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INTERVAL TYPE-2 FUZZY RULE-BASED BWM APPROACH FOR SUSTAINABLE SUPPLIER SELECTION

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ABSTRACT: Fuzzy logic is a theory based on human-specific approximate reasoning. Therefore, fuzzy logic applications can bring simple and more effective solutions to situations that classical methods cannot overcome. The type-1 fuzzy set is a set, which has a continuous (crisp) membership degree to which a membership degree between 0 and 1 is assigned, and is characterised by membership functions. Type-2 fuzzy sets, which have the power to express uncertainty better, are expressed by membership functions, where the membership degrees of each element belonging to that set also specify a fuzzy set.Therefore, type-2 fuzzy sets allow us to include the membership functions uncertainty in fuzzy set theory. Using expert knowledge and using sensitivity of human to reflect the level of the decision maker influence is expressed as a fuzzy rule based system. Recently, it has been seen that fuzzy rules are frequently used together with multi-criteria decision making (MCDM) methods. Again, combining fuzzy rules with type-2 fuzzy numbers is also found. In this study, the Best Worst Method (BWM), one of the MCDM methods, has been integrated with fuzzy rules based interval type-2. The developed hybrid method was defined as Interval Type-2 Fuzzy Rule-Based BWM (IT2 FRB BWM). The proposed hybrid method has an important place when there are alternatives with similar ranking positions. Thus, even if there is a small difference in each alternative, it will show the difference better (more sensitively). This makes the proposed hybrid method forceful and unique.The proposed approach has been applied to a sustainable supplier selection problem comparatively with the BWM. The results show that the IT2 FRB BWM approach is more successful in ordering alternatives than the classical BWM method.

Keywords: *BWM, Interval Type-2 Fuzzy Sets, MCDM, Rule-Based System, Supplier Selection, Sustainability*

Sürdürülebilir Tedarikçi Seçimi için Aralık Tip-2 Bulanık Kural Tabanlı BWM Yaklaşımı

ÖZ: Bulanık mantık, insana özgü yaklaşık akıl yürütmeye dayalı bir teoridir ve uygulamaları, klasik yöntemlerin içinden çıkamadığı durumlara daha etkili ve basit çözümler sunabilmektedir. Tip-1 bulanık küme, 0 ile 1 arasında bir üyelik derecesi atanan sürekli (keskin) bir üyelik derecesine sahip olan ve üyelik fonksiyonları ile karakterize edilen bir kümedir. Belirsizliği daha iyi ifade etme gücüne sahip olan Tip-2 bulanık kümeler, o kümedeki her elemana ait üyelik derecelerinin de bir bulanık küme işaret ettiği üyelik fonksiyonları ile belirtilir. Bu sayede Tip-2 bulanık kümeler, bulanık küme teorisine üyelik fonksiyonları belirsizliğini dâhil etmemize izin verir. Uzman bilgisinin kullanılması ve karar verici etkisinin düzeyini yansıtmak için insan duyarlılığının kullanılması bulanık kural tabanlı bir sistem olarak ifade edilmektedir. Son zamanlarda bulanık kuralların çok kriterli karar verme (ÇKKV) yöntemleri ile birlikte sıklıkla kullanıldığı görülmektedir. Yine bulanık kuralların Tip-2 bulanık sayılarla birleştirilmesi de mevcuttur.

Bu çalışmada, ÇKKV yöntemlerinden biri olan En İyi En Kötü Yöntemi (BWM), Aralık Tip-2'ye dayalı bulanık kurallarla bütünleştirilmiştir. Geliştirilen hibrit yöntem Aralık Tip-2 Bulanık Kural Tabanlı BWM Yaklaşımı olarak tanımlanmıştır. Önerilen hibrit yöntem, özellikle benzer sıralama konumlarına sahip alternatifler olduğunda bir etki faktörüne sahip olduğundan önemlidir. Nitekim her alternatifte küçük bir fark olsa bile farkı daha iyi (daha hassas) göstererek önerilen yöntemi güçlü ve benzersiz kılmaktadır. Önerilen yaklaşım, BWM ile karşılaştırmalı olarak sürdürülebilir bir tedarikçi seçimi problemine uygulanmıştır. Sonuçlar, IT2 FRB BWM yaklaşımının klasik BWM yöntemine göre alternatifleri sıralamada daha başarılı olduğunu göstermektedir.

Anahtar Kelimeler: *BWM, Aralık Tip-2 Bulanık Kümeler, ÇKKV, Kural Tabanlı Sistem, Tedarikçi Seçimi, Sürdürülebilirlik*

1. INTRODUCTION

Businesses have to supply the best quality product with the best cost and present it to the customers quickly in order to be able to sustain their existence in an increasingly competitive environment every day. Therefore, the oppression to create value for organizations and to find better ways to distribute this value to customers is increasing in today's competitive world. Businesses are looking for efficient methods to regulate management strategies and maintain competitive advantage because they face competitive market pressures such as globalization in competition and cooperation, diversifying in customer demands and shortening of product life cycle. For example, operations of the material requirements planning and the institutional resource planning are used to integrate resources. The aim of these tools is to decrease response time and increase customer satisfaction to meet customer demands. The managerial ability of each firm depends on the coordination and integration of complex business relationships between supply chain members (Chen and Huang, 2006). If we do not consider the selection and evaluation of successful suppliers in a competitive environment, it will be extremely difficult to control any production process at low cost, high quality and acceptable time.

Companies are facing new challenges that not only are the best economic performers but also require them to be more environmentally and socially responsible. As a result, firms are moving from a traditional business-related economic perspective to a more sustainable business model that consistent with notion of the triple bottom line (TBL) and includes three interconnected dimensions in their operations: economy, environment and society. Sustainability means integration of environmental and social dimensions with economic thinking. The sustainability perspective has evolved from within companies to supply chains perspective (Azevedo *et al*., 2017). Sustainable supply chain management is increasingly focused by practitioners and researchers due to legal regulations, increased competitive pressure and awareness of social and environmental issues (Carter and Easton, 2011). Although managers recognize that the integration of sustainability into their supply chain is an opportunity, they rarely take this into account in tactical management decisions (Ikram *et al*., 2020). Businesses must have effective communication not only among individual firms but also throughout the supply chain as a way to sharing the same sustainability principles with all relevant firms. As a result, suppliers, manufacturers, distributors and all other members act together for improving their TBL performance in the context of a sustainable supply chain (Azevedo *et al*., 2017). Therefore, working with sustainable suppliers is a basis for businesses to make the entire supply chain sustainable. Decisions on sustainable practices have multi-level characteristics because TBL dimensions could be divided into hierarchical variables. For this reason, MCDM is recommended to deal with decisions involving multiple criteria simultaneously (Ikram *et al*., 2020).

Supplier selection is a complex MCDM process that pays regard to qualitative/quantitative factors together to select competent suppliers (Guo & Li, 2014; Kannan *et al*., 2013; Karaöz *et al*., 2019; Özgen *et al*., 2008; Sanayei *et al*., 2008). This complexity arises from uncertain and uncontrolled factors, which are uncertain and may contradict with each other. Many decision making problems and solutions are too complex to be identified by quantitative numbers. Thanks to the fuzzy set theory, data classification is carried out with limits that cannot be precisely defined. Thus, the fuzzy set theory simulates human logic by using a mathematical model and a solution to real-world problems can be provided in accordance with the thinking style of human (Bostancı *et al*., 2017; Yilmaz *et al*., 2001). Earlier times, supplier selection problems often focused on issues such as product cost, product delivery time, and product quality for supplier companies regardless of issues such as fuzzy rule base based on expert opinions and type-2 fuzzy sets being robust for handling uncertainty. The MCDM has taken considerable attention in solution of optimization problems recently (Awasthi *et al*., 2011; Shidpour *et al*., 2013; Şengül *et al*., 2015). In the traditional MCDM problem formulations, human judgments are reflected by precise numbers. Besides, in common practical situations, the data might not be precise or the decision-makers may not be able to assign precise numerical values to the assessment (Kahraman *et al*. 2014). Some evaluation criteria are qualitative and subjective, making it tough for the decision-maker to state his/her preferences using precise numerical values (Tseng *et al*., 2008). Traditional MCDM methods aren't effective enough in dealing with the uncertain or ambiguous nature of linguistic assessments (Kahraman *et al*., 2003). The BWM, which has been used frequently recently, is a multi-criteria technique that makes comparisons using only two pairs of comparison vectors. Although BWM is both time-advantageous and offers more reliable results in controlling consistency, traditional BWM may not adequately deal with the vagueness and uncertainty present in many decision-making problems.

In type-1 fuzzy sets, a membership degree is defined with a membership function, which is valued in the interval [0,1] for each element (Zadeh, 1965). Zadeh (1975) introduced the type-2 fuzzy set as an extension of the type-1 fuzzy set. Membership degrees of type-2 fuzzy sets are themselves fuzzy sets. They are quite helpful in situations in which it is hard to determine an accurate membership function for fuzzy sets (Karnik & Mendel, 2001). Therefore, if type-1 fuzzy sets are considered as the first-rank approach to real-world uncertainties, type-2 fuzzy sets could be seen as a second-rank approach to uncertainty. That is, type-1 fuzzy set membership functions are two-dimensional, whereas type-2 fuzzy set membership functions are three-dimensional, which provides supplemental degrees of freedom to directly model uncertainties (Kahraman *et al*., 2014).

IT-2 fuzzy sets are an especial kind of classic type-2 fuzzy sets. All secondary membership functions of the IT-2 fuzzy sets take a crisp value like 1 instead of a function. Hence, secondary membership functions do not carry distinctive information in IT-2 fuzzy sets, and only use of boundary values of primary membership functions is enough in type-2 fuzzy logic operations. Therefore, IT-2 fuzzy sets are often used in general type 2 fuzzy systems, due to ease of calculation (Mendel *et al*., 2006). Because of this reason, we used IT-2 fuzzy sets for rule based approach in this study and integrated with the BWM as it produces faster, more consistent and more reliable results by requiring less comparison data than other MCDM methods.

In this study, an IT-2 rule based BWM approach is developed and introduced into the literature for the first time. We can summarize the paper contributions to the literature as follows:

- The BWM and range type-2 fuzzy numbers and expert opinions (rule base) were included in the selection and a systematic analysis of the interdependencies existing between sustainable supplier criteria and expert opinions was made.
- As a result of the study, it has been seen that the proposed approach is successfully applied to sustainable supplier selection problems.
- It was observed that many of the previous studies used MCDM methods with IT-2 fuzzy sets but ignored rule base, which based on expert opinions. With this study, an integrated approach IT2 FRB BWM was presented for companies to make a more flexible, easier and more objective supplier assessment and expert opinions were included in their selection problem. Thus, it is expected that our hybrid approach will set an example for other similar applications and will contribute to the literature in this direction.
- There is no previous study using BWM with IT-2 fuzzy rule based systems and this study is the first in this field.

• The most important contribution of the paper to the literature is to offer a new solution with hybrid (IT2 FRB BWM) approach, which takes into account the objective and subjective data together, and quickly resolves with easy procedures.

1.1. Brief review of the literature

Within the sustainable supplier selection context, there are a lot of approaches in the literature based on various MCDM methods, implemented singly or combined with a wide variety of techniques in different forms. Regarding methods used individually in sustainable supplier selection, the most frequently used is TOPSIS (Nourmohamadi Shalke *et al*. (2018); TOPSIS, Mohammed (2019); Fuzzy-TOPSIS and Li *et al*. (2019); TOPSIS with Rough Set Theory) followed by AHP (Khoshfetrat *et al*. (2020); AHP, Laosirihongthong *et al*. (2019); Fuzzy-AHP, Xu *et al*. (2019); AHP Sort II with Interval Type-2 Fuzzy Sets) with their fuzzy versions. Apart from these, other individual methods: ANP,Ghadimi *et al*. (2017); VIKOR, Demir *et al*. (2018); ELECTRE, Lu *et al*. (2018); TODIM, Qin *et al*. (2017); DEA, Zarbakhshnia and Jaghdani (2018); DEMATEL, Song *et al*. (2017) have also been used frequently (Schramm *et al*., 2020).

As for MCDM methods based on the integration of different techniques; Tavana *et al*. (2017) provided a novel integrated MCDM approach using ANP, QFD, AHP, WASPAS, MOORA and COPRAS to sustainable supplier selection problems. Yazdani *et al*. (2017) put forwarded an integrated approach using DEMATEL, QFD and COPRAS for green supplier selection. Zhou and Xu (2018) proposed an integrated decision making method using DEMATEL, ANP and FVIKOR for sustainable supplier selection. Yıldızbaşı *et al*. (2020) evaluated four automotive suppliers in terms of social sustainability using FAHP and FTOPSIS. Simic *et al*. (2021) introduced an integrated CRITIC and MABAC based type-2 neutrosophic model for public transportation pricing system selection.

BWM, one of the MCDM methods, primarily determines the best and worst criteria and only makes comparisons between these criteria and other criteria, thus using only two pairwise comparison vectors generated based on two opposite references (best and worst) in a single optimization model. Methods using a single vector, such as SMART, cannot control the consistency of pairwise comparisons, although they are time advantageous in the case of a lot of data based on pairwise comparisons. Methods using a full matrix, such as AHP, provide the ability to check the consistency of pairwise comparisons but are time-inefficient if there is a lot of data. BWM, on the other hand, stands in the middle according to the methods in both structures. In other words, it provides the opportunity to check the consistency of pairwise comparisons, while at the same time it is a time-efficient method in the case of large amounts of data (Rezaei, 2020). These conveniences motivate researchers to implement BMW instead of other MCDM methods.

In the current literature, the BWM was used in integration with different methods on sustainable supplier selection such as Gupta and Barua (2017) and Lo *et al*. (2018); BWM- Fuzzy-TOPSIS, Cheraghalipour and Farsad (2018); BWM- Revised Multi-Choice Goal Programming, Bai *et al*. (2019); BWM- Grey-TODIM, Ghoushchi *et al*. (2019); Fuzzy-BWM- Piecewise linear values function and H.C. Liu *et al*. (2019); BWM- Alternative Queuing (Schramm *et al*., 2020). Although there are studies on supplier selection using BWM with Interval type-2 fuzzy numbers by Wu *et al*. (2019) and Qin and Liu (2019), there are no previous works on sustainable supplier selection using BWM with IT-2 fuzzy rule based system. Therefore, a summary of closely related studies in the literature of the three methods we have applied for this paper is presented below.

The current studies in the literature on IT-2 fuzzy sets, Rule-based system and BWM for selection problems are summarized in Table 1.

As shown in Table 1, there is no previous study using the combination of BWM, rule-based system and IT-2 fuzzy sets. The novelty of our study is that it gives a different perspective to the evaluation of supplier alternatives with a new integrated approach that uses all three together and contributes to the literature.

Table 1. Summary of previous research on rule-based systems, interval type-2 fuzzy sets and BWM methods for selection (supplier) processes

Author / Authors	Methodology	Application Area
Chai *et al.* (2012)	Rule-Based Superiority and Inferiority Ranking Approach under Intuitionistic Fuzzy Environments	Supplier selection
Macioł *et al.* (2013)	Rule Based Reasoning Systems, AHP	Supplier evaluation and classification
Paul (2015)	Rule-Based Fuzzy Inference System	Supplier selection for managing supply risks in supply chain
Kadaifci *et al.* (2019)	Fuzzy Rule-Based System, AHP based on Absolute Measurement	Container transshipment terminal selection
Rafigh *et al.* (2021)	Fuzzy Rule-Based Multi-Criterion Approach	Cooperative green supplier selection problem
Yaakob *et al.* (2015)	**IT-2 - Fuzzy Rule based System Approach** using TOPSIS	Selection of alternatives
Kahraman *et al.* (2014)	IT-2 Fuzzy Sets, AHP	Supplier selection
Keshavarz Ghorabaee *et al.* (2014)	IT-2 Fuzzy Sets, COPRAS	Supplier selection problems
Heidarzade *et al.* (2016)	IT-2 Fuzzy Sets, Distance measure, Hierarchical clustering	Supplier selection
Zhong and Yao (2017)	IT-2 Fuzzy Sets, ELECTRE	Supplier selection
Mousakhani *et al.* (2017)	IT-2 Fuzzy Sets, TOPSIS	Green supplier selection
Qin *et al.* (2017)	IT-2 Fuzzy Sets, TODIM	Green supplier selection
Xu *et al.* (2019)	IT-2 Fuzzy Sets, AHPSort II	Sustainable supplier selection
P. Liu *et al.* (2019)	IT-2 Fuzzy Sets, QFD, Partitioned Bonferroni mean operator	Green supplier selection
Alikhani *et al.* (2019)	IT-2 Fuzzy Sets, VIKOR, DEA	Strategic supplier selection under sustainability and risk criteria
Bera *et al.* (2021)	IT-2 Fuzzy Sets, TOPSIS	Supplier selection
Yucesan *et al.* (2019)	**IT-2 Fuzzy Sets, BWM,** TOPSIS	Green supplier selection
Wu *et al.* (2019)	**IT-2 Fuzzy BWM** and VIKOR	Green supplier selection
Qin and Liu (2019)	**IT-2 Fuzzy BWM** and COPRAS	Emergency material supplier selection problem
Celik *et al.* (2021)	**IT-2 Fuzzy BWM**-TODIM	Green supplier selection
Hoseini *et al.* (2022)	**IT-2 Fuzzy BWM**-TOPSIS	Resilient supplier selection problem
Rezaei *et al.* (2015)	BWM	Supplier segmentation process for supplier evaluation
Rezaei *et al.* (2016)	BWM	Supplier selection problem for a food supply chain
Gupta and Barua (2017)	BWM, Fuzzy TOPSIS	Green supplier selection
Cheraghalipour and Farsad (2018)	BWM, Revised Multi-Choice Goal Programming	Sustainable supplier selection and order allocation problem
Lo *et al.* (2018)	BWM, Fuzzy TOPSIS and Fuzzy multi objective linear programming	Green supplier selection and order allocation problem
Aboutorab *et al.* (2018)	ZBWM method by integrating Z-numbers	Supplier development problem
Haeri and Rezaei (2019)	BWM, Fuzzy gray cognitive methods, Gray relational analysis method	Green supplier selection
Govindan *et al.* (2019)	BWM- COPRAS	Sustainable third-party reverse logistics providers selection
Gan *et al.* (2019)	Fuzzy BWM and the Modular TOPSIS	Resilient supplier selection problem
H. C. Liu *et al.* (2019)	BWM, Interval-valued intuitionistic uncertain linguistic sets, Alternative queuing method	Sustainable supplier selection
Aijun *et al.* (2019)	Interval-valued pythagorean hesitant fuzzy BWM group decision-making	Third-party reverse logistics providers selection
Pamucar *et al.* (2019)	BWM-WASPAS-MABAC model based on interval rough numbers	Assessment of third-party logistics provider
Garg and Sharma (2020)	BWM - VIKOR	Sustainable outsourcing partners selection
Javad *et al.* (2020)	BWM, Fuzzy TOPSIS	Green supplier selection
Kannan *et al.* (2020)	BWM, Interval VIKOR	Sustainable circular supplier selection
Ecer and Pamucar (2020)	Fuzzy BWM, Fuzzy CoCoSo, Bonferroni functions	Sustainable supplier selection
Amiri *et al.* (2021)	Fuzzy BWM, SAW	Sustainable supplier selection
Fallahpour *et al.* (2021)	Fuzzy DEMATEL- BWM- ANP	Sustainable-resilient supplier selection problem
Kazemitash *et al.* (2021)	Rough BWM	Green supplier selection

The remaining paper is structured as follows: General type 2 and IT-2 fuzzy sets and BWM method are presented and after all, the proposed IT-2 fuzzy rule based BWM approach and adopted solution approach are explained in Section 2. In Section 3, numerical data based on application study are given and this study is conducted for sustainable supplier selection problem by testing the proposed approach. Section 4 presents the analysis results of the application study, and Section 5 gives in the general discussion and conclusion.

2. METHODOLOGIES

2.1. General type-2 and interval type-2 fuzzy sets

In this section, a number of type 2 fuzzy sets and IT-2 fuzzy sets definitions are concisely explained (Awasthi *et al.*, 2011).

A type-2 fuzzy set $\check{\check{A}}$ in the universe of discourse X is represented by a type-2 membership function $\mu_{\check{\check{A}}}$, indicated as follows (Zadeh, 1975):

Definition 2.1.1. $\check{\check{A}} = \left\{\left((x,u), \mu_{\check{\check{A}}}(x,u)\right) / \forall_x \in X,\ \forall_u \in J_x \subseteq [0,1], 0 \leq \mu_{\check{\check{A}}}(x,u) \leq 1\right\}$ (1)

Where J_x indicates an interval [0, 1]. $\check{\check{A}}$ is represented as follows (Mendel *et al.*, 2006):

$$\check{\check{A}} = \int_{x\in X}\int_{u\in J_x} \mu_{\check{\check{A}}}(x,u)/(x,u) \tag{2}$$

Where $J_x \subseteq [0,1]$ and $\iint$ indicates union over all acceptable x and u.

Let $\check{\check{A}}$ be a type-2 fuzzy set in X represented by $\mu_{\check{\check{A}}}$. If all $\mu_{\check{\check{A}}}(x,u) = 1$, then $\check{\check{A}}$ is called an interval type-2 fuzzy set (Buckley, 1985). $\check{\check{A}}$ is regarded as a specific state of a type-2 fuzzy set, represented as follows (Mendel *et al.*, 2006):

$$\check{\check{A}} = \int_{x\in X}\int_{u\in J_x} 1/(x,u) \tag{3}$$

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

Arithmetic operations of trapezoidal IT-2 fuzzy sets are presented in following (Senturk *et al.*, 2017).

Definition 2.1.2. The upper and the lower membership function of an IT-2 fuzzy set are both type-1 membership functions (Mendel *et al.*, 2006).

$$\tilde{A}_i = \left(\tilde{A}_i^U, \tilde{A}_i^L\right) = \left(\left(a_{i1}^u, a_{i2}^u, a_{i3}^u, a_{i4}^u; h_1\left(\tilde{A}_i^U\right), h_2\left(\tilde{A}_i^U\right)\right), \left(a_{i1}^l, a_{i2}^l, a_{i3}^l, a_{i4}^l; h_2\left(\tilde{A}_i^L\right), h_2\left(\tilde{A}_i^L\right)\right)\right) \tag{4}$$

Where $\tilde{A}_i^U$ and $\tilde{A}_i^L$ are type-1 fuzzy sets, $a_{i1}^u, a_{i2}^u, a_{i3}^u, a_{i4}^u, a_{i1}^l, a_{i2}^l, a_{i3}^l, a_{i4}^l$ are the reference points of the IT-2 fuzzy set $\tilde{A}_i^U$, $h_j(\tilde{A}_i^U)$ indicates the membership value of $a_{i(j+1)}^u$ in $\tilde{A}_i^U$ while $1 \leq j \leq 2$, $h_j(\tilde{A}_i^L)$ indicates the membership value of $a_{i(j+1)}^l$ in $\tilde{A}_i^L$ while $1 \leq j \leq 2$, $h_1(\tilde{A}_i^U) \in [0,1]$, $h_2(\tilde{A}_i^U) \in [0,1]$, $h_1(\tilde{A}_i^L) \in [0,1]$, $h_2(\tilde{A}_i^L) \in [0,1]$, $1 \leq i \leq n$.

In Figure 1 as an example, it is shown that $h_1(\tilde{A}_i^L)$ is equal to $h_2(\tilde{A}_i^L)$ described with the label h_L and $h_1(\tilde{A}_i^U)$ equals $h_2(\tilde{A}_i^U)$, described with the label h_U and $a_{i1}^u, a_{i2}^u, a_{i3}^u, a_{i4}^u, a_{i1}^l, a_{i2}^l, a_{i3}^l, a_{i4}^l$ are illustrated as; $a_1^U, a_2^U, a_3^U, a_4^U, a_1^L, a_2^L, a_3^L, a_4^L$ (Türk *et al.*, 2014).

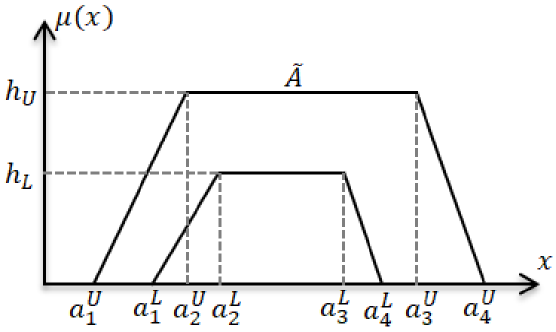

Figure 1. $\tilde{A}^U$, $\tilde{A}^L$ of the IT-2 fuzzy set $\tilde{A}$

Addition and multiplication from algebraic operations used in this paper are defined as follows for $\tilde{A}_1$ and $\tilde{A}_2$ (Mendel *et al.*, 2006);

$$\tilde{A}_1 = (\tilde{A}_1^U, \tilde{A}_1^U) = \left(a_{11}^u, a_{12}^u, a_{13}^u, a_{14}^u; h_1(\tilde{A}_1^U), h_2(\tilde{A}_1^U)\right), \left(a_{11}^l, a_{12}^l, a_{13}^l, a_{14}^l; h_2(\tilde{A}_1^L), h_2(\tilde{A}_1^L)\right) \quad (5)$$

and

$$\tilde{A}_2 = (\tilde{A}_2^U, \tilde{A}_2^U) = \left(a_{21}^u, a_{22}^u, a_{23}^u, a_{24}^u; h_1(\tilde{A}_2^U), h_2(\tilde{A}_2^U)\right), \left(a_{21}^l, a_{22}^l, a_{23}^l, a_{24}^l; h_1(\tilde{A}_2^L), h_2(\tilde{A}_2^L)\right) \quad (6)$$

Definition 2.1.3. The addition operation is:

$$\tilde{A}_1 \oplus \tilde{A}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \oplus (\tilde{A}_2^U, \tilde{A}_2^L)$$
$$= \begin{pmatrix} \left(a_{11}^u + a_{21}^u, a_{12}^u + a_{22}^u, a_{13}^u + a_{23}^u, a_{14}^u + a_{24}^u; min\left(h_1(\tilde{A}_1^U), h_1(\tilde{A}_2^U)\right), min\left(h_2(\tilde{A}_1^U), h_2(\tilde{A}_1^U)\right)\right), \\ \left(a_{11}^l + a_{21}^l, a_{12}^l + a_{22}^l, a_{13}^l + a_{23}^l, a_{14}^l + a_{24}^l; min\left(h_1(\tilde{A}_1^L), h_1(\tilde{A}_2^L)\right), min\left(h_2(\tilde{A}_1^L), h_2(\tilde{A}_2^L)\right)\right) \end{pmatrix} \quad (7)$$

(Mendel *et al.*, 2006).

Definition 2.1.4. Multiplying a fuzzy set by a constant k is:

$$k\tilde{A}_1 = k(\tilde{A}_1^U, \tilde{A}_1^L) = \left(ka_{11}^u, ka_{12}^u, ka_{13}^u, ka_{14}^u; h_1(\tilde{A}_1^U), h_2(\tilde{A}_1^U)\right), \left(ka_{11}^l, ka_{12}^l, ka_{13}^l, ka_{14}^l; h_1(\tilde{A}_1^L), h_2(\tilde{A}_1^L)\right) \quad (8)$$

(Türk *et al.*, 2014).

2.2. Best worst method (BWM)

The BWM, introduced by Rezaei in 2015, is an MCDM method, which requires fewer comparison data, provides more reliable, more consistent results compared to current MCDM methods (Rezaei, 2015).

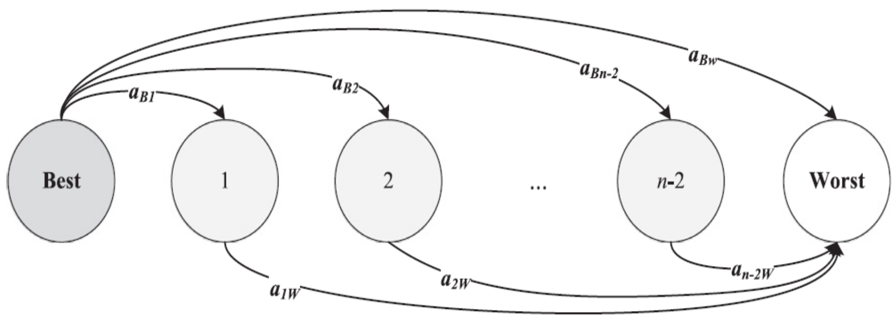

Figure 2. Reference comparisons (Rezaei, 2015)

The BWM steps are given below (Rezaei, 2015, 2016; Rezaei *et al.*, 2016; Rezaei *et al.*, 2015);

Step 1. Determining a decision criteria set. N criteria, which are effective for the decision problem are identified by the decision maker $\{c_1, c_2, \ldots, c_n\}$.

Step 2. Determining the best and the worst (most and least important) criteria.

Step 3. Determining the best criterion preference over all the other criteria, using a number between 1 and 9. The resulting best-to-others (BO) vector should be: $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$, where a_{Bj} denotes the best criterion B preference over criterion j, and it is explicit that $a_{BB}=1$.

Step 4. Determining all the criteria preference over the worst criterion, using a number between 1 and 9. The resulting others-to-worst (OW) vector should be: $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$, where a_{jw} denotes the criterion j preference over the worst criterion W, and it is explicit that $a_{WW} = 1$.

Step 5. Finding the optimal weights $(W_1^*, W_2^*, \ldots, W_n^*)$.

The goal is to identify the optimal criteria weights, such that the maximum absolute differences $|\frac{W_B}{W_j} - a_{Bj}|$ and $|\frac{W_j}{W_w} - a_{jW}|$ for all j is minimized, and it could be converted to the following minimax model:

$$min\ max_j \left\{\left|\frac{W_B}{W_j} - a_{Bj}\right|, \left|\frac{W_j}{W_w} - a_{jW}\right|\right\} \quad (9)$$

s.t.

$$\sum_j W_j = 1 \quad (10)$$

$$W_j \geq 0, \quad \forall j,\ j = 1, 2, \ldots, J \quad (11)$$

Model (9)-(11) is converted to a linear optimization model as follows:

$$min\ \xi^L \quad (12)$$

$$|W_B - a_{Bj}W_j| \leq \xi^L, \quad \forall j, j = 1, 2, \ldots, J \quad (13)$$

$$|W_J - a_{jW}W_W| \leq \xi^L, \quad \forall j, j = 1, 2, \ldots, J \quad (14)$$

$$\sum_j W_j = 1 \quad (15)$$

$$W_j \geq 0, \quad \forall j, j = 1, 2, \ldots, J \quad (16)$$

Solving Model (12)-(16), $W_1^*, W_2^*, \ldots, W_n^*$ and ξ^{L*} are obtained.

For linear model, ξ^{L*} is considered as a consistency indicator of the comparisons, and ξ^{L*} values close to zero indicate a high level of consistency.

The normalized scores of the alternatives are obtained using Eq. (17).

$$X_{ij} = \begin{cases} \frac{X_{ij}}{\max\{X_{ij}\}}, if\ x\ is\ positive(such\ as\ quality), \\ 1 - \frac{X_{ij}}{\max\{X_{ij}\}}, if\ x\ is\ negative(such\ as\ price). \end{cases} \quad (17)$$

The final aggregate score per alternative (V_i) could be calculated with the optimal criteria weights (W_j) and the normalized the alternatives scores on the different criteria (X_{ij}) as shown in Eq. (18).

$$V_i = \sum_j W_j X_{ij} \quad (18)$$

2.3. Interval type-2 fuzzy rule based BWM (IT2 FRB BWM) approach:

The BWM (Rezaei, 2015) which had been presented in five-step above, was developed by us and presented as an IT2 FRB BWM approach consisting of eight steps. The first five steps of the proposed method (the steps of BWM) are explained above and the remaining three steps (recommended by us) are explained below.

Step 6. Calculating the normalized performance value (NV_i) of each alternative;

At this stage, each V_i value calculated in Eq. (18) should be normalized as shown in Eq. (19) to ensure that they are between 0 and 1.

$$NV_i = {V_i}/{\max_i V_i} \tag{19}$$

Step 7: The premise (Λ) and result (χ) matrices

A premise matrix is calculated as shown in Eq. (20).

$$\Lambda = \begin{bmatrix} X_{11} & X_{12} & . & . & . & X_{1n} \\ X_{21} & X_{22} & . & . & . & X_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ X_{m1} & X_{m2} & . & . & . & X_{mn} \end{bmatrix} \tag{20}$$

Where, the X_{ij} value is a linguistic label of each alternative, representing the decision maker's opinion according to the criteria. Firstly, a value is obtained in Step 7 for each alternative, which are defined by the decision makers. Once NV_{ik} ($NV_i * \sigma_k$) for each alternative defined by each decision-maker is got, this value is used to assign the result of alternative rules according to the fuzzy set with higher membership in Table 2, which is prepared by consulting experts in the field. The matrix of the results is then defined as seen in Eq. (21).

Table 2. Linguistic Labels for Alternative Levels

Linguistic variables	Trapezoidal interval type-2 fuzzy scales
Very Bad (VB)	(0.04,0.1,0.15,0.20;1,1)(0.05,0.12,0.14,0.17;0.8,0.8)
Bad (B)	(0.20,0.26,0.34,0.40;1,1)(0.24,0.28,0.36,0.38;0.8,0.8)
Medium (M)	(0.40,0.46,0.54,0.60;1,1)(0.44,0.48,0.50,0.58;0.8,0.8)
Good (G)	(0.60,0.66,0.74,0.80;1,1) (0.63, 0.70, 0.76, 0.78;0.8,0.8)
Very Good (VG)	(0.80,0.85,0.95,1.00;1,1) (0.83,0.88,0.91,0.97;0.8,0.8)

$$X = \begin{bmatrix} Y_1 \\ Y_2 \\ . \\ . \\ . \\ Y_m \end{bmatrix} \tag{21}$$

Where, Y_k is an expression based on a linguistic term that shows the system output based on Table 2 of the significance level of the alternative founded in Eq. (19). For this reason, the If-Then rules of the premise and result matrices in Eq. (20) and (21) can be written as follows:

If C_1=X_{11} **and** C_2=X_{12} **and**…. **and** C_{1n}=X_{1n} **then** A_1=Y_1

If C_1=X_{21} **and** C_2=X_{22} **and** …. **and** C_{2n}=X_{2n} **then** A_1=Y_2

•
•
•

If C_1=X_{m1} **and** C_2=X_{m2} **and….and** C_{mn}=X_{mn} **then** A_1=Y_m

Step 8: The fınal score of each alternative (Γ_i) is given in Eq. (22).

$$\Gamma_i=\lambda_i{*}\Omega_i \qquad (22)$$

Where, the λ_i in Eq. (21) is the crisp value of summed (aggregated) membership function of the output, and λ_i is calculated using Eq. (23).

$$\lambda_i = \sum_{k=1}^{K}\alpha_{ik}/_{K} \qquad (23)$$

Where, $\alpha_{ik} \in Y_k$ is the maximum output membership. The IT2 FRB BWM approach will be used to obtain a better ranking in this example. This method is especially important in that it is an effect multiplier when there are alternatives with similar ranking positions. This method will show difference better (more sensitive), even if there is a small difference in every alternative. In order to calculate the influence value (Ω_i) in general, a marginal proximity coefficient with a maximum membership degree which is given in Eq. (24) below is used.

$$\Omega_i = \sum_{k=1}^{K}(NV_i * \sigma_k)/_{K} \qquad (24)$$

σ_k is the influence degree of each decision-maker and takes values between 0 and 1. After calculating λ_i and Ω_i values, Γ_i is calculated using Eq. (22). Then, the ranking order of whole alternatives could be designated from the value of Γ_i. Where, the alternative having higher value of Γ_i is specified as the best alternative.

3. AN APPLICATION STUDY

In this section, proposed IT2 FRB BWM approach is implemented to a sustainable supplier selection problem. The decision model of the problem is presented in Figure 3. The implementation process consists two stages; In the first stage, the criteria and alternatives for the problem were determined in line with the BWM and the evaluation process was initiated by the committee consisting of experts. In the next stage, the fuzzy rule-based system in the direction of three experts' evaluations with the weights obtained by BWM was applied and the alternatives were more precisely ordered.

3.1. Decision Model

Top managers of an auto part manufacturing company responsible for production, finance and marketing want to identify the most suitable sustainable suppliers for them. After the preliminary screening, company managers identified five potential suppliers for further evaluation and then, they evaluated alternatives on the sustainability factor. These evaluations were determined by the common opinions of the decision-makers in consultation with the committee. Sustainability is a holistic approach contain economic, environment and social dimensions. In determining the sustainable supplier selection criteria, previous studies (Awasthi *et al.*, 2018; Büyüközkan and Çifçi, 2012; Ecer and Pamucar, 2020; Govindan *et al.*, 2013; Li *et al.*, 2019; Luthra *et al.*, 2017; Memari *et al.*, 2019; Rashidi and Cullinane 2019) have been considered in this field. Nine criteria in total including three criteria from each dimensions, were determined under the three dimensions of sustainability for evaluation. The nine criteria with their descriptions are given in Table 3.

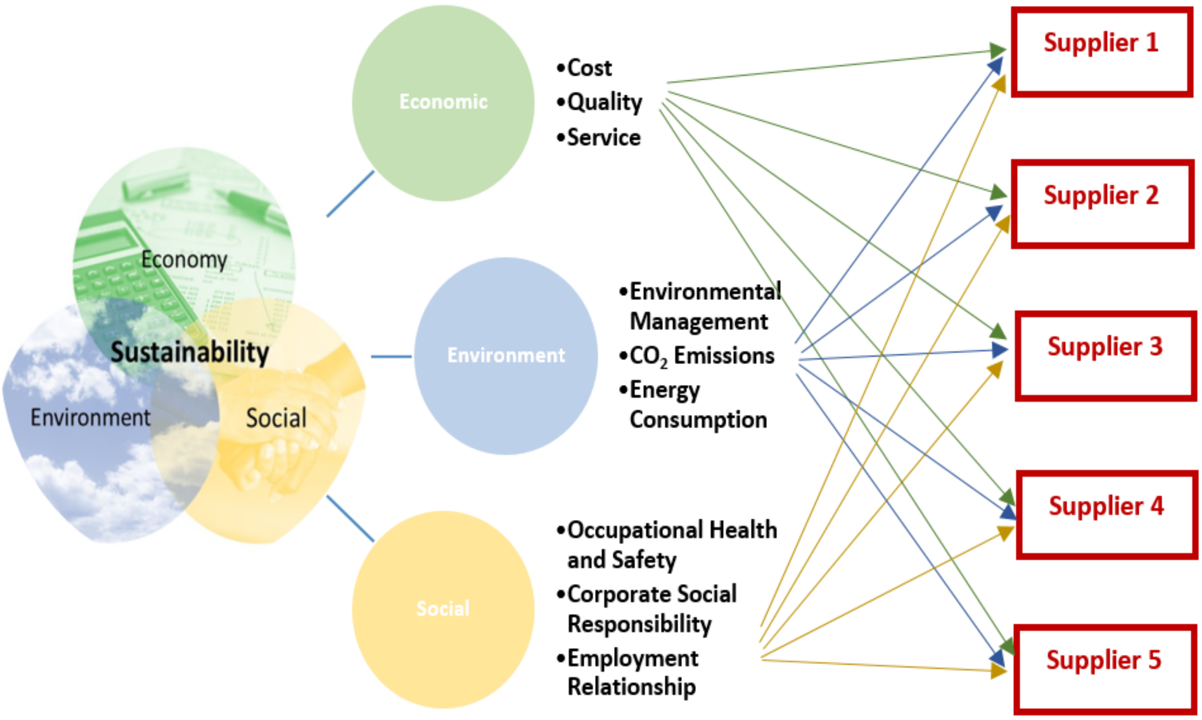

Figure 3. Hierarchical Structure of the Decision Problem

Table 3. Sustainable supplier selection criteria with their definitions

Criteria Name	Code	Definitions
Cost	**C1**	Cost is a monetary valuation incurred in the production and delivery of a good or service. / Unit product cost identified by potential suppliers.
Quality	**C2**	Quality is defined as the product performance, durability and meet the quality specifications. / The ratio of the quality product numbers to the total number of products.
Service	**C3**	Service can include supply ability, lead-time, delivery time, flexibility, communication, location, and transportation. / The ratio of the on time delivered product numbers to the total number of products.
Environmental Management	**C4**	The supplier's responsibility to perform recovery operations, minimize damage and possess environmental certificates such as environmental policies, ISO-14000. / The performance level of environmental responsibility by suppliers.
CO_2 Emissions	**C5**	The treatment and quantity control of hazardous emissions such as CO, CO_2, SO_2, NH_3, and HC_1. / The amount of CO_2 emission that occurs when the unit product is supplied.
Energy Consumption	**C6**	The controls and the reduce efforts to energy consumption, and use renewable energy. / The amount of energy consumption that occurs when the unit product is supplied.
Occupational Health and Safety	**C7**	The reviews and practices aimed at ensuring the protection of employees with laws and regulations and communiqués. / The ability to provide occupational health and safety by potential suppliers.
Corporate Social Responsibility	**C8**	The business attitude that effort to fulfill responsibilities towards society in areas such as education, environment, health and culture. / The level of fulfillment of social responsibility by potential suppliers.
Employment Relationship	**C9**	The supplier's labor relations - relationship between management, workforce and stakeholders./ The level of fulfillment of employment terms and conditions by potential suppliers.

3.2. Application of IT2 FRB BWM approach

In this section, the applicability of IT2 FRB BWM methodology in sustainable supplier selection is shown step by step. The decision problem aim is choosing the best of five alternative suppliers, taking into account nine criteria.

Step 1. The evaluation process was started by creating an expert committee and the criteria and alternatives of the problem were determined.
Step 2. The best criterion is the most important one, while the worst criterion is the least important one in sustainable supplier selection on the basis of decision-maker(s) opinion. As a result of consultations with experts, the best criterion was determined as Quality (C2) and the worst criterion was determined as Corporate Social Responsibility (C8) for sustainable supplier selection problem.
Step 3. The best criterion preference over all the other criteria (BO vector) was determined.
Step 4. The all the criteria preferences over the worst criterion (OW vector) was determined.

The pair-wise comparison vectors for the criteria are as exhibited in Table 4.

Table 4. Pair-wise comparison vectors.

BO	C1	C2	C3	C4	C5	C6	C7	C8	C9
Best objective functions: C2	2	1	3	5	6	6	7	9	7
OW	**Worst objective functions: C8**								
C1	8								
C2	9								
C3	7								
C4	5								
C5	4								
C6	4								
C7	2								
C8	1								
C9	2								

Step 5. The optimal weights were calculated. When the decision variables are written according to the Eq. (12)-(16), the final version of the model is as follows;

$$min\ \xi^L \tag{25}$$

$$\left|W_2 - a_{2j}W_j\right| \leq \xi^L, \quad \forall j, j = 1, 2, \dots, 9 \tag{26}$$

$$\left|W_J - a_{j8}W_8\right| \leq \xi^L, \quad \forall j, j = 1, 2, \dots, 9 \tag{27}$$

$$\sum_{j=1}^{9} W_j = 1 \tag{28}$$

$$W_j \geq 0, \quad \forall j, j = 1, 2, \dots, 9 \tag{29}$$

The above model that variables are weight values and target is consistency value (ξ) was solved with the General Algebraic Modeling System (GAMS) 23.3 software, a high level programming language used for solving modeling and optimization problems, and the weights minimizing consistency (ξ) were calculated as follows:

$w_1 = 0.196$, $w_2 = 0.324$, $w_3 = 0.131$, $w_4 = 0.078$, $w_5 = 0.065$, $w_6 = 0.065$, $w_7 = 0.056$, $w_8 = 0.028$, $w_9 = 0.056$ and ξ^L= 0.068. These weights will be used to obtain criteria weighted supplier performance scores by multiplying with the supplier performance scores in Table 6.

The comparisons prove a very-high consistency since the consistency indicator (ξ^L) value is close to zero. As it can be seen from the results of criteria weights above, in terms of the expert committee, the most important criterion is Quality, followed by Cost and Service for supplier selection.

The following steps have been implemented to establish the supplier selection framework.

Firstly, the supplier performances on the all different criteria are defined by decision-maker expertise. Likert scale (nine-point: 1-very low to 9-very high) is used for the qualitative criteria such as social sustainability, and objective measures ($, ratio, kg, etc.) are used for other criteria such as cost. The ratio for quality is calculated by dividing the quality product numbers by the sum of product numbers and the ratio for service is calculated by dividing the on time delivered product numbers by the sum of product numbers. The decision matrix is demonstrated in Table 5.

Table 5. Decision Matrix of supplier performances.

Unit	$/unit	Ratio (%)	Ratio (%)	Likert scale	kg/ unit	kWh/ unit	Likert scale	Likert scale	Likert scale
Criteria / Suppliers	C1	C2	C3	C4	C5	C6	C7	C8	C9
S1	97	75	86	5	1.62	0.05	9	8	7
S2	90	70	75	4	1.85	0.06	7	5	6
S3	88	60	70	4	1.77	0.04	6	7	4
S4	99	90	80	8	1.43	0.08	5	6	5
S5	95	85	90	6	1.65	0.07	4	7	6
Criteria Weights	0.196	0.324	0.131	0.078	0.065	0.065	0.056	0.028	0.056

Then, the supplier scores are normalized using Eq. (17). The normalized scores are summarized in Table 6.

Table 6. Normalized Decision Matrix.

	Economic			*Environment*			*Social*		
Criteria / Suppliers	C1	C2	C3	C4	C5	C6	C7	C8	C9
S1	0.03	0.83	0.96	0.63	0.12	0.38	1.00	1.00	1.00
S2	0.10	0.78	0.83	0.50	0.00	0.25	0.78	0.63	0.86
S3	0.12	0.67	0.78	0.50	0.04	0.50	0.67	0.88	0.57
S4	0.01	1.00	0.89	1.00	0.23	0.00	0.56	0.75	0.71
S5	0.05	0.94	1.00	0.75	0.11	0.13	0.44	0.88	0.86
Criteria Weights	**0.196**	**0.324**	**0.131**	**0.078**	**0.065**	**0.065**	**0.056**	**0.028**	**0.056**

Finally, weighted normalized scores given in Table 7 and overall scores given in Table 8 of the suppliers are found using Eq. (18).

Table 7. Weighted Normalized Decision Matrix.

	Economic			*Environment*			*Social*		
Criteria / Suppliers	C1	C2	C3	C4	C5	C6	C7	C8	C9
S1	0.006	0.270	0.125	0.049	0.008	0.024	0.056	0.028	0.056
S2	0.020	0.252	0.109	0.039	0.000	0.016	0.044	0.018	0.048
S3	0.024	0.216	0.102	0.039	0.003	0.033	0.037	0.025	0.032
S4	0.002	0.324	0.116	0.078	0.015	0.000	0.031	0.021	0.040
S5	0.010	0.306	0.131	0.059	0.007	0.008	0.025	0.025	0.048

Table 8. Outranking of Alternative Suppliers.

Supplier	Scores	Ranks
S1 (V_1)	0.622	2
S2 (V_2)	0.545	4
S3 (V_3)	0.510	5
S4 (V_4)	0.627	1
S5 (V_5)	0.618	3

According to the results presented in Table 8, the ranking of the suppliers in the order are S4, S1, S5, S2 and S3.

Step 6. Calculating the normalized performance value of each alternative (NV_i);

The calculated performance values of alternatives in Table 8 should be normalized before being matched to the linguistic labels in Table 2. As an instance in this paper; according to the score values calculated for our five supplier alternatives, $V_4 = 0.627$ is the maximum value; Using Eq. (19), normalized performance values of each alternative are calculated as follows:

$NV_1 = 0.622 / 0.627 = 0.992$ (30)
$NV_2 = 0.545 / 0.627 = 0.869$ (31)
$NV_3 = 0.510 / 0.627 = 0.813$ (32)
$NV_4 = 0.627 / 0.627 = 1$ (33)
$NV_5 = 0.618 / 0.627 = 0.985$ (34)

Step 7: The premise (Λ) and result (χ) matrices;

Each decision maker has the t matrix of each premise and the result.

$$\textbf{If}\quad \begin{matrix} R_1 \\ R_2 \\ . \\ . \\ . \\ R_m \end{matrix} \begin{bmatrix} X_{11} & X_{12} & . & . & . & X_{1n} \\ X_{21} & X_{22} & . & . & . & X_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ X_{m1} & X_{m2} & . & . & . & X_{mn} \end{bmatrix} \quad \textbf{Then} \quad \begin{bmatrix} Y_1 \\ Y_2 \\ . \\ . \\ . \\ Y_m \end{bmatrix} \tag{35}$$

Where, a rule has a form that is shown below;

If X_{11}=VS **and** X_{12}=VS **and** X_{13}=VS **and** X_{14}=VS **and**…… **and** X_{1n}=VS **then** Y_1=VG.

Here, since the influence degree of all decision-makers is 1, the NV_i value could be matched to the linguistic labels in Table 2 for all alternatives. Because NV_{ik} would be equals NV_i. For example; if NV_1 = 0.992 then Y_1 in Table 2 belongs to the VS (Very Good) interval type 2 fuzzy set. Likewise, NV_2 = 0.869 belongs to VG (Very Good), NV_3 = 0.813 belongs to VG (Very Good), NV_4 = 1 belongs to VG (Very Good) and NV_5 = 0.985 belongs to VG (Very Good) IT-2 fuzzy set. Alternative levels of alternatives corresponding to calculated NV_i values are given in Table 9.

Table 9. Calculated NV_i Values for Alternatives and Alternative Levels

	Interval Type-2 Fuzzy Values of Calculated NV_i Values	Alternative Levels of Calculated NV_i Values
S1 (NV_1)	0.992	VG
S2 (NV_2)	0.869	VG
S3 (NV_3)	0.813	VG
S4 (NV_4)	1	VG
S5 (NV_5)	0.985	VG

Step 8: Final Scores (Γ_i);

The final score (Γ_i) is calculated for each alternative by using Eq. (22). For example, assuming that the three rules R1, R2, R3 from three decision-makers (using Table 10) operate for S1 alternative, the final score (Γ_1) for the S1 alternative is calculated as follows:

Table 10. A Sample Rule Base generated by Expert Decision Makers

R1	**If** C1=VG **And** C2=VG **And** C3=VG **And** C4=VG **And** C5=VG **And** C6=VG **And** C7=VG **And** C8=VG **And** C9=VG **Then** S1=VG
R2	**If** C1=VG **And** C2=G **And** C3=G **And** C4=VG **And** C5=VG **And** C6=M **And** C7=M **And** C8=VG **And** C9=G **Then** S1=VG
R3	**If** C1=M **And** C2=G **And** C3=VG **And** C4=VG **And** C5=M **And** C6=VG **And** C7=M **And** C8=VG **And** C9=G **Then** S1=VG
R4	**If** C1=M **And** C2=M **And** C3=B **And** C4=VB **And** C5=M **And** C6=M **And** C7=B **And** C8=M **And** C9=M **Then** S1=M
R5	**If** C1=VG **And** C2=VG **And** C3=VG **And** C4=VG **And** C5=VG **And** C6=VG **And** C7=VG **And** C8=VG **And** C9=VG **Then** S2=VG
R6	**If** C1=VG **And** C2=G **And** C3=VG **And** C4=G **And** C5=VG **And** C6=G **And** C7=VG **And** C8=VG **And** C9=VG **Then** S2=VG
R7	**If** C1=VG **And** C2=G **And** C3=G **And** C4=VG **And** C5=M **And** C6=VG **And** C7=VG **And** C8=VG **And** C9=VG **Then** S2=VG
R8	**If** C1=G **And** C2=G **And** C3=G **And** C4=G **And** C5=M **And** C6=VG **And** C7=G **And** C8=VG **And** C9=G **Then** S2=G
R9	**If** C1=G **And** C2=VG **And** C3=VG **And** C4=G **And** C5=VG **And** C6=G **And** C7=VG **And** C8=M **And** C9=VG **Then** S3=VG
R10	**If** C1=VG **And** C2=G **And** C3=G **And** C4=VG **And** C5=VG **And** C6=G **And** C7=VG **And** C8=M **And** C9=VG **Then** S3=VG
R11	**If** C1=VG **And** C2=VG **And** C3=G **And** C4=M **And** C5=M **And** C6=G **And** C7=VG **And** C8=VG **And** C9=VG **Then** S3=VG
R12	**If** C1=G **And** C2=G **And** C3=M **And** C4=G **And** C5=M **And** C6=VG **And** C7=G **And** C8=G **And** C9=G **Then** S3=G
R13	**If** C1=VG **And** C2=VG **And** C3=VG **And** C4=G **And** C5=G **And** C6=VG **And** C7=VG **And** C8=M **And** C9=VG **Then** S4=VG
R14	**If** C1=VG **And** C2=M **And** C3=VG **And** C4=B **And** C5=VG **And** C6=G **And** C7=VG **And** C8=VG **And** C9=VG **Then** S4=VG
R15	**If** C1=M **And** C2=VG **And** C3=G **And** C4=VG **And** C5=M **And** C6=G **And** C7=VG **And** C8=G **And** C9=VG **Then** S4=VG
R16	**If** C1=M **And** C2=G **And** C3=M **And** C4=G **And** C5=M **And** C6=VG **And** C7=G **And** C8=G **And** C9=M **Then** S4=G
R17	**If** C1=M **And** C2=G **And** C3=G **And** C4=VG **And** C5=VG **And** C6=G **And** C7=VG **And** C8=VG **And** C9=G **Then** S5=VG
R18	**If** C1=M **And** C2=VG **And** C3=VG **And** C4=B **And** C5=VG **And** C6=VG **And** C7=VG **And** C8=G **And** C9=VG **Then** S5=VG
R19	**If** C1=VG **And** C2=VG **And** C3=M **And** C4=G **And** C5=VG **And** C6=G **And** C7=VG **And** C8=VG **And** C9=M **Then** S5=VG
R20	**If** C1=M **And** C2=G **And** C3=B **And** C4=B **And** C5=VB **And** C6=M **And** C7=G **And** C8=B **And** C9=B **Then** S5=B

R1: **If** C1=VG **And** C2=VG **And** C3=VG **And** C4=VG **And** C5=VG **And** C6=VG **And** C7=VG **And** C8=VG **And** C9=VG **Then** S1=VG

R2: **If** C1=VG **And** C2=G **And** C3=G **And** C4=VG **And** C5=VG **And** C6=M **And** C7=M **And** C8=VG **And** C9=G **Then** S1=VG

R3: **If** C1=M **And** C2=G **And** C3=VG **And** C4=VG **And** C5=M **And** C6=VG **And** C7=M **And** C8=VG **And** C9=G **Then** S1=VG

To calculate λ_1 value by using Eq. (23); the each rule output for the S1 alternative is as follows.

R1: VG = (0.799,0.849,**0.949**,0.999;1,1) (0.829,0.879,0.909,0.969;0.8,0.8)

R2: VG = (0.649,0.705,**0.792**,0.848;1,1) (0.680,0.739,0.783,0.825;0.8,0.8)

R3: VG = (0.596,0.653,**0.739**,0.796;1;1) (0.630,0.684,0.722,0.773;0.8,0.8)

Then, the λ_1 value is calculated as follows for S1 alternative:

$$\lambda_1 = \frac{0.949+0.792+0.739}{3} = 0.827 \quad (36)$$

Also, the value of Ω_1 is calculated by using Eq. (12).

Also, given that the value of each rule is R1: 0.992 R2: 0.992 R3: 0.992 for each S1 alternative (NV_1=0.992) in step 6. Again, since the influence level of all decision-makers is 1, the Ω value would be equal to the NV_i value.

$$\Omega_1 = 0.992 \quad (37)$$

Finally, Γ_1 is calculated using Eq. (24) as below:

$\Gamma_1 = \lambda_1 * \Omega_1$

= 0.827 * 0.992

= 0.820 calculated as. (38)

A similar procedure is applied for all other alternatives. The rules worked out and the calculated rule outputs for all alternatives are given in Table 11. Final score values calculated for all alternatives are given in Table 12. Afterwards, the ranks of all alternatives can be determined from the value of Γ_i. The best alternative is the one whose final score (Γ_i) is high.

The comparison of the ranking values of BWM and proposed IT2 FRB BWM approach is given in Table 13.

Table 11. Proposed IT2 FRB BWM Approach Supplier Selection Ranking Results

Alternatives	Activated Rule Value	Interval Type-2 Fuzzy Value of Rule Output	Calculated λ Value
S1	R1	(0.799,0.849,**0.949**,0.999;1,1)(0.829,0.879,0.909,0.969;0.8,0.8)	0.820
	R2	(0.649,0.705,**0.792**,0.848;1,1)(0.680,0.739,0.783,0.825;0.8,0.8)	
	R3	(0.596,0.653,**0.739**,0.796;1,1)(0.630,0.684,0.722,0.773;0.8,0.8)	
S2	R5	(0.799,0.849,**0.949**,0.999;1,1)(0.829,0.879,0.909,0.969;0.8,0.8)	0.876
	R6	(0.706,0.760,**0.851**,0.906;1;1)(0.736,0.795,0.839,0.880;0.8,0.8)	
	R7	(0.682,0.737,**0.827**,0.882;1,1)(0.713,0.771,0.814,0.857;0.8,0.8)	
S3	R9	(0.720,0.774,**0.866**,0.920;1,1)(0.750,0.807,0.847,0.894;0.8,0.8)	0.848
	R10	(0.684,0.739,**0.828**,0.884;1,1)(0.714,0.774,0.820,0.859;0.8,0.8)	
	R11	(0.703,0.756,**0.849**,0.903;1,1)(0.734,0.787,0.821,0.876;0.8,0.8)	
S4	R13	(0.759,0.811,**0.908**,0.959;1,1)(0.790,0.842,0.876,0.931;0.8,0.8)	0.819
	R14	(0.610,0.664,**0.755**,0.810;1,1)(0.644,0.691,0.724,0.784;0.8,0.8)	
	R15	(0.650,0.705,**0.795**,0.850;1,1)(0.683,0.734,0.768,0.825;0.8,0.8)	
S5	R17	(0.606,0.663,**0.748**,0.805;1,1)(0.638,0.697,0.742,0.783;0.8,0.8)	0.802
	R18	(0.668,0.721,**0.815**,0.868;1,1)(0.701,0.749,0.782,0.841;0.8,0.8)	
	R19	(0.696,0.749,**0.842**,0.896;1,1)(0.728,0.779,0.811,0.869;0.8,0.8)	

Table 12. Supplier Selection Rank Final Scores for the Proposed IT2 FRB BWM Approach.

	λ	Ω	Γ
S1	0.820	0.992	0.813
S2	0.876	0.869	0.761
S3	0.848	0.813	0.689
S4	0.819	1	0.819
S5	0.802	0.985	0.790

Table 13. Comparison of BWM and IT2 FRB BWM Approach.

	BWM Method		IT2 FRB BWM Method	
Alternatives	Weights	Ranks	Weights	Ranks
S1	0.622	2	0.813	2
S2	0.545	4	0.761	4
S3	0.510	5	0.689	5
S4	0.627	1	0.819	1
S5	0.618	3	0.790	3
Maximum Value of Weights the Alternatives	S4=0.627		S4=0.819	
Minimum Value of Weights the Alternatives	S3=0.510		S3=0.689	
Significance of the Distinction	S4-S3=0.627-0.510=**0.117**		S4-S3=0. 819- 0. 689= **0.130**	

4. ANALYSIS OF RESULTS

In this study, The BWM method has been expanded to IT2 FRB BWM. Then alternatives are listed by both methods. We solved the same problem using IT2 FRB BWM approach to compare its results with results of Rezaei's BWM. The obtained results with both methods are as in Table 13.

As it could be seen from Table 13, both methods found the same results as ranking. However, according to BWM method, IT2 FRB BWM method allows us make pairwise comparisons under uncertainty and define the membership functions with greater flexibility. This flexibility is reflected in the results with a greater distinction. In BWM method, the significance of the distinction is 0.627-0.510 = 0.117 while it is 0. 819-0. 689= 0.130 for IT2 FRB BWM approach.

The fuzzy rule-based system has been used in integration with AHP and TOPSIS methods for decision-making problems before. BMW is based on pairwise comparison like AHP, but it makes fewer pairwise comparisons and produces more consistent results (Rezaei, 2015). In addition to being used to find the importance (weight) of the criteria, it can also be used to evaluate alternatives according to criteria such as TOPSIS in cases where objective criteria are not available (Rezaei, 2020). In this direction, the use of the fuzzy rule-based system, used in previous studies, with BMW in this study has increased its performance by providing more consistency and reliability, and especially ensuring efficiency in terms of time and ease of use.

5. DISCUSSION AND CONCLUSION

5.1. Implications for theory

Supply chain management comprises all steps of the product life cycle, from designing, manufacturing and distribution to the product utilization by end-users and the disposal of the product at the end of its useful life. Here, the suppliers' role can't be ignored. In light of all, supplier selection criteria should be redesigned by companies, taking into account customer requirements and environmental norms. Therefore, the main goal of this study is to solve the problem of evaluating and rating suppliers using an integrated formulation.

Due to increasing oppressions and conditions of competition in recent years, businesses need a well-designed supply chain network to be able to gain advantage and survive in a competitive market environment. The importance of IT2 FRB BWM approach proposed in supplier selection problems for firms and organizations in the selection and ranking of alternatives is emphasized in this study. Given the studies on the use of IT-2 fuzzy rule-based systems, it is seen that the studies mostly have been done using type-1 and type-2 fuzzy methods without having fuzzy rule-base. When many of the studies have been done are examined, the same problem has been addressed both using of the type-1 and the type-2 fuzzy logic methods. As a result, it was seen that use of type-2 fuzzy sets instead of type-1 fuzzy sets provides more rational and realistic results in supplier selection problems for firms and organizations. It is also seen that the use of type-2 fuzzy logic sets by firms and organizations is more flexible, appropriate and effective than the classical logic sets for supplier selection problems in the environment where there are many criteria and alternatives but lack of information and high uncertainty.

In BWM method are partially inadequate in membership functions defining because, it is not possible to model uncertainty and vagueness sufficiently. The IT2 FRB BWM approach overcomes this problem by incorporating uncertainty into BWM. Thus, a flexible definition possibility was provided to decision-makers. In this study, Rezaei's BWM is extended using IT-2 fuzzy rule-based sets. Because IT-2 membership functions can generate significant differences in results compared to BWM.

The main purpose of proposed method; It could be summarized as being able to see the evaluation scores of the suppliers, to understand the weaknesses of the suppliers and to reach a logical decision for the future plans by the management of the company. With this proposed integrated study, we tried to create a basis for companies / firms to develop good relations with their partners in order to reduce their weaknesses. Thus, the capability to model the performance of supplier on a set of criteria will suggest the company initiate a talent development analysis for efficient management competencies. We believe that the proposed model is sufficiently robust and can be easily applied in applications MCDM problems. With this study, managers can create their decision structures more effectively and determine the relative importance of supplier qualifications. Effective evaluation of suppliers enables to improve suppliers' performance and behavior regarding their poor qualities, and also gives stronger suppliers more opportunities to take all applications to the next level.

5.2. Implications for practice

In this paper, Fuzzy Rule-Based BWM approach depending type-2 fuzzy sets was presented for the first time. Type-2 linguistic scales were developed to be utilized in the proposed approach and a flexible identification opportunity was provided for decision makers to evaluate the problem under consideration.

Considering the literature studies, Fuzzy MCDM methods were applied to supplier selection problems by many authors in comparison with traditional MCDM methods, and as a result, it was observed that fuzzy MCDM methods were more successful than traditional MCDM methods. It has been also observed that combining fuzzy rules with decision-making methods has been put forward by many researchers in the literature studies. Whereas, combining fuzzy rules with type-2 fuzzy numbers is a novel approach. In this study, BWM, one of the MCDM methods, was integrated among fuzzy rules based on interval type-2. it is important to include expert knowledge along with the type-2fuzzy numbers in the selection problem, and this is one of the major advantages of the proposed method. Another advantage of this approach is that it incorporates expert knowledge into the traditional MCDM method BWM through rule-based systems with type-2 fuzzy numbers and successfully applies to the supplier selection problem. That method is especially important as it has an impact multiplier when there are alternatives with similar ranking positions. This method will show the difference better (more sensitively) even if there is a slight difference in each alternative. This makes the proposed method important and unique. The biggest disadvantage of the proposed approach is that the type-2 based fuzzy rules are limited to the proposed fuzzy rule-based BWM. Another disadvantage of our method is that the study is limited to nine criteria, five alternatives and three experts. In future studies, different rankings can be obtained for alternatives by increasing the number of criteria, alternatives and experts. Once again, other limitation of the proposed approach is that the input data expressed in linguistic terms is based upon the decision-maker(s)'s opinions and experiences and therefore includes subjectivity.

In this study, the supplier selection problem for firms and organizations in an environment with lots of criteria and alternatives was addressed with the classical BWM and the proposed IT2 FRB BWM approach. It was seen that the selection problems to be solved by using rule based systems, were more effective (see Table 12). The IT2 FRB BWM approach, which is proposed with nine criteria and five alternatives for the best supplier selection, is used within the scope of the paper. As a result of the application, while alternative rankings both of BWM and the proposed IT2 FRB BWM approach did not change; In the proposed IT2 FRB BWM approach, the significance of the distinction in the ordering of the alternatives was higher than in the BWM method (see Table 13).

The result shows that IT2 FRB BWM approach is more successful than classical BWM method sort alternatives. It is also seen that the IT2 FRB BWM approach does not only provide useful ways of handling MCDM problems more flexibly and intelligently, but also it provides expert knowledge much more in the selection of alternatives. In addition, this study has the feature of being the first study to integrate rule-based IT-2 fuzzy numbers with the BWM and to handle this approach in supplier selection process.

For future research, the suppliers could be evaluated on different criteria in view of paradigms such as agile, global, resilient and especially smart, as we are in the age of industry 4, besides or outside the sustainability. Additionally, the developed FRB-BWM approach using IT-2 fuzzy numbers could be extended in different fuzzy environments such as intuitionistic, neutrosophic and pythagorean.

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