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FUZZY MULTI-CRITERIA DECISION-MAKING WITH MULTILEVEL CRITERIA TO EVALUATE RETAILER FINANCIAL PERFORMANCE FOR SUPPLY CHAIN MANAGEMENT

Yu-Jie Wang and Tzeu-Chen Han

Key words: multilevel FMCDM, hierarchical structure, multiplication, retailers, supply chain management.

ABSTRACT

Retailers are important components in a supply chain because they are closer to the end users than are other industrial processes of the chain. Therefore, retailer selection must be carefully examined, especially when considering the financial performance of supply chain management. Generally, the evaluation of retailer financial performance in a vague and uncertain environment is based on multilevel criteria. In the past, many researchers, including Chen, Liang, Raj and Kumar, Wang and Lee, and Chou, proposed models under uncertain environments to evaluate fuzzy multi-criteria decision-making (FMCDM) problems. They evaluated FMCDM problems based on a single level, and resolved the ties of multiplying two fuzzy numbers. Furthermore, Chou proposed a utility representation function of multiplying three fuzzy numbers for FMCDM based on multilevel criteria that were presented in a hierarchical structure. Practically, multiplication of three or more fuzzy numbers is crucial because multilevel FMCDM is mainly constructed by multiplication. Based on a utility representation function of multiplying several fuzzy numbers, we propose multilevel FMCDM to evaluate retailer financial performance for supply chain management in this paper. By adopting multilevel FMCDM, the evaluation of retailer financial performance for supply chain management under uncertain environments can result easily and quickly.

I. INTRODUCTION

Decision-making is a procedure to find the best alternative from among feasible ones. Decision-making, based on several criteria, is called multi-criteria decision-making (MCDM) (Hwang and Yoon, 1981). The multi-criteria are generally presented on a single level. Practically, an MCDM problem evaluated on single level of criteria is expressed in matrix format as follows:

$$
G = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array}
\begin{array}{c}
\begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\
\begin{bmatrix}
G_{11} & G_{12} & \cdots & G_{1n} \\
G_{21} & G_{22} & \cdots & G_{2n} \\
\vdots & \vdots & \cdots & \vdots \\
G_{m1} & G_{m2} & \cdots & G_{mn}
\end{bmatrix}
\end{array}
$$

and

$$W = [W_1, W_2, \dots, W_n],$$

where $A_1, A_2, \dots, A_m$ are feasible alternatives, $C_1, C_2, \dots, C_n$ are evaluation criteria, G_{ij} is the performance rating of A_i on C_j, and W_j is the weight of C_j.

MCDM problems evaluated on single level criteria may be classified into classical MCDM problems (Keeney and Raiffa, 1976) and fuzzy multi-criteria decision-making (FMCDM) problems (Bellman and Zadeh, 1970; Hsu and Chen, 1997). In classical MCDM problems, ratings and criteria weights are expressed by crisp values, whereas in FMCDM problems (Chen and Hwang, 1992) ratings and criteria weights are assessed under an uncertain environment and then presented by fuzzy numbers (Zadeh, 1965). To deal with the FMCDM problems on a single level, classical MCDM methods, including the analytic hierarchy process (AHP) (Saaty, 1980) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981) were often extended into FMCDM (Gumus, 2009) under uncertain environments. Related research includes the approaches of Chang (1996), Liang (1999), Raj and Kumar (1999), Chen (2000), Chou (2003), Wang (2018), and Wang and Kao (2011). For FMCDM problems with a single level, multiplying two

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fuzzy numbers or avoiding a multiplication tie is necessary (Wang, 2014). The two above computations are not easy. Sometimes, evaluation criteria may be presented in a single level, but expressed in a multilevel. In other words, multilevel criteria normally have criteria in the first level and sub-criteria in the next level or more, in order to construct a hierarchical structure, such as Chou's (2007) multilevel FMCDM. For supply chain management, the evaluation of retailer financial performance is generally based on a hierarchical structure of an uncertain environment because of the prospect of financial complexity. In the hierarchical structure of retailer financial performance, priority weights of the first level criteria are assessed according to the problem objective; priority weights of the next level criteria (i.e., sub-criteria) are measured based on their following criterion in the previous level (i.e., their main criterion), while priority weights of feasible alternatives are scored based on the final level criteria. Additionally, the above priority weights are expressed by fuzzy numbers due to the data in uncertain environments. Accordingly, retailer financial performance for supply chain management in this paper will be evaluated by multilevel FMCDM.

Based on the concepts above, multiplying three or more fuzzy numbers is important to evaluate retailer financial performance for supply chain management (Chen and Cai, 2011; Yu and Huo, 2019) by multilevel FMCDM. However, the multiplication for a set of fuzzy numbers is more complicated than multiplying two fuzzy ones. In this paper, we propose a utility representation function whereby we multiply a set of fuzzy numbers to resolve a multiplication tie of several fuzzy numbers. By means of the utility representation function, the utility representing values of multiplying some fuzzy numbers within an alternative are easily summarized into an index that can stand for the alternative performance. Thus alternatives are quickly ranked according to their corresponding performance indices; as a result, the best alternative is effectively obtained.

For the sake of clarity, mathematical preliminaries are described in Section 2. A utility representation function for multiplying some fuzzy numbers is presented in Section 3. The multilevel FMCDM constructed on the utility representation function is expressed in Section 4. In Section 5, a numerical example for the evaluation of retailer financial performance in supply chain management is illustrated. Finally, conclusions are shown in Section 6.

II. PRELIMINARIES

In this section, basic notions of fuzzy sets and fuzzy numbers (Zadeh, 1965) are described as follows:

Definition 2.1 The function $\mu_A(x)$ is the generalization of the characteristic function for a crisp subset. The fuzzy set A of U is characterized by a membership function with the value x representing the degree of membership of x in A. Thus the fuzzy set A is expressed by $A = \left\{(x, \mu_A(x)) \middle| x \in U\right\}$ or $\int_{x \in U} \mu_A(x) / x$.

Definition 2.2 The $\alpha - cut$ of fuzzy set A is a crisp set $A_\alpha = \{x | \mu_A(x) \geq \alpha\}$.

Definition 2.3 The support of fuzzy set A is a crisp set $Supp(A) = \{x | \mu_A(x) > 0\}$.

Definition 2.4 A fuzzy subset A of U is normal iff $\sup_{x \in U} \mu_A(x) = 1$.

Definition 2.5 A fuzzy subset A of U is convex iff $\mu_A(\lambda x + (1-\lambda) y) \geq (\mu_A(x) \wedge \mu_A(y))$, $\forall x, y \in U$, $\forall \lambda \in [0, 1]$, where $\wedge$ is the minimum operator.

Definition 2.6 A is a fuzzy number iff A is both normal, and convex of, U.

Definition 2.7 A triangular fuzzy number A is a fuzzy number with piecewise linear membership function μ_A expressed as:

$$\mu_A = \begin{cases} \dfrac{x - a_l}{a_m - a_r}, & a_l \leq x \leq a_m, \\ \dfrac{a_r - x}{a_r - a_m}, & a_m \leq x \leq a_r, \\ 0, & otherwise, \end{cases}$$

which can be denoted as a triplet (a_l, a_m, a_r).

Definition 2.8 A trapezoidal fuzzy number A is a fuzzy number with membership function μ_A expressed as:

$$\mu_A = \begin{cases} \dfrac{x - a_l}{a_h - a_l}, & a_l \leq x \leq a_h, \\ 1, & a_h \leq x \leq a_m, \\ \dfrac{a_r - x}{a_r - a_m}, & a_m \leq x \leq a_r, \\ 0, & otherwise, \end{cases}$$

which can be denoted as a quartet (a_l, a_h, a_m, a_r).

Definition 2.9 Let A be a fuzzy number. $A^L(\alpha)$ and $A^U(\alpha)$ are respectively expressed as:

$$A^L(\alpha) = \inf_{\mu_A(z) \geq \alpha}(z) \text{ and } A^U(\alpha) = \sup_{\mu_A(z) \geq \alpha}(z).$$

Definition 2.10 A fuzzy preference relation R is a fuzzy subset of $\Re \times \Re$ with membership function $\mu_R(A, B)$ representing the preference degree of fuzzy numbers A over B (Epp, 1990; Lee, 2005).

(1) R is reciprocal iff $\mu_R(A, B) = 1 - \mu_R(B, A)$ for all fuzzy numbers A and B.

(2) R is transitive iff $\mu_R(A,B) \geq \frac{1}{2}$ and $\mu_R(B,C) \geq \frac{1}{2} \Rightarrow \mu_R(A,C) \geq \frac{1}{2}$ for all fuzzy numbers A, B and C.
(3) R is a fuzzy total ordering relation iff R is both reciprocal and transitive.

According to the fuzzy preference relation, A is greater than B iff $\mu_R(A, B) > \frac{1}{2}$.

Definition 2.11 An extended fuzzy preference relation R is an extended fuzzy subset of $\Re \times \Re$ with membership function $-\infty \leq \mu_R(A, B) \leq \infty$ representing the preference degree of fuzzy numbers A over B.

(1) R is reciprocal iff $\mu_R(A, B) = -\mu_R(B, A)$ for all fuzzy numbers A and B.
(2) R is transitive iff $\mu_R(A, B) \geq 0$ and $\mu_R(B, C) \geq 0 \Rightarrow \mu_R(A, C) \geq 0$ for all fuzzy numbers A, B and C.
(3) R is additive iff $\mu_R(A, C) = \mu_R(A, B) + \mu_R(B, C)$.
(4) R is a total ordering relation iff R is reciprocal, transitive and additive.

Based on the extended fuzzy preference relation, A is bigger than B iff $\mu_R(A, B) > 0$.

Definition 2.12 For any two fuzzy numbers A and B, an extended fuzzy preference relation $F(A, B)$ of fuzzy numbers A over B is expressed as the following membership function (Lee, 2005; Wang and Lee, 2010):

$$\mu_F(A, B) = \int_0^1 ((A^L(\alpha) + A^U(\alpha)) - (B^L(\alpha) + B^U(\alpha)))d\alpha .$$

Lemma 2.1 F is reciprocal:

$$\mu_F(A, B) = -\mu_F(B, A) .$$

Lemma 2.2 F is transitive:

$$\mu_F(A, B) \geq 0 \text{ and } \mu_F(B,C) \geq 0 \;\Rightarrow\; \mu_F(A, C) \geq 0 .$$

Lemma 2.3 F is additive:

$$\mu_F(A, B) + \mu_F(B, C) = \mu_F(A, C) .$$

Lemma 2.4 Let $A = (a_l, a_m, a_r)$ and $B = (b_l, b_m, b_r)$ be two triangular fuzzy numbers. $\mu_F(A, B) = \frac{a_l + 2a_m + a_r - b_l - 2b_m - b_r}{2}$, and $\mu_F(A, B) \geq 0$ iff $a_l + 2a_m + a_r - b_l - 2b_m - b_r \geq 0$.

Lemma 2.5 Let $A = (a_l, a_h, a_m, a_r)$ and $B = (b_l, b_h, b_m, b_r)$ be two trapezoidal fuzzy numbers. $\mu_F(A, B) = \frac{a_l + a_h + a_m + a_r - b_l - b_h - b_m - b_r}{2}$, and $\mu_F(A, B) \geq 0$ iff $a_l + a_h + a_m + a_r - b_l - b_h - b_m - b_r \geq 0$.

Definition 2.13 Let $U(A)$ be a utility representation function value (sometimes referred to as 'utility representing value') (Wang, 2018) of a single fuzzy number A representing the extended preference relation of A over zero (Wang and Lee, 2010):

$$U(A) = \mu_F(A, 0) = \int_0^1 (A^L(\alpha) + A^U(\alpha))d\alpha .$$

Based on the utility representation function above, we propose a utility representation function of multiplying some fuzzy numbers for multilevel FMCDM as follows:

III. THE UTILITY REPRESENTATION FUNCTION OF MULTIPLYING FUZZY NUMBERS

In multi-level FMCDM, multiplying fuzzy numbers is an important issue because the computation is necessary to evaluate alternatives as both evaluation ratings and criteria weights on hierarchical structure are fuzzy numbers (Chou, 2010). According to Chen and Hsieh's (1998; 2000) graded mean integration representation, Chou respectively proposed canonical representation of multiplying two triangular fuzzy numbers (Chou, 2003) and three trapezoidal fuzzy numbers (Chou, 2007). Based on the concepts above and on Definition 2.13, we propose a utility representation function for multiplication of two or more fuzzy numbers (Wang, 2018). The definitions of utility representation function are shown in the following:

Definition 3.1 Let $U'(X_1 \otimes X_2)$ be the utility representing value of multiplying two fuzzy numbers X_1 and X_2 as with Chou's (2003) canonical representation computation. Define

$$\begin{aligned}
&U'(X_1 \otimes X_2) \\
&= \int_0^1\int_0^1 (X_1^L(\alpha_1)X_2^L(\alpha_2) + X_1^L(\alpha_1)X_2^U(\alpha_2) + X_1^U(\alpha_1)X_2^L(\alpha_2) + X_1^U(\alpha_1)X_2^U(\alpha_2))d\alpha_1 d\alpha_2 \\
&= \int_0^1\int_0^1 (X_1^L(\alpha_1)\times(X_2^L(\alpha_2) + X_2^U(\alpha_2)) + X_1^U(\alpha_1)\times(X_2^L(\alpha_2) + X_2^U(\alpha_2)))d\alpha_1 d\alpha_2 \\
&= \int_0^1\int_0^1 ((X_1^L(\alpha_1) + X_1^U(\alpha_1))\times(X_2^L(\alpha_2) + X_2^U(\alpha_2)))d\alpha_1 d\alpha_2 \\
&= (\int_0^1 (X_1^L(\alpha_1) + X_1^U(\alpha_1))d\alpha_1)\times(\int_0^1 (X_2^L(\alpha_2) + X_2^U(\alpha_2))d\alpha_2) \\
&= U(X_1)\times U(X_2) \\
&= \prod_{i=1}^2 U(X_i)
\end{aligned}$$

Definition 3.2 Let $U'(X_1 \otimes X_2 \otimes X_3)$ be the utility representing value of multiplying three fuzzy numbers X_1, X_2 and X_3 as with the previous multiplication representation computations (Chou, 2010; Wang and Kao, 2011). Define

$$
\begin{aligned}
&U'(X_1 \otimes X_2 \otimes X_3) \\
&= \int_0^1\int_0^1\int_0^1 (X_1^L(\alpha_1)X_2^L(\alpha_2)X_3^L(\alpha_3) + X_1^L(\alpha_1)X_2^L(\alpha_2)X_3^U(\alpha_3) + X_1^L(\alpha_1)X_2^U(\alpha_2)X_3^L(\alpha_3) \\
&\quad + X_1^L(\alpha_1)X_2^U(\alpha_2)X_3^U(\alpha_3) + X_1^U(\alpha_1)X_2^L(\alpha_2)X_3^L(\alpha_3) + X_1^U(\alpha_1)X_2^L(\alpha_2)X_3^U(\alpha_3) \\
&\quad + X_1^U(\alpha_1)X_2^U(\alpha_2)X_3^L(\alpha_3) + X_1^U(\alpha_1)X_2^U(\alpha_2)X_3^U(\alpha_3))d\alpha_1 d\alpha_2 d\alpha_3 \\
&= \int_0^1\int_0^1\int_0^1 (X_1^L(\alpha_1)X_2^L(\alpha_2)\times(X_3^L(\alpha_3)+X_3^U(\alpha_3)) \\
&\quad + X_1^L(\alpha_1)X_2^U(\alpha_2)\times(X_3^L(\alpha_3)+X_3^U(\alpha_3)) \\
&\quad + X_1^U(\alpha_1)X_2^L(\alpha_2)\times(X_3^L(\alpha_3)+X_3^U(\alpha_3)) \\
&\quad + X_1^U(\alpha_1)X_2^U(\alpha_2)\times(X_3^L(\alpha_3)+X_3^U(\alpha_3)))d\alpha_1 d\alpha_2 d\alpha_3 \\
&= \int_0^1\int_0^1\int_0^1 ((X_1^L(\alpha_1)X_2^L(\alpha_2) + X_1^L(\alpha_1)X_2^U(\alpha_2) + X_1^U(\alpha_1)X_2^L(\alpha_2) + X_1^U(\alpha_1)X_2^U(\alpha_2)) \\
&\quad \times(X_3^L(\alpha_3)+X_3^U(\alpha_3)))d\alpha_1 d\alpha_2 d\alpha_3 \\
&= \int_0^1\int_0^1\int_0^1 ((X_1^L(\alpha_1)\times(X_2^L(\alpha_2)+X_2^U(\alpha_2)) + X_1^U(\alpha_1)\times(X_2^L(\alpha_2)+X_2^U(\alpha_2))) \\
&\quad \times(X_3^L(\alpha_3)+X_3^U(\alpha_3)))d\alpha_1 d\alpha_2 d\alpha_3 \\
&= \int_0^1\int_0^1\int_0^1 ((X_1^L(\alpha_1)+X_1^U(\alpha_1))\times(X_2^L(\alpha_2)+X_2^U(\alpha_2)) \\
&\quad \times(X_3^L(\alpha_3)+X_3^U(\alpha_3)))d\alpha_1 d\alpha_2 d\alpha_3 \\
&= (\int_0^1 (X_1^L(\alpha_1)+X_1^U(\alpha_1))d\alpha_1)\times(\int_0^1 (X_2^L(\alpha_2)+X_2^U(\alpha_2))d\alpha_2) \\
&\quad \times(\int_0^1 (X_3^L(\alpha_3)+X_3^U(\alpha_3))d\alpha_3) \\
&= U(X_1)\times U(X_2)\times U(X_3) \\
&= \prod_{i=1}^3 U(X_i).
\end{aligned}
$$

Definition 3.3 Let $U'(X_1 \otimes X_2 \otimes \ldots \otimes X_n)$ be the utility representing value of multiplying n fuzzy numbers X_1, X_2, …, X_n expressed as:

$$
\begin{aligned}
&U'(X_1 \otimes X_2 \otimes \ldots \otimes X_n) \\
&= \int_0^1\int_0^1 \ldots \int_0^1 (X_1^L(\alpha_1)X_2^L(\alpha_2)\ldots X_n^L(\alpha_n) \\
&\quad + X_1^L(\alpha_1)X_2^L(\alpha_2)\ldots X_n^U(\alpha_n) + \ldots \\
&\quad + X_1^U(\alpha_1)X_2^U(\alpha_2)\ldots X_n^U(\alpha_n))d\alpha_1 d\alpha_2 \ldots d\alpha_n \\
&= \int_0^1\int_0^1 \ldots \int_0^1 (X_1^L(\alpha_1)X_2^L(\alpha_2)\ldots X_{n-1}^L(\alpha_{n-1})\times(X_n^L(\alpha_n)+X_n^U(\alpha_n)) \\
&\quad + X_1^L(\alpha_1)X_2^L(\alpha_2)\ldots X_{n-1}^U(\alpha_{n-1})\times(X_n^L(\alpha_n)+X_n^U(\alpha_n)) + \ldots \\
&\quad + X_1^U(\alpha_1)X_2^U(\alpha_2)\ldots X_{n-1}^U(\alpha_{n-1})\times(X_n^L(\alpha_n)+X_n^U(\alpha_n)))d\alpha_1 d\alpha_2 \ldots d\alpha_n \\
&= \int_0^1\int_0^1 \ldots \int_0^1 ((X_1^L(\alpha_1)+X_1^U(\alpha_1))\times(X_2^L(\alpha_2)+X_2^U(\alpha_2))\times \ldots \\
&\quad \times(X_n^L(\alpha_n)+X_n^U(\alpha_n)))d\alpha_1 d\alpha_2 \ldots d\alpha_n \\
&= (\int_0^1 (X_1^L(\alpha_1)+X_1^U(\alpha_1))d\alpha_1)\times(\int_0^1 (X_2^L(\alpha_2)+X_2^U(\alpha_2))d\alpha_2)\times \ldots \\
&\quad \times(\int_0^1 (X_n^L(\alpha_n)+X_n^U(\alpha_n))d\alpha_n) \\
&= U(X_1)\times U(X_2)\times \ldots \times U(X_n) \\
&= \prod_{i=1}^n U(X_i)
\end{aligned}
$$

Lemma 3.1 Let X_1, X_2, …, X_n be a set of triangular fuzzy numbers, where $X_i = (x_{il}, x_{im}, x_{ir})$, $i = 1, 2, \ldots, n$. Then,

$$
\begin{aligned}
&U'(X_1 \otimes X_2 \otimes \ldots \otimes X_n) \\
&= \prod_{i=1}^n U(X_i) \\
&= \prod_{i=1}^n (\frac{x_{il} + 2x_{im} + x_{ir}}{2}).
\end{aligned}
$$

Lemma 3.2 Let X_1, X_2, …, X_n be a set of trapezoidal fuzzy numbers, where $X_i = (x_{il}, x_{ih}, x_{im}, x_{ir})$, $i = 1, 2, \ldots, n$. Then,

$$
\begin{aligned}
&U'(X_1 \otimes X_2 \otimes \ldots \otimes X_n) \\
&= \prod_{i=1}^n U(X_i) \\
&= \prod_{i=1}^n (\frac{x_{il} + x_{ih} + x_{im} + x_{ir}}{2}).
\end{aligned}
$$

Through the utility representation function of multiplying a set of fuzzy numbers, we develop multi-level FMCDM to evaluate retailer financial performance for supply chain management.

IV. MULTI-LEVEL FMCDM CONSTRUCTED ON THE UTILITY REPRESENTATION FUNCTION OF MULTIPLYING A SET OF FUZZY NUMBERS

To evaluate retailer financial performance for supply chain management, we propose multi-level FMCDM constructed on the utility representation function of multiplying a set of fuzzy numbers. Assume that m retailers A_1, A_2, …, A_m are evaluated on n levels criteria, shown as Fig. 1. The n levels criteria connecting financial performance with m retailers are presented by a hierarchical structure in Fig. 1. In the tth level, C_1^t, $C_2^t, \ldots, C_{n_t}^t$ indicated as Criterion 1(t), Criterion 2(t), …, Criterion $n_t(t)$ in Fig. 1 are evaluation criteria for $t = 1, 2, \ldots, n$, $C_{j_t}^t$ (i.e., Criterion $j_t(t)$) denotes the j_tth criterion for j_t = $1, 2, \ldots, n_t$, and n_t is criteria number of the level.

Therefore, a criterion commonly has several sub-criteria in the next level besides the criteria in the final level. Additionally, each sub-criterion only belongs to a criterion in the previous level. Therefore, we assume that criteria $C_1^t, C_2^t, \ldots, C_{n_t}^t$ in the tth level have sub-criteria in the $(t + 1)$th level as follows:

$$
\begin{aligned}
&C_1^t : C_1^{t+1}, C_2^{t+1}, \ldots, C_{n'_1}^{t+1}; \\
&C_2^t : C_{n'_1+1}^{t+1}, C_{n'_1+2}^{t+1}, \ldots, C_{n'_2}^{t+1}; \\
&\ldots \\
&C_{j_t}^t : C_{n'_{j_t-1}+1}^{t+1}, C_{n'_{j_t-1}+2}^{t+1}, \ldots, C_{n'_{j_t}}^{t+1}; \\
&\ldots \\
&C_{n_t}^t : C_{n'_{n_t-1}+1}^{t+1}, C_{n'_{n_t-1}+2}^{t+1}, \ldots, C_{n'_{n_t}}^{t+1};
\end{aligned}
$$

where

$n'_{j_t} - n'_{j_t-1}$ represents sub-criteria number of $C_{j_t}^t$, for j_t = $1, 2, \ldots, n_t$, and $n'_0 = 0$.

Based on the above,

Table 1. Priority weights of categories derived based on retailer financial performance.

	Priority weights of categories
C_1	(0.556, 0.714, 0.865)
C_2	(0.311, 0.386, 0.533)
C_3	(0.515, 0.533, 0.601)
C_4	(0.322, 0.391, 0.512)

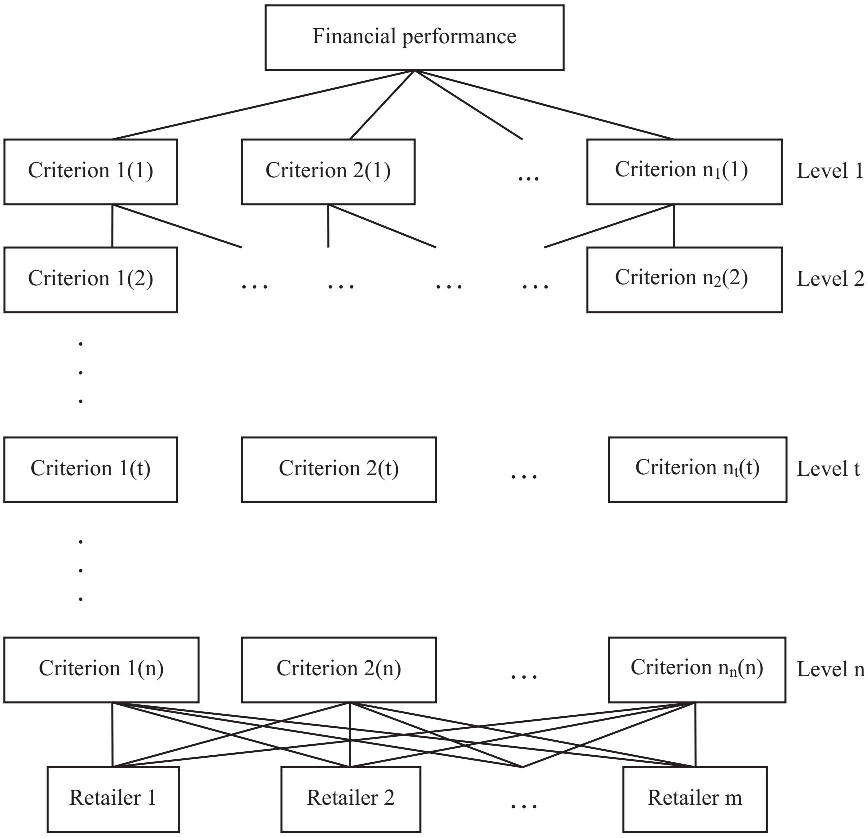

Fig. 1. The hierarchical structure of evaluating retailer financial performance based on *n* levels criteria.

$$\left\{C_1^{t+1}, C_2^{t+1}, \ldots, C_{n'_1}^{t+1}\right\} \cup \left\{C_{n'_1+1}^{t+1}, C_{n'_1+2}^{t+1}, \ldots, C_{n'_2}^{t+1}\right\} \cup \ldots \cup \left\{C_{n'_{n_t-1}+1}^{t+1}, C_{n'_{n_t-1}+2}^{t+1}, \ldots, C_{n'_{n_t}}^{t+1}\right\} = \left\{C_1^{t+1}, C_2^{t+1}, \ldots, C_{n_{t+1}}^{t+1}\right\}$$

and the intersection of any two sets within

$$\left\{C_1^{t+1}, C_2^{t+1}, \ldots, C_{n'_1}^{t+1}\right\}, \left\{C_{n'_1+1}^{t+1}, C_{n'_1+2}^{t+1}, \ldots, C_{n'_2}^{t+1}\right\}, \ldots, \left\{C_{n'_{n_t-1}+1}^{t+1}, C_{n'_{n_t-1}+2}^{t+1}, \ldots, C_{n'_{n_t}}^{t+1}\right\} \text{ will be } \varnothing.$$

Assume $\tilde{G}_{j_n,i} = (g^l_{j_n,i}, g^m_{j_n,i}, g^r_{j_n,i})$ to denote the priority weight of A_i on $C^n_{j_n}$, and $G_{j_n,i}$ to be the normalized value of $\tilde{G}_{j_n,i}$ for $i = 1, 2, \ldots, m$; $j_n = 1, 2, \ldots, n_n$. $G_{j_n,i}$ can be classified into three following situations:

(1) As $\tilde{G}_{j_n,i}$ is evaluated by linguistic terms (Delgado et al., 1992; Herrera et al., 1996) and presented by a fuzzy number in the interval [0, 1], $G_{j_n,i} = \tilde{G}_{j_n,i}$.

(2) As $\tilde{G}_{j_n,i}$ belongs to cost criteria, $G_{j_n,i}$ = $\left(\frac{g^-_{j_n}}{g^r_{j_n,i}}, \frac{g^-_{j_n}}{g^m_{j_n,i}}, \frac{g^-_{j_n}}{g^l_{j_n,i}}\right)$ for $g^-_{j_n} = \min_i\{g^l_{j_n,i}\}$, $\forall j$.

(3) As G belongs to benefit criteria, $G_{j_n,i}$ = $\left(\frac{g^l_{j_n,i}}{g^+_{j_n}}, \frac{g^m_{j_n,i}}{g^+_{j_n}}, \frac{g^r_{j_n,i}}{g^+_{j_n}}\right)$ for $g^+_{j_n} = \max_i\{g^r_{j_n,i}\}$, $\forall j$.

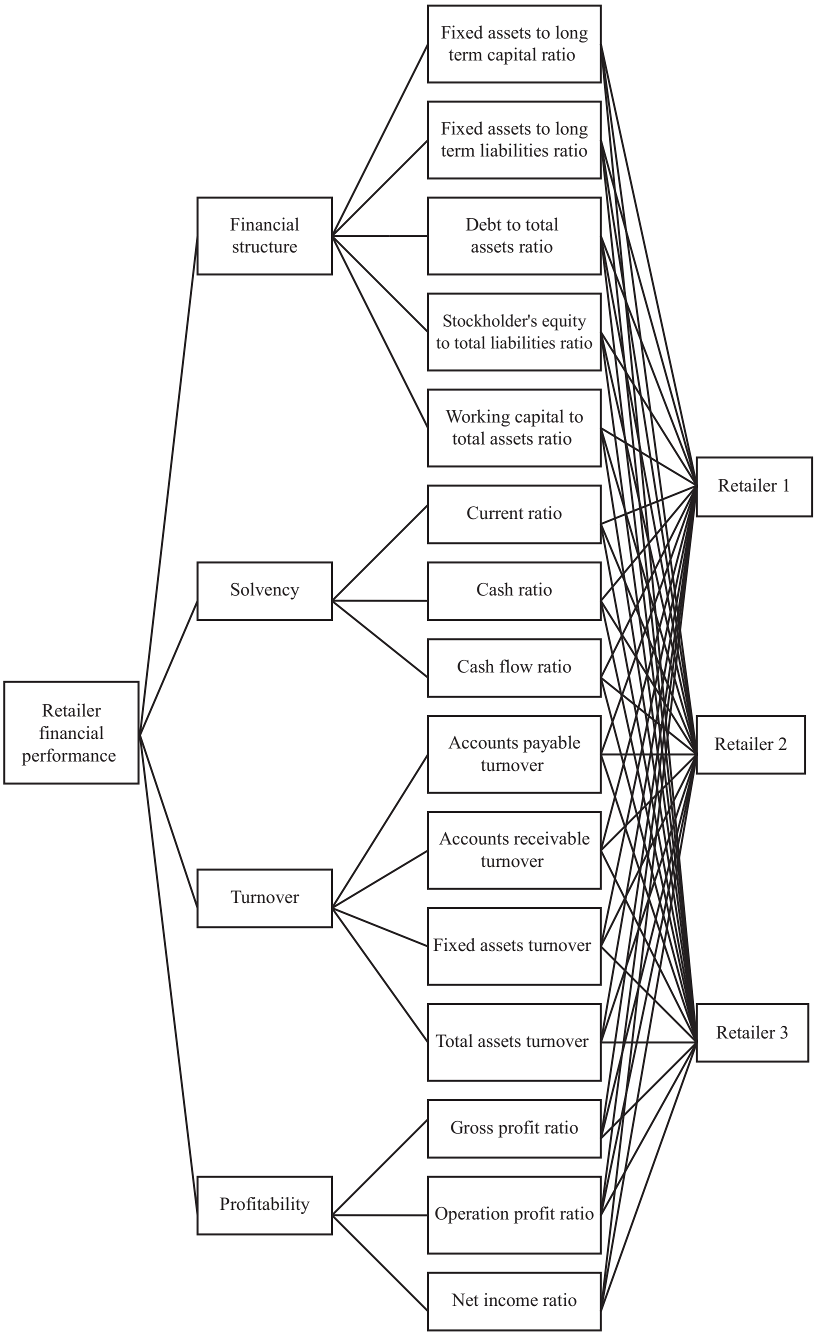

Fig. 2. The hierarchical structure for evaluating retailer financial performance.

Let $W_{j_t}^t = (w_{j_t}^{tl}, w_{j_t}^{tm}, w_{j_t}^{tr})$ indicate priority weight of $C_{j_t}^t$ being from $C_{j_{t-1}}^{t-1}$, where $j_t = 1, 2, \ldots, n_t$. Then financial performance index of the *i*th retailer (i.e., A_i) is yielded as

$$(W_1^1 \otimes W_1^2 \otimes \ldots \otimes W_1^n \otimes G_{1,i}) \oplus \ldots \oplus (W_{n_1}^1 \otimes W_{n_2}^2 \otimes \ldots \otimes W_{n_n}^n \otimes G_{n_n,i})$$

$$= \sum_{\{j_1, j_2, \ldots, j_t, \ldots, j_n\}} (W_{j_1}^1 \otimes W_{j_2}^2 \otimes \ldots \otimes W_{j_t}^t \otimes \ldots \otimes W_{j_n}^n \otimes G_{j_n,i}).$$

By Definition 3.3, we propose an integrated utility representing value of financial performance index of A_i as

$$TU(A_i)$$

$$= \sum_{\{j_1, j_2, \ldots, j_t, \ldots, j_n\}} U'(W_{j_1}^1 \otimes W_{j_2}^2 \otimes \ldots \otimes W_{j_t}^t \otimes \ldots \otimes W_{j_n}^n \otimes G_{j_n,i})$$

$$= \sum_{\{j_1, j_2, \ldots, j_t, \ldots, j_n\}} (U(W_{j_1}^1) \times U(W_{j_2}^2) \times \ldots \times U(W_{j_t}^t) \times \ldots \times U(W_{j_n}^n) \times U(G_{j_n,i})),$$

where $W_{j_1}^1, W_{j_2}^2, \ldots, W_{j_t}^t, \ldots, W_{j_n}^n, G_{j_n,i}$ are fuzzy numbers. The alternatives are then ranked according to their integrated utility

Table 2. Priority weights of financial ratios assessed along the four categories.

	Priority weights of financial ratios
C_{11}	(0.65, 0.95, 1)
C_{12}	(0.55, 0.725, 0.95)
C_{13}	(0.55, 0.725, 0.95)
C_{14}	(0.45, 0.625, 0.775)
C_{15}	(0.45, 0.65, 0.85)
C_{21}	(0.55, 0.725, 0.95)
C_{22}	(0.45, 0.65, 0.85)
C_{23}	(0.45, 0.65, 0.85)
C_{31}	(0.375, 0.55, 0.725)
C_{32}	(0.45, 0.65, 0.85)
C_{33}	(0.525, 0.75, 1)
C_{34}	(0.45, 0.65, 0.85)
C_{41}	(0.55, 0.725, 0.95)
C_{42}	(0.625, 0.95, 1)
C_{43}	(0.625, 0.95, 1)

representing values: $TU(A_1)$, $TU(A_2)$, …, $TU(A_m)$, where $i = 1, 2, \ldots, m$. To clearly describe the multi-level FMCDM, we illustrate a numerical example of evaluating retailer financial performance for supply chain management.

V. A NUMERICAL EXAMPLE OF EVALUATING RETAILER FINANCIAL PERFORMANCE

A numerical example for the evaluation of retailer financial performance in supply chain management is illustrated to clearly demonstrate multi-level FMCDM. Suppose that three candidate chains of retail stories, indicated as retailer 1, retailer 2, and retailer 3, for the supply chain are evaluated according to their financial performance in the illustrating example. From a financial perspective, financial ratios were first classified into four categories (Walter and Robert, 1988; Gu et al., 2017): financial structure (C_1), solvency (C_2), turnover (C_3), and profitability (C_4) in the first level. In the past approaches (Wang and Lee, 2008; 2010), the four categories in the first level were respectively divided into fifteen financial ratios: fixed assets to long term capital ratio (C_{11}), fixed assets to long term liabilities ratio (C_{12}), debt to total assets ratio (C_{13}), stockholder's equity to total liabilities ratio (C_{14}), working capital to total assets ratio (C_{15}), current ratio (C_{21}), cash ratio (C_{22}), cash flow ratio (C_{23}), accounts payable turnover (C_{31}), accounts receivable turnover (C_{32}), fixed assets turnover (C_{33}), total assets turnover (C_{34}), gross profit ratio (C_{41}), operation profit ratio (C_{42}), and net income ratio (C_{43}) in the second level. Therefore, each category is regarded as a criterion within level 1 and its corresponding ratios are sub-criteria in level 2. Additionally, a hierarchical structure connecting categories with their following ratios for the evaluation of retailer financial performance is shown in Fig. 2.

In the hierarchical structure of the figure above, the priority weights of four categories (i.e., criteria): C_1, C_2, C_3, C_4 are derived from the evaluation of retailer financial performance, the priority weights of fifteen financial ratios (i.e., sub-criteria): C_{11}, C_{12}, C_{13}, C_{14}, C_{15}, C_{21}, C_{22}, C_{23}, C_{31}, C_{32}, C_{33}, C_{34}, C_{41}, C_{42}, C_{43} (Walter and Robert, 1988; Wang and Lee, 2010) are respectively assessed through the four categories above, and the priority weights of three candidate retailers Retailer 1, Retailer 2, and Retailer 3 are evaluated based on the varied financial ratios. The three kinds of priority weights are presented by fuzzy numbers in these following tables. First, fuzzy priority weights: $w_1^1, w_2^1, w_3^1, w_4^1$ of the four categories: C_1, C_2, C_3, C_4 derived based on retailer financial performance are shown in Table 1.

Then fuzzy priority weights: $w_{11}^2, w_{12}^2, w_{13}^2, w_{14}^2, w_{15}^2$, w_{21}^2, w_{22}^2, w_{23}^2, $w_{31}^2, w_{32}^2, w_{33}^2, w_{34}^2$, $w_{41}^2, w_{42}^2, w_{43}^2$ of fifteen financial ratios: $C_{11}, C_{12}, C_{13}, C_{14}, C_{15}$, C_{21}, C_{22}, C_{23}, C_{31}, C_{32}, C_{33} C_{34}, C_{41}, C_{42}, C_{43} along the four categories above are assessed and expressed in Table 2.

Finally, fuzzy priority weights: $G_{11,i}, G_{12,i}, G_{13,i}, G_{14,i}, G_{15,i}$, $G_{21,i}, G_{22,i}, G_{23,i}$, $G_{31,i}, G_{32,i}$, $G_{33,i}, G_{34,i}$, $G_{41,i}, G_{42,i}, G_{43,i}$ of the three candidate retailers evaluated on the varied financial ratios are expressed in Table 3, where $i = 1, 2, 3$.

As can be determined from the entries of Tables 1-3, the integrated utility representing values of financial performance indices denoted as TU_1, TU_2, and TU_3 for the three retailers become evident. Obviously, the following computations of integrated utility representing values and ones of Section 4 are not all the same in algebraic expression. For demonstrated convenience and consistent description in this section, these computations of integrated utility representing values are slightly modified

Table 3. Normalized priority weights of retailers evaluated on the financial ratios.

	Priority weights of retailers		
	Retailer 1	Retailer 2	Retailer 3
C_{11}	(0.257, 0.364, 0.562)	(0.612, 0.805, 0.905)	(0.324, 0.425, 0.559)
C_{12}	(0.169, 0.534, 0.891)	(0.296, 0.506, 0.751)	(0.345, 0.564, 0.854)
C_{13}	(0.133, 0.377, 0.790)	(0.453, 0.714, 0.951)	(0.278, 0.438, 0.832)
C_{14}	(0.219, 0.602, 0.815)	(0.394, 0.556, 0.757)	(0.425, 0.507, 0.616)
C_{15}	(0.260, 0.328, 0.778)	(0.439, 0.678, 0.980)	(0.134, 0.403, 0.640)
C_{21}	(0.643, 0.792, 0.866)	(0.310, 0.414, 0.525)	(0.371, 0.430, 0.558)
C_{22}	(0.276, 0.352, 0.453)	(0.604, 0.753, 0.837)	(0.455, 0.536, 0.713)
C_{23}	(0.471, 0.527, 0.595)	(0.628, 0.708, 0.782)	(0.408, 0.462, 0.549)
C_{31}	(0.296, 0.310, 0.326)	(0.686, 0.711, 0.743)	(0.590, 0.630, 0.664)
C_{32}	(0.271, 0.318, 0.350)	(0.445, 0.555, 0.706)	(0.630, 0.755, 0.829)
C_{33}	(0.206, 0.265, 0.316)	(0.281, 0.541, 0.846)	(0.480, 0.732, 0.912)
C_{34}	(0.543, 0.584, 0.646)	(0.530, 0.568, 0.660)	(0.510, 0.573, 0.650)
C_{41}	(0.231, 0.263, 0.311)	(0.393, 0.500, 0.634)	(0.738, 0.819, 0.887)
C_{42}	(0.454, 0.554, 0.627)	(0.425, 0.585, 0.655)	(0.426, 0.571, 0.681)
C_{43}	(0.382, 0.492, 0.569)	(0.339, 0.574, 0.810)	(0.340, 0.596, 0.767)

in algebraic expression:

$$
\begin{aligned}
TU_1 &= \sum\nolimits_{\{1\le\alpha\le4,1\le\beta\le5\}} U'(W_\alpha^1 \otimes W_{\alpha\beta}^2 \otimes G_{\alpha\beta,1}) \\
&= \sum\nolimits_{\{1\le\alpha\le4,1\le\beta\le5\}} (U(W_\alpha^1)\times U(W_{\alpha\beta}^2)\times U(G_{\alpha\beta,1})) \\
&= U(W_1^1)\times U(W_{11}^2)\times U(G_{11,1}) + U(W_1^1)\times U(W_{12}^2)\times U(G_{12,1}) \\
&\quad + U(W_1^1)\times U(W_{13}^2)\times U(G_{13,1}) + U(W_1^1)\times U(W_{14}^2)\times U(G_{14,1}) \\
&\quad + U(W_1^1)\times U(W_{15}^2)\times U(G_{15,1}) + U(W_2^1)\times U(W_{21}^2)\times U(G_{21,1}) \\
&\quad + U(W_2^1)\times U(W_{22}^2)\times U(G_{22,1}) + U(W_2^1)\times U(W_{23}^2)\times U(G_{23,1}) \\
&\quad + U(W_3^1)\times U(W_{31}^2)\times U(G_{31,1}) + U(W_3^1)\times U(W_{32}^2)\times U(G_{32,1}) \\
&\quad + U(W_3^1)\times U(W_{33}^2)\times U(G_{33,1}) + U(W_3^1)\times U(W_{34}^2)\times U(G_{34,1}) \\
&\quad + U(W_4^1)\times U(W_{41}^2)\times U(G_{41,1}) + U(W_4^1)\times U(W_{42}^2)\times U(G_{42,1}) \\
&\quad + U(W_4^1)\times U(W_{43}^2)\times U(G_{43,1}) \\
&= U((0.556, 0.714, 0.865))\times U((0.65, 0.95, 1))\times U((0.257, 0.364, 0.562)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.55, 0.725, 0.95))\times U((0.169, 0.534, 0.891)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.55, 0.725, 0.95))\times U((0.133, 0.377, 0.790)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.45, 0.625, 0.775))\times U((0.219, 0.602, 0.815)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.45, 0.65, 0.85))\times U((0.260, 0.328, 0.778)) \\
&\quad + U((0.311, 0.386, 0.533))\times U((0.55, 0.725, 0.95))\times U((0.643, 0.792, 0.866)) \\
&\quad + U((0.311, 0.386, 0.533))\times U((0.45, 0.65, 0.85))\times U((0.276, 0.352, 0.453)) \\
&\quad + U((0.311, 0.386, 0.533))\times U((0.45, 0.65, 0.85))\times U((0.471, 0.527, 0.595)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.375, 0.55, 0.725))\times U((0.296, 0.310, 0.326)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.45, 0.65, 0.85))\times U((0.271, 0.318, 0.350)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.525, 0.75, 1))\times U((0.206, 0.265, 0.316)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.45, 0.65, 0.85))\times U((0.543, 0.584, 0.646)) \\
&\quad + U((0.322, 0.391, 0.512))\times U((0.55, 0.725, 0.95))\times U((0.231, 0.263, 0.311)) \\
&\quad + U((0.322, 0.391, 0.512))\times U((0.625, 0.95, 1))\times U((0.454, 0.554, 0.627)) \\
&\quad + U((0.322, 0.391, 0.512))\times U((0.625, 0.95, 1))\times U((0.382, 0.492, 0.569)) \\
&= 20.952
\end{aligned}
$$

$$
\begin{aligned}
TU_2 &= \sum\nolimits_{\{1\le\alpha\le4,1\le\beta\le5\}} U'(W_\alpha^1 \otimes W_{\alpha\beta}^2 \otimes G_{\alpha\beta,2}) \\
&= \sum\nolimits_{\{1\le\alpha\le4,1\le\beta\le5\}} (U(W_\alpha^1)\times U(W_{\alpha\beta}^2)\times U(G_{\alpha\beta,2})) \\
&= U(W_1^1)\times U(W_{11}^2)\times U(G_{11,2}) + U(W_1^1)\times U(W_{12}^2)\times U(G_{12,2}) \\
&\quad + U(W_1^1)\times U(W_{13}^2)\times U(G_{13,2}) + U(W_1^1)\times U(W_{14}^2)\times U(G_{14,2}) \\
&\quad + U(W_1^1)\times U(W_{15}^2)\times U(G_{15,2}) + U(W_2^1)\times U(W_{21}^2)\times U(G_{21,2}) \\
&\quad + U(W_2^1)\times U(W_{22}^2)\times U(G_{22,2}) + U(W_2^1)\times U(W_{23}^2)\times U(G_{23,2}) \\
&\quad + U(W_3^1)\times U(W_{31}^2)\times U(G_{31,2}) + U(W_3^1)\times U(W_{32}^2)\times U(G_{32,2}) \\
&\quad + U(W_3^1)\times U(W_{33}^2)\times U(G_{33,2}) + U(W_3^1)\times U(W_{34}^2)\times U(G_{34,2}) \\
&\quad + U(W_4^1)\times U(W_{41}^2)\times U(G_{41,2}) + U(W_4^1)\times U(W_{42}^2)\times U(G_{42,2}) \\
&\quad + U(W_4^1)\times U(W_{43}^2)\times U(G_{43,2}) \\
&= U((0.556, 0.714, 0.865))\times U((0.65, 0.95, 1))\times U((0.612, 0.805, 0.905)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.55, 0.725, 0.95))\times U((0.296, 0.506, 0.751)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.55, 0.725, 0.95))\times U((0.453, 0.714, 0.951)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.45, 0.625, 0.775))\times U((0.394, 0.556, 0.757)) \\
&\quad + U((0.556, 0.714, 0.865))\times U((0.45, 0.65, 0.85))\times U((0.439, 0.678, 0.980)) \\
&\quad + U((0.311, 0.386, 0.533))\times U((0.55, 0.725, 0.95))\times U((0.310, 0.414, 0.525)) \\
&\quad + U((0.311, 0.386, 0.533))\times U((0.45, 0.65, 0.85))\times U((0.604, 0.753, 0.837)) \\
&\quad + U((0.311, 0.386, 0.533))\times U((0.45, 0.65, 0.85))\times U((0.628, 0.708, 0.782)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.375, 0.55, 0.725))\times U((0.686, 0.711, 0.743)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.45, 0.65, 0.85))\times U((0.445, 0.555, 0.706)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.525, 0.75, 1))\times U((0.281, 0.541, 0.846)) \\
&\quad + U((0.515, 0.533, 0.601))\times U((0.45, 0.65, 0.85))\times U((0.530, 0.568, 0.660)) \\
&\quad + U((0.322, 0.391, 0.512))\times U((0.55, 0.725, 0.95))\times U((0.393, 0.500, 0.634)) \\
&\quad + U((0.322, 0.391, 0.512))\times U((0.625, 0.95, 1))\times U((0.425, 0.585, 0.655)) \\
&\quad + U((0.322, 0.391, 0.512))\times U((0.625, 0.95, 1))\times U((0.339, 0.574, 0.810)) \\
&= 28.910
\end{aligned}
$$

$$TU_3 = \sum_{\{1\le\alpha\le4,1\le\beta\le5\}} U'(W_\alpha^1 \otimes W_{\alpha\beta}^2 \otimes G_{\alpha\beta,3})$$
$$= \sum_{\{1\le\alpha\le4,1\le\beta\le5\}} (U(W_\alpha^1)\times U(W_{\alpha\beta}^2)\times U(G_{\alpha\beta,3}))$$
$$= U(W_1^1)\times U(W_{11}^2)\times U(G_{11,3}) + U(W_1^1)\times U(W_{12}^2)\times U(G_{12,3})$$
$$+U(W_1^1)\times U(W_{13}^2)\times U(G_{13,3}) + U(W_1^1)\times U(W_{14}^2)\times U(G_{14,3})$$
$$+U(W_1^1)\times U(W_{15}^2)\times U(G_{15,3}) + U(W_2^1)\times U(W_{21}^2)\times U(G_{21,3})$$
$$+U(W_2^1)\times U(W_{22}^2)\times U(G_{22,3}) + U(W_2^1)\times U(W_{23}^2)\times U(G_{23,3})$$
$$+U(W_3^1)\times U(W_{31}^2)\times U(G_{31,3}) + U(W_3^1)\times U(W_{32}^2)\times U(G_{32,3})$$
$$+U(W_3^1)\times U(W_{33}^2)\times U(G_{33,3}) + U(W_3^1)\times U(W_{34}^2)\times U(G_{34,3})$$
$$+U(W_4^1)\times U(W_{41}^2)\times U(G_{41,3}) + U(W_4^1)\times U(W_{42}^2)\times U(G_{42,3})$$
$$+U(W_4^1)\times U(W_{43}^2)\times U(G_{43,3})$$
$$= U((0.556, 0.714, 0.865))\times U((0.65, 0.95, 1))\times U((0.324, 0.425, 0.559))$$
$$+U((0.556, 0.714, 0.865))\times U((0.55, 0.725, 0.95))\times U((0.345, 0.564, 0.854))$$
$$+U((0.556, 0.714, 0.865))\times U((0.55, 0.725, 0.95))\times U((0.278, 0.438, 0.832))$$
$$+U((0.556, 0.714, 0.865))\times U((0.45, 0.625, 0.775))\times U((0.425, 0.507, 0.616))$$
$$+U((0.556, 0.714, 0.865))\times U((0.45, 0.65, 0.85))\times U((0.134, 0.403, 0.640))$$
$$+U((0.311, 0.386, 0.533))\times U((0.55, 0.725, 0.95))\times U((0.371, 0.430, 0.558))$$
$$+U((0.311, 0.386, 0.533))\times U((0.45, 0.65, 0.85))\times U((0.455, 0.536, 0.713))$$
$$+U((0.311, 0.386, 0.533))\times U((0.45, 0.65, 0.85))\times U((0.408, 0.462, 0.549))$$
$$+U((0.515, 0.533, 0.601))\times U((0.375, 0.55, 0.725))\times U((0.590, 0.630, 0.664))$$
$$+U((0.515, 0.533, 0.601))\times U((0.45, 0.65, 0.85))\times U((0.630, 0.755, 0.829))$$
$$+U((0.515, 0.533, 0.601))\times U((0.525, 0.75, 1))\times U((0.480, 0.732, 0.912))$$
$$+U((0.515, 0.533, 0.601))\times U((0.45, 0.65, 0.85))\times U((0.510, 0.573, 0.650))$$
$$+U((0.322, 0.391, 0.512))\times U((0.55, 0.725, 0.95))\times U((0.738, 0.819, 0.887))$$
$$+U((0.322, 0.391, 0.512))\times U((0.625, 0.95, 1))\times U((0.426, 0.571, 0.681))$$
$$+U((0.322, 0.391, 0.512))\times U((0.625, 0.95, 1))\times U((0.340, 0.596, 0.767))$$
$$= 26.015$$

The ranking order of the three retailers is $A_2 > A_3 > A_1$ due to TU_2 (28.910) > TU_3 (26.015) > TU_1 (20.952) as derived by the integrated utility representation computation. Therefore, Retailer 2 has the best financial performance of the three retailers. By multi-level FMCDM, the three retailers in supply chain management are easily ranked under an uncertain environment.

VI. CONCLUSIONS

In this paper, we proposed multi-level FMCDM to evaluate retailer financial performance of supply chain management under an uncertain environment, and illustrate a numerical example to clearly demonstrate the FMCDM. In the illustrating example, the priority weights of financial categories, financial ratios and retailers on their related evaluation items are expressed by fuzzy numbers. To evaluate retailer financial performance of supply chain management, we yielded utility representing values by multiplying three fuzzy numbers in a finance hierarchical structure and then integrated these values into the total utility, representing ones for ranking retailers by multi-level FMCDM. Generally, multiplying three fuzzy numbers is difficult. The multi-level FMCDM can provide an easy computation to derive utility representing values of multiplying fuzzy numbers; thus, total utility representing values of retailer financial performance indices are quickly obtained. Besides, the utility representing value of multiplying four or more fuzzy numbers is also easily derived by multi-level FMCDM as the evaluation problem is necessary, and not merely for multiplying three fuzzy numbers as in the computation in the above example.

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