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A Fuzzy MCDM Framework Based on Fuzzy Measure and Fuzzy Integral for Agile Supplier Evaluation

Mehtap Dursun

Galatasaray University, Industrial Engineering Department, Ortaköy, Istanbul, Turkey
mdursun@gsu.edu.tr

Abstract. Supply chains need to be agile in order to response quickly to the changes in today's competitive environment. The success of an agile supply chain depends on the firm's ability to select the most appropriate suppliers. This study proposes a multi-criteria decision making technique for conducting an analysis based on multi-level hierarchical structure and fuzzy logic for the evaluation of agile suppliers. The ideal and anti-ideal solutions are taken into consideration simultaneously in the developed approach. The proposed decision approach enables the decision-makers to use linguistic terms, and thus, reduce their cognitive burden in the evaluation process. Furthermore, a hierarchy of evaluation criteria and their related sub-criteria is employed in the presented approach in order to conduct a more effective analysis.

Keywords. Agile suppler evaluation, fuzzy integral, fuzzy set theory, hierarchical multi-criteria decision making

INTRODUCTION

Supply chain is composed of a complex sequence of processing stages, ranging from raw materials supplies, parts manufacturing, components and end-products assembling, to the delivery of end products. Supply chain is an integrated network that links suppliers, production centers, warehouses, distribution centers, retail shops, raw materials, in-process inventories, and the flow of finished products. Recently, industries face significant changes especially in marketing competition, technological innovation, and customer demands. Situations and possibilities are varied and organizations are responsible for adapting themselves to this various cases. These changes lead to necessity of a new concept called as 'Agility'. Supply chain agility becomes a requirement that refers to firm's ability to quickly respond or adopt to changes, opportunities or threats in the environment [1]. In this regard, it can be said that supply chain agility is needed in the sharply competitive markets that includes high scale of variety.

This study aims to develop a fuzzy multi-criteria decision making approach for evaluating agile suppliers. Supplier evaluation process requires the consideration of multiple conflicting criteria, yielding in a multi-level hierarchical structure, incorporating vagueness and imprecision with the involvement of a group of experts. Fuzzy set theory is one of the effective tools to deal with uncertainty and vagueness in criteria values. The objective of this study is to propose a hierarchical fuzzy multi-criteria decision making methodology for agile supplier evaluation.

In the literature, there are a few papers that evaluate agile suppliers. Wu et al. [2] proposed a two-stage approach, based on the application of analytic network process (ANP) and mixed integer multi-objective programming model, to solve the problem of partner selection in agile supply chains. Wu and Barnes [3] presented a four phase dynamic feedback model for supply partner selection in agile supply chains. Alminardi et al. [4] combined SWARA and VIKOR for supplier selection in an agile environment. Abdollahi et al. [5] integrated analytic network process (ANP) and data envelopment analysis (DEA), and DEMATEL method for evaluating suppliers considering lean and agile criteria. Lee et al. [6] employed fuzzy AHP and fuzzy TOPSIS to select suppliers. Beikkhakhian et al. [7] identified the criteria to evaluate agile suppliers and then they used fuzzy TOPSIS to rank alternative suppliers.

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The rest of the paper is organized as follows. The following section gives a brief explication of fuzzy set theory and fuzzy integral. Section 3 presents the proposed fuzzy decision making algorithm. The application of the proposed methodology is illustrated in Section 4. Finally, conclusions are provided in Section 5.

FUZZY SET THEORY AND FUZZY INTEGRAL

Fuzzy set theory was introduced by Zadeh [8] to express factors, which can be addressed by neither crisp values nor random process, in an effective way. A fuzzy set $\tilde{A}$ can be defined mathematically by a membership function $\mu_{\tilde{A}}(x)$, which assigns each element x in the universe of discourse X a real number in the interval [0,1].

A convex and normalized fuzzy set defined on $\Re$ whose membership function is piecewise continuous is called a fuzzy number. A triangular fuzzy number $\tilde{A}$ can be defined by a triplet (a_1, a_2, a_3) with the membership function given as

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2, \\ \dfrac{x-a_3}{a_2-a_3}, & a_2 \le x \le a_3, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

The distance between the triangular fuzzy numbers $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$ can be calculated using a distance measure as follows [9]:

$$d_v(\tilde{A}, \tilde{B}) = \frac{1}{2}\left\{\max\left(|a_1 - b_1|, |a_3 - b_3|\right) + |a_2 - b_2|\right\} \quad (2)$$

The distance formula provides the size of the trapezoidal area with lower base given by the larger value of $|a_1 - b_1|$ or $|a_3 - b_3|$, upper base given by $|a_2 - b_2|$, and height equal to one. Smaller the trapezoidal area, closer are the triangular fuzzy numbers $\tilde{A}$ and $\tilde{B}$.

In the following, basic notation and definitions regarding fuzzy measure and fuzzy integral are provided.

Definition 1. Consider a set of n evaluation criteria $K = \{s_1, s_2, ..., s_n\}$. If a function $g: 2^K \to [0,1]$ has the following properties, g is called a fuzzy measure [10].

$$(1)\ g(\phi) = 0, \quad g(K) = 1 \quad (3)$$

$$(2)\ A, B \in 2^K, \quad A \subset B \to g(A) \le g(B) \quad (4)$$

The triplet $(K, 2^K, g)$ is called a fuzzy measure space.

Definition 2. If a fuzzy measure g has the following properties, then g is a λ-measure [10]. If $A, B \in 2^K$ and $A \cap B = \phi$, then

$$g(A \cup B) = g(A) + g(B) + \lambda g(A) g(B) \quad (5)$$

where $\lambda \in [-1, \infty)$.

The value of λ is determined by solving the following equation [11]

$$\lambda + 1 = \prod_{j=1}^{n} \left(1 + \lambda g^{j}\right) \tag{6}$$

Although $(n-1)$ roots will be obtained, there exists only a unique $\lambda \in [-1, \infty)$, and $\lambda \neq 0$, which satisfies Eq. (6).

Definition 3. Consider a fuzzy measure space $\left(K, 2^{K}, g\right)$ The fuzzy integral of a function $h : K \to [0,1]$ with respect to g is defined as follows [10].

$$\int_{K} h(s) \cdot g(\cdot) = \bigvee_{j=1}^{n} \left[h\left(s_j\right) \wedge g\left(K_j\right) \right] \tag{7}$$

where

$$h\left(s_j\right) \leq h\left(s_j + 1\right), \quad \text{for } 1 \leq j \leq n-1$$
$$K_j = \left\{s_1, s_2, ..., s_j\right\}, \quad j = 1, 2, ..., n.$$

The values of $g\left(K_j\right)$ can be determined recursively as [11]

$$\begin{aligned} &g\left(K_1\right) = g\left(\left\{s_1\right\}\right) = g^{1}, \\ &g\left(K_j\right) = g^{j} + g\left(K_{j-1}\right) + \lambda g^{j} g\left(K_{j-1}\right), \quad \text{for } 1 < j \leq n \end{aligned} \tag{8}$$

where $g^{j} = g\left(\left\{s_j\right\}\right)$, g^{j} is called the *j*th fuzzy density and interpreted as the degree of importance of the evaluation criteria s_j, $j = 1,2,...,n$. In addition, the value of λ is determined by solving Eq. (6).

FUZZY DECISION MAKING FRAMEWORK BASED ON FUZZY MEASURE AND FUZZY INTEGRAL

Real-world decision problems such as the supplier selection often involve the consideration of numerous performance attributes. When a large number of performance attributes are to be considered in the evaluation process, it may be preferred to structure them in a multi-level hierarchy in order to conduct a more effective analysis.

This study employs a fuzzy MCDM methodology based on the principles of fuzzy measure and fuzzy integral for the evaluation of agile suppliers. The decision making framework employs a hierarchy of evaluation criteria and their related sub-criteria to conduct a more effective analysis. The problem is structured as a hierarchy that shows the criteria and sub-criteria and their relationships. This approach enables to consider imprecise data by the use of fuzzy set theory. Moreover, as individuals attempt to be both as close as possible to the ideal and as distant as possible from the anti-ideal, ideal and anti-ideal solutions are considered simultaneously in the decision making approach.

***Step* 1.** Construct the decision matrix that denotes the fuzzy assessments corresponding to qualitative sub-criteria and the crisp values corresponding to quantitative sub-criteria for the considered alternatives. Let the fuzzy value assigned to alternative i $(i = 1,2,...,m)$ with respect to sub-criterion k $(k = 1,2,..., p)$ of criterion j $(j = 1,2,...,n)$, importance weight of sub-criterion *k* of criterion *j*, and importance weight of criterion *j* be $\tilde{x}_{ijk} = (x_{ijk}^{1}, x_{ijk}^{2}, x_{ijk}^{3})$, $\tilde{w}_{jk} = (w_{jk}^{1}, w_{jk}^{2}, w_{jk}^{3})$ and $\tilde{w}_{j} = (w_{j}^{1}, w_{j}^{2}, w_{j}^{3})$, respectively. If there exist crisp data x_{ijk}, it can be represented as $\tilde{x}_{ijk} = (x_{ijk}^{1}, x_{ijk}^{2}, x_{ijk}^{3})$ in triangular fuzzy number format, where $x_{ijk} = x_{ijk}^{1} = x_{ijk}^{2} = x_{ijk}^{3}$.

***Step* 2.** Normalize the decision matrix to obtain unit-free and comparable sub-criteria values. The normalized values for the data regarding benefit-related as well as cost-related sub-criteria are calculated via a linear scale transformation as

$$\tilde{r}_{ijk}=\left(r_{ijk}^{1},r_{ijk}^{2},r_{ijk}^{3}\right)=\begin{cases}\left(\dfrac{x_{ijk}^{1}-x_{jk}^{-}}{x_{jk}^{*}-x_{jk}^{-}},\dfrac{x_{ijk}^{2}-x_{jk}^{-}}{x_{jk}^{*}-x_{jk}^{-}},\dfrac{x_{ijk}^{3}-x_{jk}^{-}}{x_{jk}^{*}-x_{jk}^{-}}\right), \\ k\in CB_j;\ i=1,2,\ldots,m;\ j=1,2,\ldots,n \\ \left(\dfrac{x_{jk}^{*}-x_{ijk}^{3}}{x_{jk}^{*}-x_{jk}^{-}},\dfrac{x_{jk}^{*}-x_{ijk}^{2}}{x_{jk}^{*}-x_{jk}^{-}},\dfrac{x_{jk}^{*}-x_{ijk}^{1}}{x_{jk}^{*}-x_{jk}^{-}}\right), \\ k\in CC_j;\ i=1,2,\ldots,m;\ j=1,2,\ldots,n\end{cases} \quad (9)$$

where $\tilde{r}_{ijk}$ denotes the normalized value of $\tilde{x}_{ijk}$, $x_{jk}^{*}=\max_i x_{ijk}^{3}$, $x_{jk}^{-}=\min_i x_{ijk}^{1}$, m is the number of alternatives, n is the number of criteria, CB_j is the set of benefit-related sub-criteria of criterion j for which the greater the performance value the more its preference, and CC_j is the set of cost-related sub-criteria of criterion j for which the greater the performance value the less its preference.

***Step* 3.** Define the fuzzy max rating $\tilde{P}^{*}$ and fuzzy min rating $\tilde{P}^{-}$, and compute the distance between $\tilde{w}_{jk}$ and $\tilde{P}^{*}$ as $wd_{jk}^{*}=d_v\left(\tilde{w}_{jk},\tilde{P}^{*}\right)$, $\tilde{w}_j$ and $\tilde{P}^{*}$ as $wd_{j}^{*}=d_v\left(\tilde{w}_{j},\tilde{P}^{*}\right)$, and $\tilde{r}_{ijk}$ and $\tilde{P}^{*}$ as $d_{ijk}^{*}=d_v\left(\tilde{r}_{ijk},\tilde{P}^{*}\right)$. Similarly, the distance between $\tilde{w}_{jk}$ and $\tilde{P}^{-}$, $\tilde{w}_j$ and $\tilde{P}^{-}$, and $\tilde{r}_{ijk}$ and $\tilde{P}^{-}$ are computed as $wd_{jk}^{-}=d_v\left(\tilde{w}_{jk},\tilde{P}^{-}\right)$, $wd_{j}^{-}=d_v\left(\tilde{w}_{j},\tilde{P}^{-}\right)$, and $d_{ijk}^{-}=d_v\left(\tilde{r}_{ijk},\tilde{P}^{-}\right)$, respectively. For all these computations, $d_v(*,*)$ denotes the distance between two fuzzy numbers, which can be calculated by using Eq. (2).

***Step* 6.** Compute the transformation values of fuzzy weights of all sub-criteria and criteria respectively as [12]

$$RW_{jk}=\frac{wd_{jk}^{-}}{wd_{jk}^{-}+wd_{jk}^{*}} \quad (10)$$

and

$$RW_{j}=\frac{wd_{j}^{-}}{wd_{j}^{-}+wd_{j}^{*}} \quad (11)$$

***Step* 7.** Compute the transformation values of all normalized fuzzy assessments as [12]

$$RI_{ijk}=\frac{d_{ijk}^{-}}{d_{ijk}^{-}+d_{ijk}^{*}} \quad (12)$$

***Step* 8.** Calculate the λ value of fuzzy measures and fuzzy integral (FI) values of all alternatives with respect to each criterion using Eqs. (6)-(8). In Eqs. (7) and (8), the function h is represented as the transformation values of normalized fuzzy assessments $\left(RI_{ijk}\right)$, and $g(K_1)=g^{1}=RW_1$.

***Step* 9.** Compute the final λ value and the final fuzzy integral values of alternatives.

***Step* 10.** Rank the alternatives according to the final fuzzy integral values in descending order.

CASE STUDY

In order to illustrate the application of the proposed decision making method, a case study conducted in a private hospital on the Asian side of Istanbul is presented. Benefiting from the literature, management capability,

manufacturing capability, collaboration capability, and agility, and their related sub-criteria are identified as the selection attributes as in Table 1.

TABLE 1. Criteria and related sub-criteria

Main criteria	Sub-criteria
Management capability (C_1)	Management and Organization (C_{11})
	Financial position (C_{12})
	Customer relation (C_{13})
	Training aids (C_{14})
	Reputation (C_{15})
Manufacturing capability (C_2)	Production capacity (C_{21})
	Product diversity (C_{22})
	R&D (C_{23})
	Quality (C_{24})
Collaboration capability (C_3)	Delivery reliability (C_{31})
	Warranties and claim policies (C_{32})
Agility (C_4)	Delivery speed (C_{41})
	Delivery flexibility (C_{42})
	Agile customer responsiveness (C_{43})
	Collaboration with partners (C_{44})
	Make flexibility (C_{45})
	Source flexibility (C_{46})

The expert used the linguistic variables given in Figure 1 to evaluate the importance of the criteria and sub-criteria, and also the ratings of alternatives with respect to various subjective criteria and sub-criteria. There are 4 suppliers who are in contact with the hospital.

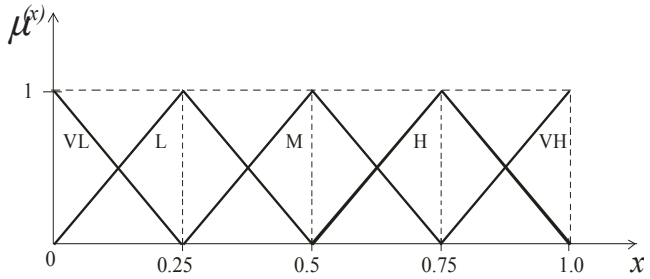


FIGURE 1. A linguistic term set where VL = (0, 0, 0.25), L = (0, 0.25, 0.5), M = (0.25, 0.5, 0.75), H = (0.5, 0.75, 1), VH = (0.75, 1, 1)

The evaluations are represented in Tables 2, 3, and 4.

TABLE 2. Importance weights of criteria

Criteria	Importance weight
C_1	H
C_2	H
C_3	M
C_4	VH

TABLE 3. Importance weights of sub-criteria

Sub-Criteria	Importance weight
C_{11}	VH
C_{12}	H
C_{13}	VH
C_{14}	M
C_{15}	H
C_{21}	H
C_{22}	VH
C_{23}	H
C_{24}	VH
C_{31}	H
C_{32}	H
C_{41}	H
C_{42}	H
C_{43}	VH
C_{44}	H
C_{45}	VH
C_{46}	VH

TABLE 4. Data related to agile supplier evaluation problem

Sub-Criteria	S_1	S_2	S_3	S_4
C_{11}	M	M	M	H
C_{12}	VL	L	L	VH
C_{13}	VH	VH	VH	VH
C_{14}	M	H	H	H
C_{15}	VL	VL	VL	VL
C_{21}	VH	H	H	L
C_{22}	VH	H	H	M
C_{23}	M	M	L	H
C_{24}	L	L	M	M
C_{31}	VH	H	H	M
C_{32}	VH	H	H	M
C_{41}	VH	H	H	L
C_{42}	H	H	H	VH
C_{43}	H	H	H	H
C_{44}	M	M	H	H
C_{45}	H	VH	H	VH
C_{46}	H	M	M	H

The fuzzy max rating $\widetilde{P}^*$ and fuzzy min rating $\widetilde{P}^-$ are defined as $\widetilde{P}^* = (1,1,1)$ and $\widetilde{P}^- = (0,0,0)$, respectively. Then, using Eqs. (2), (10) and (11), the transformation values of fuzzy weights of sub-criteria and criteria are computed as in Table 5.

TABLE 5. Transformation values of fuzzy weights of all criteria and related sub-criteria

Criteria / Sub-Criteria	Transformation weights
C_1	0.700
C_{11}	0.778
C_{12}	0.556
C_{13}	0.778
C_{14}	0.333
C_{15}	0.556
C_2	0.700
C_{21}	0.556
C_{22}	0.778
C_{23}	0.556
C_{24}	0.778
C_{25}	0,333
C_3	0.500
C_{31}	0.556
C_{32}	0.556
C_4	0.889
C_{41}	0.556
C_{42}	0.556
C_{43}	0.778
C_{44}	0.556
C_{45}	0.778
C_{46}	0.778

The transformation values of all normalized fuzzy ratings are calculated by utilizing Eqs. (2) and (12). By using Eqs. (6)-(8), the λ values of fuzzy measures and fuzzy integral values of all alternatives with respect to each criterion are computed. The final λ value is calculated as $\lambda = -0.995$. The ranking order of the alternatives is $S_1 \succ S_4 \succ S_2 \succ S_3$.

According to the results of the analysis, supplier 1 is determined as the most suitable supplier, which is followed by supplier 4. Supplier 3 is ranked at the bottom due to inadequate financial position, reputation, and R&D.

CONCLUSIONS

In this study, a multi-criteria decision making technique based on fuzzy logic for the evaluation of agile suppliers is proposed. The ideal and anti-ideal solutions are taken into consideration simultaneously in the developed approach to account for the individuals' desire to be both as close as possible to the ideal and as distant as possible from the anti-ideal. In classical MCDM methods, the ratings and the weights of the criteria are assumed to be known precisely. In general, crisp data are inadequate to model real-life situations. The proposed decision approach enables the decision-makers to use linguistic terms, and thus, reduce their cognitive burden in the evaluation process.

Furthermore, a hierarchy of evaluation criteria and their related sub-criteria is employed in the presented approach in order to conduct a more effective analysis.

Further researches might focus on the extensions of the proposed methodology by employing both subjective and objective weight assessments of the criteria and related sub-criteria.

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