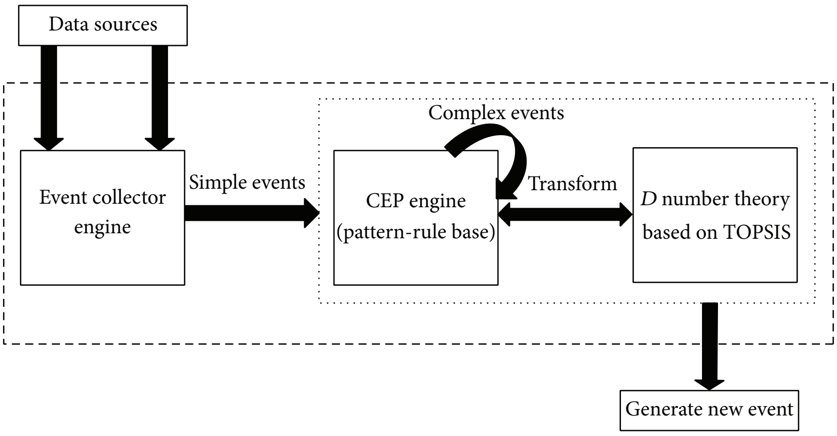

Figure 2: The system architecture of intelligent CEP.

Table 4: The fuzzy numbers of three candidates by experts under all criteria.

(a)

Alternative	Expert$_1$			
	C_1	C_2	C_3	C_4
PRA$_1$	(5, 7, 9)	(3, 5, 7)	(7, 9, 10)	(7, 9, 10)
PRA$_2$	(3, 5, 7)	(5, 7, 9)	(3, 5, 7)	(5, 7, 9)
PRA$_3$	(7, 9, 10)	(3, 5, 7)	(7, 9, 10)	(5, 7, 9)

(b)

Alternative	Expert$_2$			
	C_1	C_2	C_3	C_4
PRA$_1$	(9, 10, 10)	(3, 5, 7)	(7, 9, 10)	(7, 9, 10)
PRA$_2$	(9, 10, 10)	(5, 7, 9)	(9, 10, 10)	(3, 5, 7)
PRA$_3$	(9, 10, 10)	(5, 7, 9)	(9, 10, 10)	(7, 9, 10)

(c)

Alternative	Expert$_3$			
	C_1	C_2	C_3	C_4
PRA$_1$	(3, 5, 7)	(7, 9, 10)	(3, 5, 7)	(7, 9, 10)
PRA$_2$	(5, 7, 9)	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)
PRA$_3$	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)	(9, 10, 10)

based on TOPSIS method. We will explain each component in detail.

Component 1: Event Collector Engine. The event collector engine, which collects events from data sources, first generates a unified formal definition of the event flow.

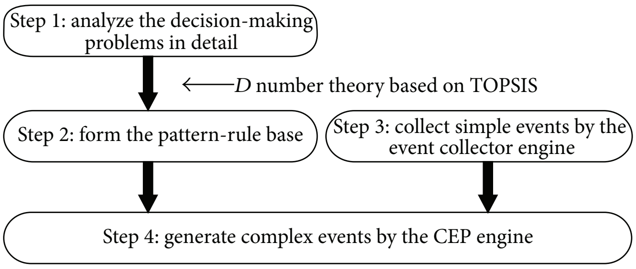

Figure 3: The flowchart of the proposed method.

Component 2: CEP Engine under D Number Theory Based on TOPSIS Method. Then, the CEP engine processes the collected simple events through the pattern rules in which the events generated at this component are called complex events, whereas the D number theory based on TOPSIS method, which is the addition to the CEP engine, in view of the detected uncertainty event set, is used for pattern-rules analysis to select the best one from the decision candidates. Finally, the generated new events are sent out directly to particular users, or reused as input events, or used to do further analysis.

The main steps of the proposed method are shown as follows, and the basic flowchart is given in Figure 3 for the better understanding of the concept.

Step 1. Make certain of the detailed information of the decision-making problems, including the goal and criteria.

Table 5: The fuzzy normalized decision matrix.

(a)

Alternative	Expert$_1$			
	C_1	C_2	C_3	C_4
PRA$_1$	(0.50, 0.70, 0.90)	(0.30, 0.50, 0.70)	(0.70, 0.90, 1.00)	(0.70, 0.90, 1.00)
PRA$_2$	(0.30, 0.50, 0.70)	(0.56, 0.78, 1.00)	(0.30, 0.50, 0.70)	(0.56, 0.78, 1.00)
PRA$_3$	(0.70, 0.90, 1.00)	(0.50, 0.70, 0.70)	(0.70, 0.90, 1.00)	(0.50, 0.70, 0.90)

(b)

Alternative	Expert$_2$			
	C_1	C_2	C_3	C_4
PRA$_1$	(0.90, 1.00, 1.00)	(0.30, 0.50, 0.70)	(0.70, 0.90, 1.00)	(0.70, 0.90, 1.00)
PRA$_2$	(0.90, 1.00, 1.00)	(0.56, 0.78, 1.00)	(0.90, 1.00, 1.00)	(0.33, 0.56, 0.78)
PRA$_3$	(0.90, 1.00, 1.00)	(0.50, 0.70, 0.90)	(0.90, 1.00, 1.00)	(0.70, 0.90, 1.00)

(c)

Alternative	Expert$_3$			
	C_1	C_2	C_3	C_4
PRA$_1$	(0.30, 0.50, 0.70)	(0.70, 0.90, 1.00)	(0.30, 0.50, 0.70)	(0.70, 0.90, 1.00)
PRA$_2$	(0.50, 0.70, 0.90)	(0.56, 0.78, 1.00)	(0.70, 0.90, 1.00)	(0.33, 0.56, 0.78)
PRA$_3$	(0.50, 0.70, 0.90)	(0.70, 0.90, 1.00)	(0.30, 0.50, 0.70)	(0.90, 1.00, 1.00)

Table 6: The closeness coefficient of each alternative.

(a)

Alternative	Expert$_1$			
	C_1	C_2	C_3	C_4
PRA$_1$	0.6779	0.5000	0.8275	0.8275
PRA$_2$	0.5000	0.7357	0.5000	0.7357
PRA$_3$	0.8275	0.5000	0.8275	0.6779

(b)

Alternative	Expert$_2$			
	C_1	C_2	C_3	C_4
PRA$_1$	0.9437	0.5000	0.8275	0.8275
PRA$_2$	0.9437	0.7357	0.9437	0.5490
PRA$_3$	0.9437	0.6779	0.9437	0.8275

(c)

Alternative	Expert$_3$			
	C_1	C_2	C_3	C_4
PRA$_1$	0.5000	0.8275	0.5000	0.8275
PRA$_2$	0.6779	0.7357	0.8275	0.5490
PRA$_3$	0.6779	0.8275	0.5000	0.9437

Step 2. After determining the goal and criteria, it forms the pattern-rule base by leveraging D number theory based on TOPSIS method.

Step 3. For the intelligent CEP, it then collects simple events by the event collector engine from the data sources.

Step 4. Based on the pattern-rule base, the intelligent CEP system can process the collected simple events and generate new complex events by the CEP engine.

4. Numerical Example

In this section, in order to illustrate the application of the proposed method, a simple numerical example is given. Suppose that there are three pattern-rule alternatives (PRA) which may be considered for further generating a composite event in the CEP system, namely, $\text{PRA}_1 = \text{SEQ}(E_1, \ldots, E_i, \ldots, E_k)$, $\text{PRA}_2 = \text{SEQ}(E_1, \ldots, E_j, \ldots, E_k)$, and $\text{PRA}_3 = \text{SEQ}(E_1, \ldots, E_j, \ldots, E_n)$. Meanwhile, there are four evaluation criteria and three experts need to select the most suitable pattern-rule candidate from them for better supporting decision making in CEP systems. Three experts give different assessment results to different alternatives in terms of different evaluation criteria. Four benefit criteria are considered:

(1) Accuracy (C_1).

(2) Response Time (C_2).

(3) Cost (C_3).

(4) Operability (C_4).

The proposed method is now applied to solve this decision problem. Then, computational procedure is summarized as follows.

Step 1. The experts use linguistic weighting variables to assess the importance of the criteria, which is shown in Table 1.

Step 2. In this paper, the criteria weights for different experts determined by variation coefficient method are adopted and presented in Table 2.

Step 3. Using the linguistic rating variables of Table 1, the ratings of the three decision alternatives by different experts under four evaluation criteria are obtained as shown in

Table 7: The representation of D number for PRA_1.

PRA_1	D numbers
Expert_1	$D_{\mathrm{PRA}_1}^{\mathrm{Expert}_1} = \{(0.6779, 0.1478), (0.5000, 0.3222), (0.8275, 0.1269), (0.8275, 0.4031)\}$
Expert_2	$D_{\mathrm{PRA}_1}^{\mathrm{Expert}_2} = \{(0.9437, 0.2632), (0.5000, 0.4358), (0.8275, 0.0971), (0.8275, 0.2039)\}$
Expert_3	$D_{\mathrm{PRA}_1}^{\mathrm{Expert}_3} = \{(0.5000, 0.3069), (0.8275, 0.2255), (0.5000, 0.2663), (0.8275, 0.2013)\}$

Table 8: The results of $D_{\mathrm{PRA}_1}^{\mathrm{Expert}_1} \oplus D_{\mathrm{PRA}_1}^{\mathrm{Expert}_2} \oplus D_{\mathrm{PRA}_1}^{\mathrm{Expert}_3}$.

b	v	b	v
0.6554	0.0563	0.6637	0.1338
0.7082	0.0477	0.8191	0.0441
0.5000	0.0636	0.5445	0.0599
0.8275	0.0702	0.6109	0.0600
0.8565	0.0630	0.6783	0.0427
0.6928	0.0366	0.7901	0.0318
0.6997	0.0432	0.7817	0.0278
0.7456	0.0879	0.7747	0.0478
0.6708	0.0500	0.7153	0.0250
0.7442	0.0230		

Table 9: The ranking of alternatives.

Alternative	PRA_1	PRA_2	PRA_3
$I(D)$	0.7000	0.6301	0.6499
Ranking	1	3	2

Table 3. Furthermore, the fuzzy numbers of three candidates by experts under all criteria can be obtained as shown in Table 4.

Step 4. Based on the fuzzy numbers of Table 4, the fuzzy normalized decision matrix can be constructed as shown in Table 5.

Step 5. The closeness coefficient of each alternative can be calculated as shown in Table 6.

Step 6. Based on Table 6, the D number for PRA_1 can be represented as shown in Table 7.

Step 7. The results of $D_{\mathrm{PRA}_1}^{\mathrm{Expert}_1} \oplus D_{\mathrm{PRA}_1}^{\mathrm{Expert}_2} \oplus D_{\mathrm{PRA}_1}^{\mathrm{Expert}_3}$ can be represented as shown in Table 8.

Step 8. The integration representation of every D_{PRA_i} is calculated by using (12). Table 9 shows these values of $I(DA_1)$, $I(DA_2)$, and $I(DA_3)$. According to these values, the ranking of alternative is obtained; it is $\mathrm{PRA}_1 \succ \mathrm{PRA}_3 \succ \mathrm{PRA}_2$, where "$\succ$" represents "better than."

5. Conclusion

In this paper, we started off with identifying the uncertainty problems in terms of pattern rules of CEP systems. We proposed an intelligent complex event processing strategy with D numbers under fuzzy environment, which could fully support decision making for guaranteeing effective complex event processing. The main idea of the proposed strategy is that we applied D numbers based on TOPSIS method into the CEP systems. A numerical example was provided to evaluate the effectiveness of our proposed method.

Competing Interests

The author declares that he has no competing interests.

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