Int. J. Production Economics 153 (2014) 95–112

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

A fuzzy logic approach to supplier evaluation for development

Lauro Osiro, Francisco R. Lima-Junior, Luiz Cesar R. Carpinetti *

Production Engineering Department, School of Engineering of São Carlos, University of São Paulo, Avenida Trabalhador Sancarlense 400, 13566-590 São Carlos, SP, Brazil

ARTICLE INFO

Article history:
Received 27 September 2013
Accepted 8 February 2014
Available online 24 February 2014

Keywords:
Supplier evaluation
Supplier development
Fuzzy logic
Fuzzy pattern classification

ABSTRACT

Decision making techniques used to help evaluate current suppliers should aim at classifying performance of individual suppliers against desired levels of performance so as to devise suitable action plans to increase suppliers' performance and capabilities. Moreover, decision making related to what course of action to take for a particular supplier depends on the evaluation of short and long term factors of performance, as well as on the type of item to be supplied. However, most of the propositions found in the literature do not consider the type of supplied item and are more suitable for ordering suppliers rather than categorizing them. To deal with this limitation, this paper presents a new approach based on fuzzy inference combined with the simple fuzzy grid method to help decision making in the supplier evaluation for development. This approach follows a procedure for pattern classification based on decision rules to categorize supplier performance according to the item category so as to indicate strengths and weaknesses of current suppliers, helping decision makers review supplier development action plans. Applying the method to a company in the automotive sector shows that it brings objectivity and consistency to supplier evaluation, supporting consensus building through the decision making process. Critical items can be identified which aim at proposing directives for managing and developing suppliers for leverage, bottleneck and strategic items. It also helps to identify suppliers in need of attention or suppliers that should be replaced.

1. Introduction

Nowadays, manufacturing companies rely heavily on suppliers for providing materials and components used in finished products. Some authors say that approximately 50–70% of production costs are spent on purchased materials and components (Prajogo et al., 2012). Purchasing decisions affect important activities such as inventory management and production planning and control (Katsikeas et al., 2004; Govindan et al., 2010) and have a significant influence on the cost, quality and delivery of products of the buying company (Talluri and Sarkis, 2002). Thus, managing the performance of suppliers and supporting their continuous improvement has become very critical for managing organizations and supply chains (Schoenherr et al., 2012).

Managing buyer–supplier relationships includes activities such as supplier selection and development (Park et al., 2010; Chen, 2011; Inemek and Matthyssens, 2011). Supplier evaluation helps to make decisions about supplier selection and development (Schmitz and Platts, 2004). Supplier development is commonly defined as any effort or set of practices of a buying company with its supplier aiming at increasing the performance and capabilities of the supplier so as to better meet the buying firm's supply needs (Govindan et al., 2010; Bai and Sarkis, 2011). There are many supplier development practices that may be used (Krause, 1997; Govindan et al., 2010; Bai and Sarkis, 2011; Blome et al., 2013; Dekkers et al., 2013; He et al., 2014). Choosing what type of supplier development practice or what course of action to deploy to a particular supplier first of all depends on the supplier's evaluation.

There are variety of models proposed in the literature aimed at evaluating and segmenting the base of suppliers based on the evaluation of the suppliers related to several factors such as quality, delivery, financial health and technical capabilities, among others (Olsen and Ellram, 1997; Araz and Ozkarahan, 2007; Sarkar and Mohapatra, 2006; Omurca, 2013; Rezaei and Ortt, 2013a, 2013b). Most of them are two dimensional models and the supplier base segmentation process is based on dimensions related to supplier performance, such as attractiveness of the supplier and intensity of the relationship (Olsen and Ellram, 1997), short-term performance and long-term capability (Sarkar and Mohapatra, 2006) and willingness and capabilities (Rezaei and Ortt, 2013a, 2013b). However, decision making related to what type of supplier development practice or what course of action to take regarding a particular supplier depends not only on the categorization of the supply based on its evaluation of performance. The type of item to be supplied and what implications it may have on supply management should also be considered. A much cited item classification model was proposed by Kraljic (1983), which classifies items into four categories: strategic; bottleneck; leverage and noncritical. Kraljic

* Corresponding author.
E-mail addresses: lauro.osiro@gmail.com (L. Osiro), eng.franciscojunior@gmail.com (F.R. Lima-Junior), carpinet@sc.usp.br (L.C.R. Carpinetti).

http://dx.doi.org/10.1016/j.ijpe.2014.02.009
0925-5273

(1983) proposes that each of these categories demands a distinctive purchasing strategy. According to a study carried out by Nellore and Söderquist (2000) in the automotive industry, leverage, bottleneck and strategic items all require increasing degrees of collaboration in the specification process. Consequently, the higher the evaluation of the potential for partnership of a particular supplier, the higher the chance of developing a strategic partner will be.

Another important issue to be considered refers to the techniques used in the decision making process. Different decision making techniques are proposed in the literature to deal with the process of supplier evaluation, especially in supplier selection (De Boer et al., 2001; Wu and Barnes, 2011; Ho et al., 2010; Chai et al., 2013). Evaluation for the purpose of supplier development differs from the case of supplier selection, in the sense that the latter seeks to define an order of preference among potential suppliers while the former aims to categorize suppliers (De Boer et al., 2001; Keskin et al., 2010; Omurca, 2013). However, the techniques proposed by most of the studies on supplier evaluation found in the literature are more adequate for ordering suppliers (Chen et al., 2006; Sarkar and Mohapatra, 2006; Araz and Ozkarahan, 2007; Çelebi and Bayraktar, 2008; Wang, 2008; Lee et al., 2009; Lin, 2009; Park et al., 2010; Chen, 2011; Zeydan et al., 2011; Baskarahan et al., 2012; Pitchipoo et al., 2013; Rezaei and Ortt, 2013a). Another limitation regards the use of techniques based on comparison between suppliers (Olsen and Ellram, 1997; Sarkar and Mohapatra, 2006; Araz and Ozkarahan, 2007; Tuzkaya et al., 2009; Lee et al., 2009; Park et al., 2010; Shirinfar and Haleh, 2011; Zeydan et al., 2011; Rezaei and Ortt, 2013a). Since the main aim of evaluation for supplier development is to classify individual suppliers based on gaps between real and desired performance, techniques that yield relative performance evaluations are not the most adequate ones. On the other hand, fuzzy rule-based classification methods (Ishibuchi et al., 1992; Nozaki et al., 1996; Castellano and Fanelli, 1999; Nguyen et al., 2012; Lima et al., 2013) are especially useful for categorizing alternatives, as is the case of segmenting products or suppliers in purchasing models. However, none of the proposals found in the literature dealing with supplier evaluation and segmentation adopts a procedure for fuzzy pattern classification based on decision rules.

Therefore, this paper proposes a new approach for evaluation of suppliers for development purposes. Categorization of suppliers for development is dependent on the evaluation of the suppliers, as well as on the categorization of the supplied items. Items are categorized according to the dimension complexity of item and complexity of supply market. Evaluation of suppliers is made on the basis of short-term delivery performance and long-term potential for partnership. Fuzzy inference system combined with the simple fuzzy grid method (Ishibuchi et al., 1992) is also proposed in a procedure for pattern classification so as to categorize items and suppliers. In doing so, it is possible to categorize supplier performance according to the item category so as to indicate strengths and weaknesses of current suppliers and to aid decision making concerning action planning for supplier development. Representation of classes of supplier performance and items by fuzzy numbers allows for subjectivity of the decision makers. Also, the base of decision rules of a fuzzy inference system is designed grounded on *if–then* scenarios devised by specialists, therefore modeling human reasoning.

A descriptive quantitative approach was adopted as a research method (Bertrand and Fransoo, 2002). The fuzzy inference systems were implemented in FuzzyTech® and MATLAB® and applied to a case in the automobile industry. A 3^k factorial design was used to test the consistency and sensitivity of the inference systems. This paper is organized as follows: Section 2 briefly revises the subject of supplier management, presenting the contributions from the literature on supplier evaluation. Section 3 presents some fundamental concepts regarding the fuzzy set theory used in the proposition. The proposed fuzzy inference systems combined with the fuzzy grid method are described in detail in Section 4. Section 5 presents the application case and the sensitivity analysis. Final remarks and conclusion about this research are made in Section 6.

2. Supplier evaluation and development

Supplier evaluation is a fundamental activity to manage buyer–supplier relationship. There are at least two distinct phases in the supply management process in which supplier evaluation happens. First, evaluation is made during the selection process. In this case, the final goal of the evaluation process is to define an order of preference among the potential suppliers so as to select those preferred ones. After selecting, in the supplier development phase, supplier evaluation is made on a regular basis with the aim of managing and improving the buyer–supplier relationship. In the development phase, the main aim is to assess individual suppliers in order to plan and implement initiatives aiming at improving the performance and capabilities of the supplier so as to better fulfill the supply needs. Unlike the selection phase, the main point of evaluation in the development phase is to assess the performance of individual suppliers compared to desired levels of performance.

Supplier development initiatives may include continuous improvement programs for certification of management systems, knowledge and resource transfer for improving co-design and production capabilities (Krause, 1997; Blome et al., 2014; Dekkers et al., 2013; He et al., 2014). Supplier development is especially important for critical items such as leverage, bottleneck and strategic items (Kraljic, 1983; Nellore and Söderquist, 2000; De Boer et al., 2001). Leverage items, despite the possibility of several suppliers, have a high impact on the quality and cost of final products. On the contrary, bottleneck items, despite their relatively low profit impact, present supply risks because of scarcity or a monopolistic market. Strategic items are critical as they have a high impact on quality and cost and at the same time there are few suppliers which can attend the specification requirements (Nellore and Söderquist, 2000; De Boer et al., 2001). Thus, supplier development is important to establish long-term collaborative relationship so as to minimize supply risks and enable supply chain management strategies to be used such as early supplier involvement (He et al., 2014), vendor management inventory and collaborative planning, forecasting and replenishment (Yao et al., 2013).

There are variety of quantitative and qualitative criteria used to evaluate supplier performance. Table 1 presents a review of the criteria for supplier evaluation found in the literature. Criteria such as price, quality, delivery, financial and technological capabilities are the most commonly used.

Several studies presented in the literature group these criteria into one or two dimensions of supplier evaluation and classification. Olsen and Ellram (1997) propose a segmentation model to evaluate suppliers regarding two dimensions: supplier attractiveness and strength of the relationship. They suggest that supplier attractiveness is dependent on technological, organizational, financial and economic factors, production performance, culture and strategy. As for the strength of the relationship, they suggest economic factors, characteristics of the exchange relationship, cooperation and proximity. Based on these dimensions, the supplier is then categorized into one out of nine categories depending on the level (low, moderate or high) that a particular supplier is evaluated concerning these two dimensions. Araz and Ozkarahan (2007) propose a uni-dimensional model to evaluate and classify suppliers according to their co-design ability and overall performance. Based on 10 criteria, including design-related criteria, suppliers are categorized as pruning, competitive, promising or strategic. Omurca (2013) also propose a uni-dimensional model to group suppliers in clusters based on a set of 11 criteria. Sarkar and

Table 1
A review of criteria for supplier evaluation.

Performance dimension	Criteria	Kraljic (1983)	Olsen and Ellram (1997)	Dyer et al. (1998)	Bensaou (1999)	Toni and Nassimbeni (2001)	Jain et al. (2004)	Ohdar and Ray (2004)	Chin et al. (2006)	Sarkar and Mohapatra (2006)	Araz and Ozkarahan (2007)	Lee et al. (2009)	Shih et al. (2009)
Financial performance	Financial capability		X	X	X					X	X	X	
	Price	X	X	X	X			X		X		X	X
Logistic performance	Delivery	X	X	X	X		X	X		X	X	X	X
	Flexibility		X										X
	Geographical location			X						X			
	Reserve capacity		X							X			
	Service level							X					X
Organizational and cultural factors	Compatibility of organizational cultures	X	X									X	
	Competitive pressure	X		X									
	Evaluation and certification system								X				
	Organization and management	X	X										
	Supplier strategic objective				X								
	Training and education			X					X				
Quality management and improvement	Commitment to improvement and cost reduction			X							X	X	
	Problem resolution		X	X						X			
	Product quality	X	X	X	X		X	X	X	X	X	X	X
	Warranty and after sales support									X			
Sustainability	Environmental effects and preventive actions												
	Reputation for integrity									X			
	Work safety and labor health									X			
Technological capability	Design and development capabilities		X	X	X								
	Process/manufacturing capability		X	X	X								
	Technological capability		X	X	X	X				X	X	X	
Trust and information sharing	Asset specificity			X	X								
	Ease of communication		X	X	X	X				X	X		
	Long-term relationship	X	X	X	X				X			X	
	Reciprocal arrangement	X	X	X								X	
	Top management support	X	X	X						X		X	
	Trust		X	X	X							X	
	Willingness to share information		X	X	X	X			X				

Performance dimension	Criteria	Govindan et al. (2010)	Keskin et al. (2010)	Lee and Drake (2010)	Pagell et al. (2010)	Park et al. (2010)	Chen (2011)	Zeydan et al. (2011)	Amindoust et al. (2012)	Luzzini et al. (2012)	Prajogo et al. (2012)	García et al. (2013)	Omurca (2013)	Rezaei and Ortt (2013a)
Financial performance	Financial capability		X		X	X			X				X	
	Price	X		X	X	X	X		X	X	X	X	X	X

Table 1 (*continued*)

Performance dimension	Criteria	Proposed by												
		Govindan et al. (2010)	Keskin et al. (2010)	Lee and Drake (2010)	Pagell et al. (2010)	Park et al. (2010)	Chen (2011)	Zeydan et al. (2011)	Amindoust et al. (2012)	Luzzini et al. (2012)	Prajogo et al. (2012)	García et al. (2013)	Omurca (2013)	Rezaei and Ortt (2013a)
Logistic performance	Delivery	X		X	X	X	X	X	X	X	X	X	X	X
	Flexibility	X		X			X		X		X		X	
	Geographical location		X			X			X					
	Reserve capacity					X			X					
	Service level						X		X				X	
Organizational and cultural factors	Compatibility of organizational cultures				X	X								
	Competitive pressure	X												
	Evaluation and certification system	X	X					X			X			
	Organization and management				X	X		X	X				X	
	Supplier strategic objective	X			X									
	Training and education													
Quality management and improvement	Commitment to improvement and cost reduction	X					X			X	X			X
	Problem resolution	X	X			X	X	X						X
	Product quality	X		X	X	X	X	X	X	X	X	X	X	X
	Warranty and after sales support							X						
Sustainability	Environmental effects and preventive actions		X		X				X	X			X	
	Reputation for integrity					X							X	
	Work safety and labor health		X		X				X				X	
Technological capability	Design and development capabilities		X	X				X		X			X	X
	Process/manufacturing capability		X										X	X
	Technological capability				X	X			X				X	
Trust and information sharing	Asset specificity	X												
	Ease of communication	X			X	X	X							
	Long-term relationship				X	X					X			
	Reciprocal arrangement	X					X							
	Top management support	X						X						X
	Trust	X				X								
	Willingness to share information					X								

Mohapatra (2006) propose a two-dimensional model in which suppliers are segmented into motivated and de-motivated categories based on evaluating short-term performance and long-term capability. Short-term performance criteria are price, quality, delivery, lead time and attitude. As for long-term capability the authors consider quality system, financial capability, production facilities, management and organization, technological capability and reputation, among others. Rezaei and Ortt (2013a, 2013b) also propose a two-dimensional model to evaluate and classify suppliers based on the dimensions' willingness and capability. However, their understanding of capability differs from what is proposed by Sarkar and Mohapatra (2006) as they consider criteria such as price, delivery, quality, etc. On the other hand, criteria such as commitment to quality, communication openness, relationship among others which are associated to capability are considered by them under the dimension willingness.

The decision making techniques used in supplier evaluation also varies widely. It includes multi-attribute decision making techniques (MADM), mathematical programming and artificial intelligence techniques (Wu and Barnes, 2011; Ho et al., 2010; Chai et al., 2013). Most of the studies do not clearly differentiate the evaluation method proposed if either for selection or development (Chen et al., 2006; Çelebi and Bayraktar, 2008; Lin, 2009; Chen, 2011; Pitchipoo et al., 2013). Table 2 presents a summarized review of decision making approaches more suitable for evaluating suppliers for development purposes. Comparative techniques such as AHP (Olsen and Ellram, 1997; Park et al., 2010), ANP (Lee et al., 2009), Fuzzy AHP (Zeydan et al., 2011; Rezaei and Ortt, 2013a), Fuzzy ANP (Shirinfar and Haleh, 2011) and PROMETHEE (Araz and Ozkarahan, 2007; Tuzkaya et al., 2009) present some limitations to deal with the problem of evaluation for supplier development. First, the main purpose of evaluation is to classify individual suppliers based on gaps between real and desired performance and not relative performance evaluation. Furthermore, these techniques limit the number of simultaneous evaluated alternatives. Saaty (1990) suggests that the number criteria or alternatives to be compared should be limited to nine so as not to compromise human judgment and its consistency.

Decision making in supplier evaluation is affected by uncertainty mainly due to the vagueness intrinsic to appraisal of qualitative criteria, as well as imprecise weighing of different criteria by different decision makers. The importance of qualitative factors in business performance has increased despite its subjective nature and difficulties to measure (Kannan and Tan, 2002). Artificial intelligence techniques can cope better with the uncertainty of supplier evaluation than other techniques because they are designed to mimic human judgment (Amindoust et al., 2012; Lima et al., 2013). Fuzzy set theory has been extensively used to deal with the uncertainty intrinsic to supplier evaluation (Ho et al., 2010; Chai et al., 2013). However, most of the fuzzy-based approaches presented in Table 2 are more suitable for ordering suppliers and not for categorizing them, which would be desirable in supplier evaluation for development purposes. Keskin et al. (2010) propose the use of fuzzy adaptive resonance theory (fuzzy ART) as a categorization method for supplier evaluation and selection. Rezaei and Ortt (2013b) propose the use of fuzzy inference for supplier segmentation. However, these two studies do not use fuzzy numbers to model the range vagueness of the classes used in the categorization process.

Finally, none of the reviewed models based on the fuzzy set theory presented in the literature propose an approach that considers the type of item to be supplied and what the implications are for supplier management (Ohdar and Ray, 2004; Sarkar and Mohapatra, 2006; Tuzkaya et al. 2009; Awasthi et al., 2010; Keskin et al., 2010; Shirinfar and Haleh, 2011; Zeydan et al., 2011; Omurca, 2013; Rezaei and Ortt, 2013a, 2013b). Considering this, the item classification proposed by Kraljic (1983) can help in the supplier development decision process, as proposed in Section 4. Fundamental fuzzy concepts are briefly reviewed in the following section.

3. Fuzzy set theory

The fuzzy set theory (Zadeh, 1965, 1973) is used for modeling decision making processes based on imprecise and vague information such as judgment of decision makers. Qualitative aspects are represented by the means of linguistic variables, which are expressed qualitatively by linguistic terms and quantitatively by a fuzzy set in the universe of discourse and respective membership function. Operations between linguistic variables involve the concepts presented next.

Table 2
Summarized review of decision making techniques for supplier evaluation.

Approach	Technique(s)	Proposed by	Scope
Single method	Analytic Hierarchy Process (AHP)	Park et al. (2010)	Supplier relationship management
	An approach based on Grey Set Theory	Baskarahan et al. (2012)	Sustainability evaluation of textile suppliers
	Analytic Network Process (ANP)	Lee et al. (2009)	Evaluation of buyer–supplier relationships in high-tech industry
	Fuzzy inference	Frayret et al. (1998)	An approach to model and manage cost-risk trade-off in networked manufacturing
	PROMETHEE	Araz and Ozkarahan (2007)	Supplier evaluation and management system for strategic sourcing
	Comparison of fuzzy numbers	Sarkar and Mohapatra (2006)	Evaluation of supplier capability and performance
Hybrid method	ANP and VIKOR	Hsu et al. (2013)	Carbon performance evaluation of supplier in the electronics industry
	Fuzzy AHP	Rezaei and Ortt (2013a)	Supplier segmentation based on multicriteria
	Fuzzy ANP and fuzzy PROMETHEE	Tuzkaya et al. (2009)	Environmental performance evaluation of suppliers
	Fuzzy ANP, fuzzy TOPSIS and fuzzy PROMETHEE	Shirinfar and Haleh (2011)	Supplier performance evaluation and allocation of ordered quantities
	Fuzzy ART algorithm	Keskin et al. (2010)	Supplier evaluation and selection
	Fuzzy c-means combined with rough set theory	Omurca (2013)	Supplier evaluation, selection and development
	Fuzzy inference	Rezaei and Ortt (2013b)	Supplier segmentation based on multicriteria
	Fuzzy logic combined with genetic algorithm	Ohdar and Ray (2004)	Performance measurement and evaluation of suppliers
	Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Awasthi et al. (2010)	Environmental performance evaluation of suppliers
	Fuzzy TOPSIS, Fuzzy AHP and DEA	Zeydan et al. (2011)	Supplier selection and performance evaluation

3.1. Fundamental definitions

3.1.1. Definition 1: fuzzy set

A fuzzy set $\tilde{A}$ in X is defined by

$$\tilde{A} = \{x,\ \mu_A(x)\}, \qquad x \in X \tag{1}$$

where $\mu_A(x)\ :\ X \to [0,1]$ is the membership function of $\tilde{A}$ and $\mu_A(x)$ is the degree of pertinence of x in $\tilde{A}$. If $\mu_A(x)$ equals 0, x does not belong to the fuzzy set $\tilde{A}$. If $\mu_A(x)$ equals 1, x completely belongs to the fuzzy set $\tilde{A}$. However, unlike the classical set theory, if $\mu_A(x)$ has a value between 0 and 1, x partially belongs to the fuzzy set $\tilde{A}$. That is, the pertinence of x is true with a degree of membership given by $\mu_A(x)$ (Zadeh, 1965; Zimmermann, 1991).

3.1.2. Definition 2: fuzzy numbers

A fuzzy number is a fuzzy set in which the membership function satisfies the conditions of normality

$$\sup \tilde{A}\ [x]_{x\ \epsilon\ X} = 1 \tag{2}$$

and of convexity

$$\tilde{A}[\lambda\, x_1 + (1-\lambda)x_2 \geq \min\,[A(x_1), A(x_2)]] \tag{3}$$

for all x_1, $x_2 \text{Є} X$ and all $\lambda \text{Є}[0,1]$. The triangular fuzzy number is commonly used in decision making due to its intuitive membership function, $\mu_A(x)$, given by

$$\mu_A(x) = \begin{cases} 0 & \text{for } x < l, \\ \frac{x-l}{m-l} & \text{for } a \leq x\ \leq m, \\ \frac{u-x}{u-m} & \text{for } m \leq x\ \leq u, \\ 0 & \text{for } x > u, \end{cases} \tag{4}$$

where l, m, and u are real numbers with $l < m < u$ (Fig. 1a). Outside the interval $[l, u]$, the pertinence degree is null, and m represents the point in which the pertinence degree is maximum. Trapezoidal fuzzy numbers are also frequently used in decision making processes, as illustrated in Fig. 1b (Zimmermann, 1991; Kahraman, 2008).

3.1.3. Definition 3: t-norm

A t-norm is a binary operation $t:\ [0,1] \times [0,1] \to [0,1]$ that satisfies the following properties of commutativity (Eq. (5)), associativity (Eq. (6)), monotocity (Eq. (7)) and boundary conditions (Eqs. (8) and (9)):

$$a\ t\ b\ = b\ t\ a \tag{5}$$

$$a\ t\ (b\ t\ c) = (a\ t\ b)\ t\ c \tag{6}$$

$$\text{if } \ b \leq c, \ \text{ then } \ a\ t\ b \leq a\ t\ c \tag{7}$$

$$a\ t\ 1\ = a \tag{8}$$

$$a\ t\ 0\ = 0 \tag{9}$$

where a, b, $c \in [0,1]$. Any t-norm produces a result equivalent to the intersection of fuzzy sets, that is, $\tilde{A} \cap X = \tilde{A}$, $\tilde{A} \cap \varnothing = \varnothing$ (Zimmermann, 1991; Kahraman, 2008).

3.1.4. Definition 4: s-norm

A s-norm is a function $s:\ [0,1] \times [0,1] \to [0,1]$ that, similarly to t-norm, satisfies the conditions of commutativity, associativity and monotocity. However, their boundary conditions are defined by

$$a\ s\ 0\ = a \tag{10}$$

$$a\ s\ 1 = 1 \tag{11}$$

where a, b, $c \in [0,1]$. s-norms are used in union operations of fuzzy sets, that is, $\tilde{A} \cup X = X$, $\tilde{A} \cup \varnothing = \tilde{A}$ (Pedrycz and Gomide, 2007; Kahraman, 2008).

3.1.5. Definition 5: fuzzy relation

Relations represent and quantify associations between objects. A relation R defined over the Cartesian product of X and Y is a collection of selected pairs (x, y) expressed by

$$R:\ X\ \times\ Y \to [0,1] \tag{12}$$

where $x \in X$ and $y \in Y$. If $R(x,y) = 1$, then x and y are related; if $R(x,y) = 0$ then these two elements are unrelated; otherwise, if $0 < R(x,y) < 1$, there is a partial association between x and y (Pedrycz and Gomide, 2007; Kahraman, 2008).

3.2. Fuzzy pattern classification

A fuzzy pattern is defined as a set of values of characteristics associated with a class of representation, which are immersed in an environment of uncertainty (Pedrycz, 1990). Several approaches based on fuzzy logic have been proposed for pattern classification, such as methods based on fuzzy clustering (Pedrycz and Kwak, 2006), fuzzy pattern matching (Dubois et al., 1988) and fuzzy rules (Ishibuchi et al., 1992, 1993; Nozaki et al., 1996; Castellano and Fanelli, 1999; Nguyen et al., 2012). In problems where the classes of patterns can be characterized by general relationship among entities, it becomes attractive to build classifiers based on rules (Duda et al., 2000). In decision making problems, fuzzy rule-based classification methods are especially useful for categorizing sets of alternatives according to their similarity. Ishibuchi et al. (1992) proposed a rule-based classification method known as the simple fuzzy grid method. This method has been extensively used to develop new approaches for fuzzy pattern classification (Ishibuchi et al., 1993; Nozaki et al., 1996; Castellano and Fanelli, 1999). The simple fuzzy grid method partitions the pattern space into fuzzy subspaces and defines a fuzzy rule for each subspace, as shown in Fig. 2. The fuzzy rules are simultaneously used in fuzzy inference. Thus, the knowledge for classification problems is expressed by each fuzzy rule. The pattern classification method proposed by

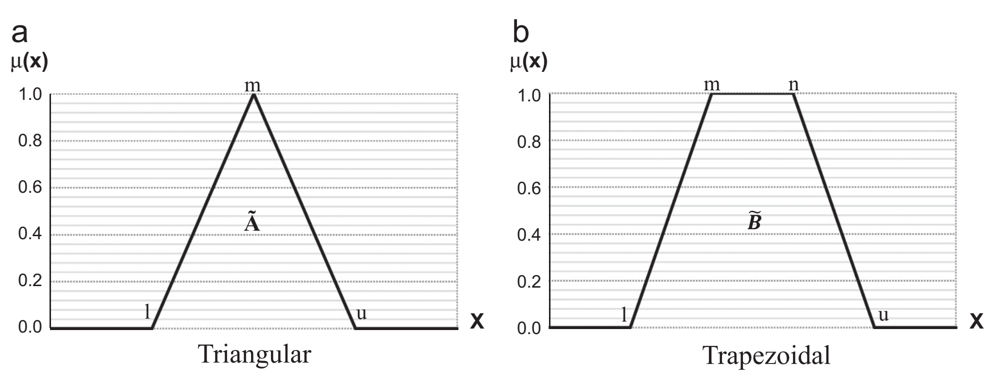

Fig. 1. Triangular and trapezoidal fuzzy numbers.

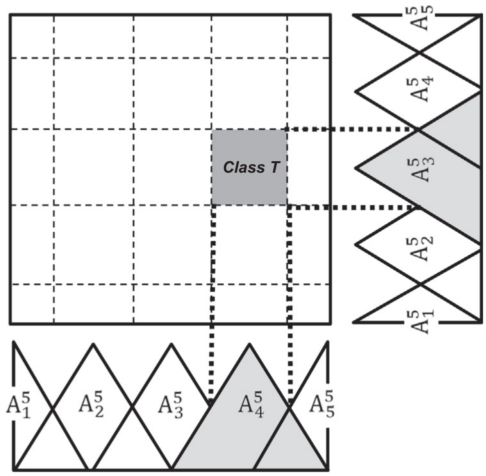

Fig. 2. Fuzzy classes and patterns.

Ishibuchi et al. (1992) consists of two procedures described in the following sections.

3.2.1. Fuzzy rule generation procedure

Suppose that k patterns $x_p=(x_1^p,\ldots,x_i^p,\ldots,x_n^p)$, $p=1,2,\ldots k$, with x_i^p defined in the continuum interval [0,1], are given as training patterns from m classes: Class 1 (C_1), Class 2 (C_2),…, Class t (C_t), …, Class m (C_m). In the context of supplier evaluation, x_p relates to a supplier performance pattern concerning the n criteria used in the evaluation process. As for the classes, they relate to group of suppliers with similar performance. In this step, the objective is to generate fuzzy rules that associate m classes with the patterns defined by x_p. For this, fuzzy rules of the following type are used:

Rule r

$$\text{IF } x_1^p \text{ is } A_1^r \text{ AND}\ldots\text{AND } x_n^p \text{ is } A_n^r$$
$$\text{THEN } x_p \text{ belongs to } C^r \text{ with } CF=CF^r \quad (13)$$

where r is the label of fuzzy rule, A_i^r $(i=1,2,\ldots,n)$ are fuzzy subsets in the unit interval [0,1], C^r is the consequent and CF is the grade of certainty (or grade of activation) of the fuzzy rule. The value of C^r is defined by one of the m classes, according to the following equation (Ishibuchi et al., 1992):

$$\beta_{Cr}= \max\{\beta_{C1},\ \beta_{C2},\ldots,\beta_{Ct},\ldots,\ \beta_{Cm}\} \quad (14)$$

where β_{Cr} indicates the largest compatibility grade of one of the m classes with the rth fuzzy rule. When the set of data for training of the rules are not available, the value of C^r can be defined based on experts' knowledge.

3.2.2. Classification procedure

Assuming that a rule set S is given to form a fuzzy rule-based classification system, an unknown pattern $x_p=(x_1^p,\ldots,x_i^p,\ldots,x_n^p)$ can be classified by two procedures:

(1) Calculate α_{Cr} for $r=1,\ldots,m$ as

$$\alpha_{Cr}= \max\left\{\sum_{i=1}^{m}\mu_{A_i^r}(x_i)CF^r \;\middle|\; C^r=C_t;\ \ r \in S\right\} \quad (15)$$

and

(2) Classify x_p in the class that maximize α_{Cr}. When multiple classes take the maximum value, the pattern x cannot be classified (Ishibuchi et al., 1992; Castellano and Fanelli, 1999).

3.3. Fuzzy inference system

In a fuzzy inference system, output fuzzy variables are inferred from input fuzzy variables according to a set of logic inference rules in linguistic terms, which form the knowledge base of a fuzzy system (Mamdani and Assilian, 1975; Amindoust et al., 2012; Olugu and Wong, 2012). A particular inference method, proposed by Mamdani and Assilian (1975), has been applied in a variety of problems. For instance, Liu et al. (2012) combine fuzzy inference with life cycle assessment techniques to estimate environmental aspects in environmental management system. Lin et al. (2012) apply fuzzy inference to potential hazard analysis and risk assessment of debris flows. Other studies found in the literature apply the Takagi–Sugeno fuzzy inference (Lin and Chen, 2010; Chen et al., 2010; Chen, 2010, 2006).

Fig. 3 illustrates the main components of a fuzzy inference system (Bojadziev and Bojadziev, 2007; Lima et al., 2013). The data base contains the input and output variables and corresponding fuzzy numbers. Fuzzification is the process that relates the numerical values of the crisp input variables to the values of the activated linguistic variables. The rule base contains the inference rules relating output variable (consequents) levels to input variable levels. Most usually *if…and…then* rules are used (Zimmermann, 1991; Amindoust et al., 2012; Olugu and Wong, 2012).

In the Mamdani inference method, the consequents in the base of rules are given by specialist opinions making this method more suitable for supporting decisions in the supplier selection process (Pedrycz and Gomide, 2007; Olugu and Wong, 2012; Lima et al., 2013). The product *t-norm* operator is adopted for the logic connective "and", as expressed in Eq. (16). For the logic connective "or" *s-norm V* (maximum) is usually adopted (Eq. (17)).

$$\mu_A(x)\ \text{ AND }\ \mu_B(y)=\{\mu_A(x)\ \times\ \mu_B(y)\} \quad (16)$$

$$\mu_A(x)\ \text{ OR }\ \mu_B(y)= \text{Max}\{\mu_A(x),\mu_B(y)\} \quad (17)$$

For each activated rule, the inference engine applies an implication relation R between the fuzzy number resulting from the logic operations, $\tilde{A}$, and the consequent, $\tilde{B}$. Commonly used implication operators are Product (Larsen), Minimum (Mamdani) and Max–Min (Zadeh), respectively in Eqs. (18), (19) and (20) (Bojadziev and Bojadziev, 2007; Pedrycz and Gomide, 2007).

$$\mu_{R_{A\to B}}(x,\ y)=\{\mu_A(x)\times\mu_B(y)\} \quad (18)$$

$$\mu_{R_{A\to B}}(x,y)= \text{Min}\{\mu_A(x),\mu_B(y)\} \quad (19)$$

$$\mu_{R_{A\to B}}(x,\ y)= \text{Max}\{1-\ \mu_A(x),\ \text{Min}\{\mu_A(x),\ \mu_B(y)\}\} \quad (20)$$

The output fuzzy number of each rule is defined by the composition between a fuzzy singleton and the implication relation. Composition operators of fuzzy relations commonly used are Max–Min, Max–Prod and Max–Media, respectively in Eqs. (21), (22) and (23) (Zimmermann, 1991; Pedrycz and Gomide, 2007).

$$S\ o\ R(x,y)= \text{Max}\{\ \text{Min}(\mu_S(x,y),\ \mu_R(y,z))\} \quad (21)$$

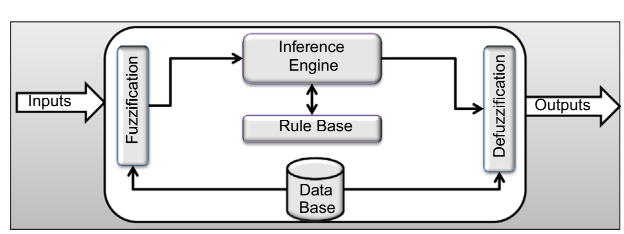

Fig. 3. Fuzzy inference method.

$$S \bullet R(x,z) = \text{Max}\,\{\mu_S(x,y) \times \mu_R(y,z)\} \tag{22}$$

$$S \oplus R = \text{Max}\,\{\tfrac{1}{2}(\mu_R(x,y) + \mu_s(y,z)\} \tag{23}$$

Aggregation of the resulting composition operations for each rule is the final step in the inference process. Aggregation can be performed by different operators, such as arithmetic, geometric or harmonic means, Min and Max (Zimmermann, 1991; Bojadziev and Bojadziev, 2007). The Max operator is preferred when compensation between input variables is desirable (Lima et al., 2013). The Max operator is given by

$$AG(.) = \text{Max}(\mu_{R1}(x), \mu_{R2}(x), ..., \mu_{Rn}(x)) \tag{24}$$

In the defuzzification interface, output fuzzy numbers are converted to a crisp number. A defuzzification technique commonly used is Center of Area (CoA), as in the following equation where n is the number of discrete points of the fuzzy set (Pedrycz and Gomide, 2007):

$$\text{CoA} = \frac{\sum_{k=1}^{n} \mu_A(x_k) * x_k}{\sum_{k=1}^{n} \mu_A(x_k)} \tag{25}$$

Alternatively, defuzzification can be made using the Mean of Maximum (MoM) and the First of Maximum (FoM) techniques given in Eqs. (26) and (27) respectively.

$$\text{MoM} = \frac{1}{m} \sum_{k=1}^{m} x_k, \tag{26}$$

where m is the number maximum points in the membership function A (Zimmermann, 1991; Pedrycz and Gomide, 2007).

$$\text{FoM} = \underset{X}{\text{Min}}\,\{\,\text{Max}\,\{\mu_A\}\} \tag{27}$$

The choice of operators in the inference engine depends on the situation at hand, as well as computational complexity of the inference process.

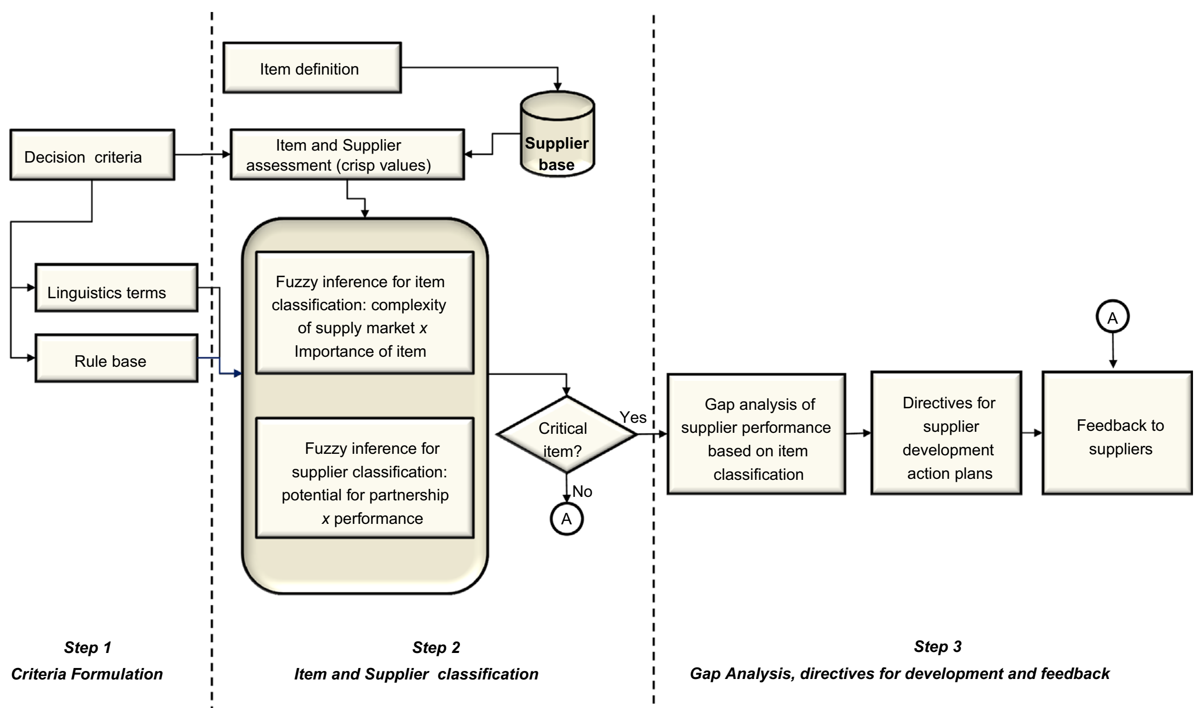

Fig. 4. Framework of the proposed method for supplier evaluation.

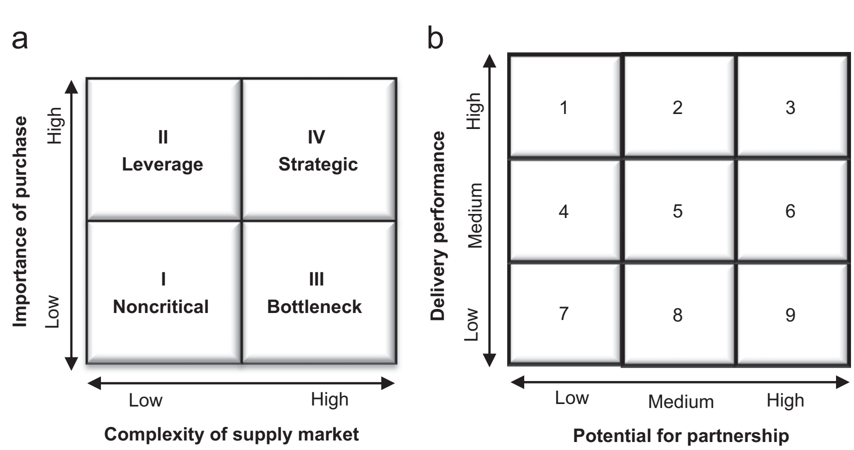

Fig. 5. Item and supplier classification models.

4. The proposed method of supplier evaluation for development

Fig. 4 illustrates the framework of the proposed method for evaluation of suppliers for development purposes. In step one, criteria formulation, the set of criteria used for item and supplier classification are defined based on the proposed dimensions of item and supplier classification, as well as on the requirements posed by the buyer–supplier relationship. In step two, the item and supplier classification are based on the two-dimensional models for items as well as supplier classification illustrated in Fig. 5. Item classification is based on the dimensions proposed by Kraljic (1983), that is, complexity of supply market and importance of items (Fig. 5a). As for supplier classification, the dimensions proposed are related to short-term delivery performance and long-term potential for partnership (Fig. 5b). The dimension short-term delivery performance is aligned with the dimensions proposed by Olsen and Ellram (1997), Sarkar and Mohapatra (2006) and Rezaei and Ortt (2013a, 2013b). The second dimension, long-term potential for partnership, seeks to bring together criteria related to long-term capabilities, the potential for collaboration in co-development and strategic partnership. In this sense, it follows the dimensions proposed by Sarkar and Mohapatra (2006), Rezaei and Ortt (2013a, 2013b) and Olsen and Ellram (1997).

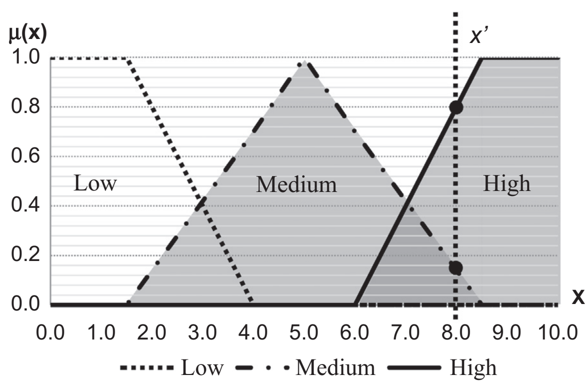

Fig. 6. Categorization of crisp output into a fuzzy class of performance.

Item classification (step 2) is the result of two fuzzy inference systems combined with the simple fuzzy grid method. The first system classifies complexity of supply market of a particular item as either high or low. The second system classifies importance of purchase for the particular item also as either high or low. The combination of the classifications of these two inference systems yield the item categorization as proposed by Kraljic (1983), which is strategic, bottleneck, leverage and non-critical items. Still in step two, supplier evaluation is also the result of a fuzzy inference process combined with the simple fuzzy grid method. The third system categorizes the supplier's potential for partnership as either low, medium or high. Finally, the fourth system categorizes the supplier's delivery performance also as either low, medium or high.

The base of rules of the inference systems consists of *if…and…then* rules. The antecedents are the input criteria. The consequent is the output dimension. The inference process is defined as in the Mamdani method:

- the consequents are given by specialist opinions;
- the Product operator is defined for the logic connective “and”, as expressed in Eq. (16);
- the Larsen implication relation is used as expressed in Eq. (18);
- the Max–Min composition operator is defined as expressed in Eq. (21);
- aggregation is performed by a Max operator as defined in Eq. (24); and

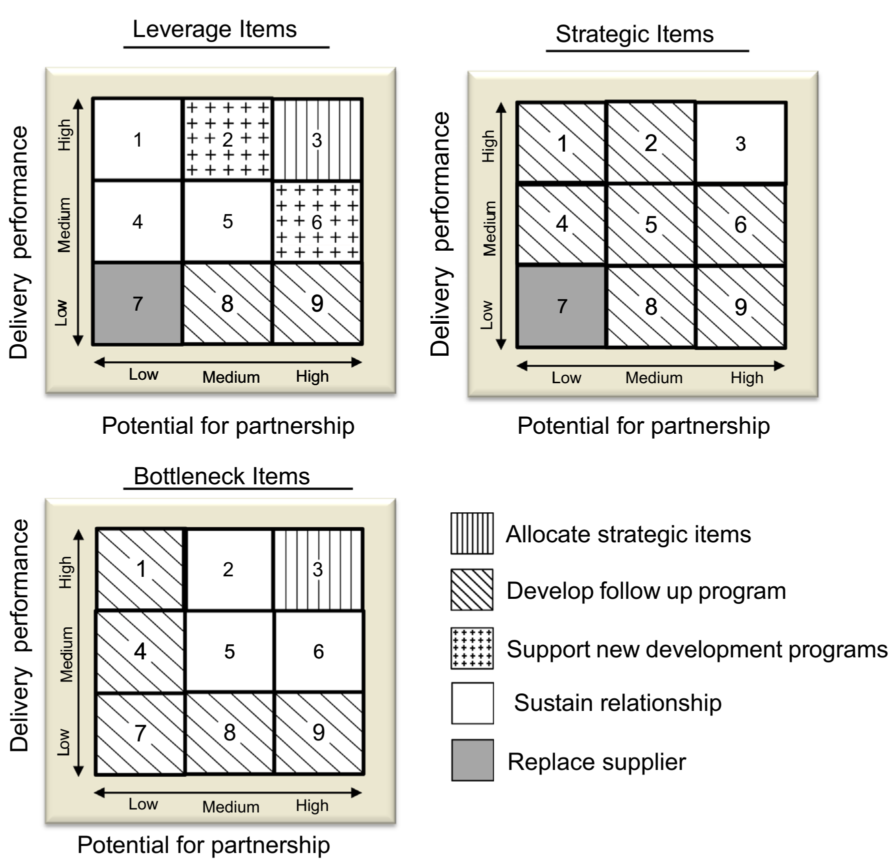

Fig. 7. Directives for supplier development dependent on the type of item.

Table 3
Item and supplier criteria used in the application case.

Classification model	Dimension	Criterion	Reference
Item	Complexity of supply market	Entry barriers (C_1)	Kraljic (1983)
		Co-development of product specification (C_2)	Nellore and Söderquist (2000) Luzzini et al. (2012)
		Market Concentration (C_3)	Kraljic (1983)
		Product uniqueness (C_4)	Kraljic (1983)
	Importance of purchase	Environmental contribution (C_5)	Pagell et al. (2010)
		Alignment with the core competencies of the buyer (C_6)	Olsen and Ellram (1997)
		Value-added profile (C_7)	Olsen and Ellram (1997)
Supplier	Potential for partnership	Commitment to improvement and cost reduction (C_8)	Chen (2011) Rezaei and Ortt (2013a)
		Ease of communication (C_9)	Park et al. (2010) Chen (2011)
		Financial capability (C_{10})	Amindoust et al. (2012) Park et al. (2010)
		Technical capability (C_{11})	Amindoust et al. (2012) Omurca (2013)
	Delivery performance	Delivery reliability (C_{12})	García et al. (2013) Omurca (2013)
		Price performance (C_{13})	Prajogo et al. (2012) Rezaei and Ortt (2013a)
		Quality of conformance (C_{14})	Luzzini et al. (2012) Rezaei and Ortt (2013b)
		Problem resolution (C_{15})	Sarkar and Mohapatra (2006) Zeydan et al. (2011)

Table 4
Membership functions of criteria related to complexity of supply market.

Criteria	Linguistic terms and membership functions								
	Low Trapezoidal			Medium Triangular			High Trapezoidal		
	$l_L = m_L$	n_L	u_L	l_M	m_M	u_M	l_H	m_H	$n_H = u_H$
C_1	0.00	2.50	5.50	2.50	5.50	8.00	5.50	8.00	10.00
C_2	0.00	1.50	5.50	2.00	5.50	9.00	5.50	9.50	10.00
C_3	0.00	1.00	6.00	1.00	6.00	9.00	6.00	9.50	10.00
C_4	0.00	2.50	6.00	2.50	6.00	8.50	6.00	8.50	10.00

Table 5
Membership functions of criteria related to importance of purchase.

Criteria	Linguistic terms and membership functions							
	Low Trapezoidal			Medium Triangular			High Triangular	
	$l_L = m_L$	n_L	u_L	l_M	m_M	u_M	l_H	$m_H = u_H$
C_5	0.00	1.00	6.00	1.00	6.00	10.00	6.00	10.00
C_6	0.00	2.50	6.00	2.50	6.00	10.00	6.00	10.00
C_7	0.00	1.00	5.00	1.00	5.00	10.00	5.00	10.00

- the Center of Area (CoA) technique as shown in Eq. (25) is used for defuzzification.

After defuzzification, the crisp output of each inference system is classified into a fuzzy class of performance. For instance, in case the crisp output is 8.0, as indicated in Fig. 6, it activates class "medium" with $\mu_m(x') = 0.16$ and class "high" with $\mu_H(x') = 0.8$. The performance class is the one with greater membership, which is "high".

In step three of the proposed method (Fig. 4), according to the classification of the item, it is possible to recommend directives for supplier development based on analyzing the gap between real and desired supplier performance. As illustrated in Fig. 7, the supplier performance expectations depend on the type of item and therefore the directives can be as follows:

- For strategic items, the supplier should be classified in cell three. Otherwise, the supplier needs closer supervision or it should be replaced.
- For leverage items, competitive bidding can be sustained when the supplier is classified in cells one or four. If it is classified in cells two or six, new development programs could be used so as to increase the opportunities of suppliers of strategic items. If it is classified into cell three, strategic items could be located to this supplier. Otherwise, the supplier needs closer supervision or it should be replaced.
- For bottleneck items, sustain the relationship if the supplier is classified into cells two, five or six. If it is classified in cell three, strategic items could be located to this supplier. Otherwise, the supplier needs closer supervision as in most situations it is not possible to easily replace a supplier of a bottleneck item.

In the case of noncritical items, since they are of low importance and there are many suppliers that could supply the items, the effort should be directed mainly to select alternative suppliers rather than trying to develop current suppliers. Therefore, in step three of the proposed method, suppliers of non-critical items is not evaluated with the objective of planning development initiatives but only to provide feedback to them.

The computational routines for the proposed decision process were implemented in FUZZYTECH® and MATLAB®. The membership functions of the linguistic terms of each criterion as well as the rule bases are dependent on the chosen criteria in the application cases.

5. Application case

The proposed method was applied in a manufacturing division of a transnational manufacturing company which is more than 80 years old; it has over 130,000 employees and plants in more than 180 countries. The plant under study manufactures off-road vehicles and equipment for construction and mining. Thousands of parts are purchased, ranging from simple screws to complex product sub-systems such as chassis and driver's cabin. Suppliers also differ, varying from small to large companies, as well as companies that cooperate in the product development process.

Decision makers from purchasing, quality management and manufacturing were interviewed with the aim of defining the criteria, linguistic terms, base of inference rules and rating some supplied materials and respective suppliers, following the steps proposed in the method (Fig. 4).

Table 6
Membership functions of criteria related to potential for partnership.

Criteria	Linguistic terms and membership functions							
	Low Trapezoidal			Medium Triangular			High Triangular	
	$l_L=m_L$	n_L	u_L	l_M	m_M	u_M	l_H	$m_H=u_H$
C_8	0.00	3.00	6.00	3.00	6.00	9.50	6.00	10.00
C_9	0.00	2.00	6.00	2.00	6.00	10.00	6.00	10.00
C_{10}	0.00	3.50	7.00	3.50	7.00	10.00	7.00	10.00
C_{11}	0.00	2.50	6.00	2.50	6.00	9.50	6.00	10.00

Table 7
Membership functions of criteria related to delivery performance.

Criteria	Linguistic terms and membership functions							
	Low Trapezoidal			Medium Triangular			High Triangular	
	$l_L=m_L$	n_L	u_L	l_M	m_M	u_M	l_H	$m_H=u_H$
C_{12}	0.00	3.00	6.00	3.00	6.00	9.50	6.00	10.00
C_{13}	0.00	2.00	6.00	3.00	6.00	9.00	6.00	10.00
C_{14}	0.00	3.50	6.50	3.50	6.50	9.50	6.50	10.00
C_{15}	0.00	2.50	6.00	2.50	6.00	9.50	6.00	10.00

Table 8
Membership functions of output variables, FIS 1 and 2.

FIS	Output variable	Linguistic terms and membership functions					
		Low Trapezoidal			High Trapezoidal		
		$l_L=m_L$	n_L	u_L	l_H	m_H	$n_H=u_H$
1	Complexity of supply market	0.00	3.00	8.00	3.00	8.00	10.00
2	Importance of purchase	0.00	2.00	8.00	2.00	8.00	10.00

5.1. Definition of criteria, linguistic terms and bases of rules

The criteria used to characterize the evaluation dimensions used in step two are presented in Table 3. The criteria used in the implementation of the method were chosen based on company requirements and are in line with the criteria presented in the literature.

The universe of discourse for all the input and output variables of the inference systems range from 0 to 10. Tables 4–7 present the linguistic terms of the input variables. The choices for triangular or trapezoidal membership functions, as well as their parameters were chosen so as to better represent the linguistic terms of each criterion. Tables 8 and 9 present the membership functions of the output variables.

The bases of rules of the inference systems were designed by the decision makers so as to represent the specialists' knowledge. The inference rules implement the expected influence of the antecedents on the consequents according to the perceptions of the decision makers. Table 10 illustrates the set of rules defined for the second FIS. The set of *if…and…then* logic rules relates the categories of importance of purchase to the antecedent fuzzy patterns. For instance, if value-added profile is “medium”, cost related to total cost is “medium” and environmental contribution is “high”, then the importance of purchase is “high”. It is important to emphasize that the weights of the sub-criteria are implicit in the rules.

5.2. Evaluation of item and suppliers and gap analysis

Table 11 presents a list of suppliers selected for evaluation and respective items supplied by them. The decision makers first rated each item regarding the chosen criteria, as presented in Table 12. Fig. 8 illustrates the rule viewer of Matlab© for the second FIS of the item classification model. Each rule is a row of plots and the antecedent and consequent variables are in the columns. For instance, for rule 5, the activated terms for variables C_5, C_6 and C_7 are respectively “low”, “medium” and “medium”. The graph in the last line and last column represents the output resulting from aggregation of the activated rules (4, 5, 7, 8, 13, 14 and 17).

Based on these scores and on the inference processes, items were classified as indicated in Table 13. Items I_3, I_8 and I_{15} were classified as strategic. Items I_1, I_{14} and I_{18} were classified as bottleneck. Items I_4, I_6, I_{10}, I_{13}, I_{17} and I_{19} were classified as leverage. The other items were classified as non-critical. To proceed with the decision process, following the proposed procedure, it was decided to focus on the leverage, bottleneck and strategic items.

After that, the decision makers rated the suppliers, as presented in Table 14. Table 15 presents the crisp output of the inference processes and the corresponding linguistic classes of supplier performance as a result from the categorization process. Table 16 presents the gap analysis based on the model presented in Fig. 7 and the consequent directives for action plans. The evaluated performance presented in the second column of Table 16 refers to the categories of supplier performance related to the potential for partnership and delivery

Table 9
Membership functions of output variables, FIS 3 and 4.

FIS	Output variable	Linguistic terms and membership functions								
		Low Trapezoidal			Medium Triangular			High Trapezoidal		
		$l_L=m_L$	n_L	u_L	l_M	m_M	u_M	l_H	m_H	$n_H=u_H$
3	Potential for partnership	0.00	1.50	5.00	2.50	5.00	7.50	5.00	8.50	10.00
4	Delivery performance	0.00	2.00	6.00	3.00	6.00	9.00	6.00	9.00	10.00

performance, as illustrated in Fig. 7. The expected performance indicated in the third column of Table 16 refers to expected categories of supplier performance in each dimension. In case the supplier supplies items of different categories, the expectation relates to the most demanding situation. For instance, since supplier S_2 supplies bottleneck, noncritical and leverage items (respectively I_1, I_2 and I_4), the ranges of expected performance for a supplier of a bottleneck item are considered in this case.

Analysis of the results presented in Table 16 shows that suppliers S_3 and S_{15} have an evaluated performance compatible with the expectations for suppliers of strategic items and therefore the directive is only to sustain the relationship. Since suppliers S_1, S_2, S_{13}, S_{17} and S_{18} were also evaluated as having a performance suitable for suppliers of bottleneck or leverage items, the directive for them is the same as before. Suppliers S_4, S_6 and S_{10} outperform in some way the expectations for suppliers of leverage items. Suppliers S_4 and S_6 are worth the effort of investing in development programs. Supplier S_4 outperforms the expected potential for partnership and therefore it is worth the effort of investing in development programs to improve delivery performance. As for supplier S_6, since it outperforms in delivery performance, the directive would be to support initiatives to further develop its potential for partnership. Supplier S_{10} outperforms expectations in both dimensions, an indication that could be considered for being involved in the co-development and supplying of strategic items. Finally, suppliers S_8, S_{14} and S_{19} underperform expectations regarding delivery performance. Thus, the directives would be to develop follow up programs for S_8 and S_{14} so as to improve their performance. As for supplier S_{19}, the recommendation would be to replace it since it performs well below expectation.

These directives as well as the item classifications presented in Table 13 were discussed with the decision makers interviewed during the application case. Based on their intuition and experience, they all agreed with the item classification output by the inference systems. They all reckoned that the directives were sound and positive. Some directives were also aligned with decisions already made by the company. For instance, the decision makers were already planning to involve supplier S_{10} in the co-development of a new strategic item. The company was also planning to develop alternative suppliers to replace supplier S_{19}.

5.3. Sensitivity analysis

Tests of the outputs of the inference systems were made with the aim of analyzing consistency and sensitivity of the inference systems. Sensitivity analysis aimed to evaluate

- the interaction effects of the input variables of the FIS on the output variables and
- the relative weight of the input variables implicit in the inference rules of each FIS.

To test the rules and fuzzy operations of the inference systems of the segmentation models, a full 3^k factorial design technique was used (Montgomery, 1991) with three or four factors depending on the FIS. Each factor was tested in three levels, corresponding to the three linguistic terms defined for the input variables. An inference system with three factors and with three linguistic terms each will have 3^3 decision rules to be tested.

Table 10
Base of rules of the second inference system.

Rule	Antecedents			Consequents
	Environmental contribution	Core competence	Value-added profile	Importance of purchase
1	Low	Low	Low	Low
2	Low	Low	Medium	Low
3	Low	Low	High	Low
4	Low	Medium	Low	Low
5	Low	Medium	Medium	Low
6	Low	Medium	High	High
7	Low	High	Low	Low
8	Low	High	Medium	High
9	Low	High	High	High
10	Medium	Low	Low	Low
11	Medium	Low	Medium	Low
12	Medium	Low	High	High
13	Medium	Medium	Low	Low
14	Medium	Medium	Medium	Low
15	Medium	Medium	High	High
16	Medium	High	Low	Low
17	Medium	High	Medium	High
18	Medium	High	High	High
19	High	Low	Low	Low
20	High	Low	Medium	Low
21	High	Low	High	High
22	High	Medium	Low	Low
23	High	Medium	Medium	High
24	High	Medium	High	High
25	High	High	Low	High
26	High	High	Medium	High
27	High	High	High	High

Table 12
Scores of items on evaluated criteria.

Item	Complexity of supply market				Importance of purchase		
	C_1	C_2	C_3	C_4	C_5	C_6	C_7
I_1	7.00	7.50	7.00	3.00	2.50	7.50	4.00
I_2	6.50	5.00	3.00	6.00	3.50	6.50	3.00
I_3	4.00	8.00	6.00	3.00	10.00	10.00	7.00
I_4	7.00	3.50	3.50	4.00	9.00	10.00	9.00
I_5	5.00	6.00	7.50	4.00	2.50	6.50	5.00
I_6	6.00	7.00	9.00	7.00	8.00	7.50	9.50
I_7	1.00	3.00	3.00	1.00	1.00	2.00	0.50
I_8	7.00	9.00	5.00	2.00	6.00	9.00	8.50
I_9	6.50	4.00	3.50	4.50	3.00	8.00	3.00
I_{10}	2.00	8.00	4.50	7.00	10.00	7.00	10.00
I_{11}	4.00	3.00	8.00	4.00	4.00	6.50	2.50
I_{12}	4.00	6.00	1.50	1.00	2.00	7.50	4.00
I_{13}	6.50	4.00	4.50	5.00	9.00	7.00	6.00
I_{14}	9.00	8.00	10.00	6.00	3.50	7.00	4.50
I_{15}	8.00	9.00	5.00	3.00	9.50	9.50	8.00
I_{16}	6.50	4.00	4.00	3.00	8.50	3.00	4.00
I_{17}	4.50	6.50	4.00	4.50	7.00	9.00	9.00
I_{18}	8.00	7.00	5.00	3.00	7.50	3.50	4.50
I_{19}	7.00	4.00	2.50	3.50	6.50	8.00	10.00
I_{20}	7.00	3.50	5.00	3.00	0.50	1.50	4.00

Table 11
Analyzed items and respective suppliers.

Item	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}	I_{14}	I_{15}	I_{16}	I_{17}	I_{18}	I_{19}	I_{20}
Supplier	S_1, S_2	S_1, S_2	S_3	S_2, S_5	S_1, S_4	S_2, S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{10}, S_{12}	S_{13}	S_{14}	S_{15}	S_7, S_{16}	S_{17}	S_{18}	S_{13}, S_{19}	S_{20}

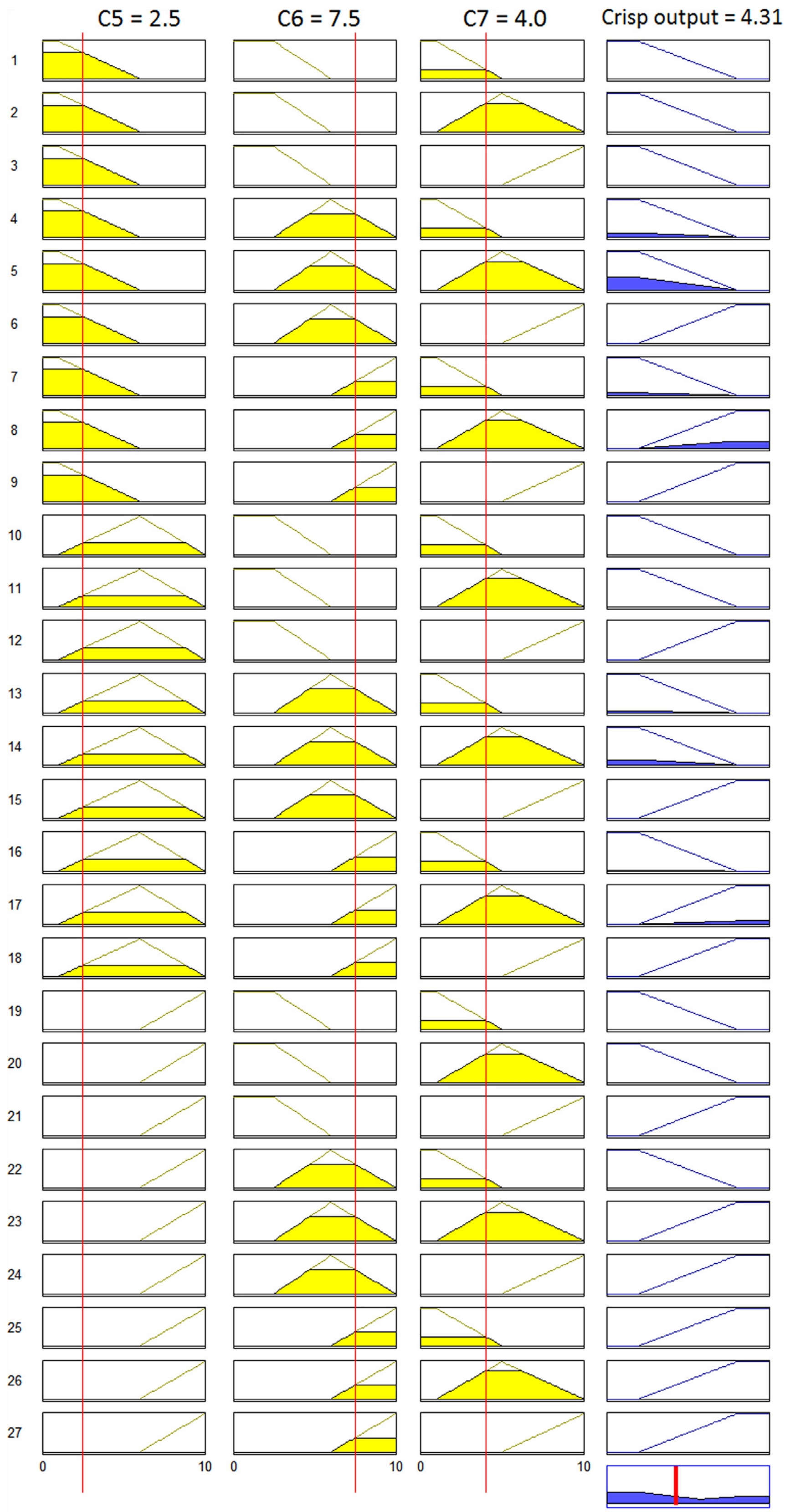

Fig. 8. Rule viewer for the second FIS of the item classification model.

To test the second inference system, the importance of purchase, the input variables were set to crisp values in the range of the linguistic terms defined in each rule so that the pertinence degree was one. For instance, to test rule 6 in Table 17, the input variables environmental contribution, core competence and value-added profile were set to crisp values of 0.0, 6.0 and 10.0 respectively. Each of these crisp values corresponds to a linguistic term of the factors to be tested. Table 17 presents the crisp values for the three

Table 13
Crisp and linguistic output values for analyzed items (data in Table 12).

Item	Complexity of supply market		Importance of purchase		Item classification
	Crisp output	Linguistic output	Crisp output	Linguistic output	
I_1	8.59	High	4.31	Low	Bottleneck
I_2	3.81	Low	3.16	Low	Noncritical
I_3	7.27	High	7.23	High	Strategic
I_4	4.96	Low	9.00	High	Leverage
I_5	5.05	Low	3.40	Low	Noncritical
I_6	4.86	Low	7.97	High	Leverage
I_7	1.50	Low	1.00	Low	Noncritical
I_8	8.67	High	7.95	High	Strategic
I_9	4.50	Low	4.20	Low	Noncritical
I_{10}	5.14	Low	8.50	High	Leverage
I_{11}	5.25	Low	3.40	Low	Noncritical
I_{12}	3.31	Low	4.43	Low	Noncritical
I_{13}	4.50	Low	7.00	High	Leverage
I_{14}	9.00	High	4.20	Low	Bottleneck
I_{15}	8.79	High	8.88	High	Strategic
I_{16}	4.50	Low	4.43	Low	Noncritical
I_{17}	4.91	Low	8.38	High	Leverage
I_{18}	7.50	High	4.00	Low	Bottleneck
I_{19}	3.75	Low	8.97	High	Leverage
I_{20}	4.96	Low	1.00	Low	Noncritical

Table 14
Scores of suppliers on evaluated criteria.

Supplier	Potential for partnership				Delivery performance			
	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
S_1	8.00	9.00	8.50	9.50	8.50	6.50	5.50	5.50
S_2	6.00	7.00	8.00	10.00	7.00	2.00	5.00	9.00
S_3	9.00	8.00	7.00	9.00	10.00	8.00	9.00	6.00
S_4	7.00	9.00	6.00	8.50	4.00	7.00	8.00	6.00
S_5	10.00	6.00	5.50	9.00	6.00	7.50	9.00	8.50
S_6	7.50	6.00	6.00	8.00	7.50	9.50	10.00	6.50
S_7	4.00	7.00	3.00	6.00	9.00	7.00	5.00	8.00
S_8	8.00	8.50	7.00	9.00	8.50	4.00	7.50	8.50
S_9	6.00	3.00	8.00	5.50	5.00	7.50	6.00	8.50
S_{10}	9.00	8.00	9.00	8.50	9.00	8.50	8.00	9.00
S_{11}	1.00	3.00	2.50	5.00	5.50	5.00	4.50	1.00
S_{12}	9.00	3.00	5.00	5.50	9.00	6.50	4.00	5.00
S_{13}	8.00	1.00	7.00	6.50	7.00	7.50	7.50	5.00
S_{14}	6.00	6.00	4.50	8.00	5.00	4.00	1.00	4.00
S_{15}	10.00	8.00	6.00	9.00	8.50	8.00	9.00	8.50
S_{16}	2.00	1.50	2.00	3.50	8.00	6.00	9.00	3.50
S_{17}	8.00	7.00	4.00	7.00	7.00	3.00	8.00	5.00
S_{18}	6.00	7.00	3.00	8.00	8.50	8.00	9.00	9.00
S_{19}	8.00	1.00	4.00	1.00	2.50	4.00	7.50	1.00
S_{20}	4.00	1.00	4.00	3.00	8.50	9.00	7.00	5.00

Table 15
Crisp and linguistic output values for evaluated suppliers (data in Table 14).

Supplier	Potential for partnership		Delivery performance	
	Crisp output	Linguistic output	Crisp output	Linguistic output
S_1	8.63	High	7.51	Medium
S_2	7.04	Medium	5.27	Medium
S_3	8.36	High	8.63	High
S_4	8.21	High	6.25	Medium
S_5	7.70	Medium	7.76	Medium
S_6	6.85	Medium	8.63	High
S_7	4.05	Medium	7.16	Medium
S_8	8.16	High	6.86	Medium
S_9	5.35	Medium	6.77	Medium
S_{10}	8.50	High	8.52	High
S_{11}	2.30	Low	3.06	Low
S_{12}	5.27	Medium	5.96	Medium
S_{13}	6.23	Medium	6.94	Medium
S_{14}	6.00	Medium	3.06	Low
S_{15}	8.35	High	8.33	High
S_{16}	1.75	Low	7.29	Medium
S_{17}	6.23	Medium	5.10	Medium
S_{18}	6.00	Medium	8.48	High
S_{19}	2.52	Low	2.69	Low
S_{20}	2.17	Low	8.25	High

input variables for all the 27 rules of the FIS importance of purchase.

The output given by the inference system (last column in Table 17) was then analyzed using Minitab 16®. The same tests were run for the four inference systems; however the results presented are for the second and fourth inference systems, respectively are importance of purchase and delivery performance.

The graphs in Fig. 9 show the interaction effects of the input variables of the FIS of importance of purchase. The y-axis of the graphs indicates the crisp output of the FIS. The x-axis indicates the levels or linguistic terms of the factors being tested. Level 1 refers to the linguistic term “low” and levels 2 and 3 refer respectively to terms “medium” and “high”. The lines in the graphs show the variation of the crisp output depending on the level of the interacting criteria. For instance, in graph (a) the lines indicate the output variation as function of the level of the factor core competence (from 1 to 3). And each of the three lines in graph (a) represents the effect on the value of the output variable caused by variation of the criterion environmental contribution in its three levels. For instance, in graph (a), output variation caused core competence variation (from 1 to 3) is higher when environmental contribution is set to level 3. Analyzing the set of graphs in Fig. 9, it can be seen that the decision rules leads to no significant interaction effects between the input variables, which means there is no trade-off between them. The graphs also show that the criterion value-added profile has a higher impact than the other two criteria concerning the importance of purchase, meaning that the weights of the criteria are implicit in the decision rules. This can be clearly seen in graphs (e) and (f). When the value-added profile is low, the importance of purchase will be low no matter the level of the criteria environmental contribution and core competencies. On the other hand, when the value-added profile is high, the importance of purchase will also be high even for low or medium levels of the criteria environmental contribution and core competencies.

Fig. 10 shows the graphs of the interaction effects of the input variables of the FIS of delivery performance. For all the graphs, when the level of one criterion increases from level 1 to 3, the output increases approximately the same no matter the level of the interacting criterion. This is a clear indication of the inexistence of significant interaction effects between the input variables. At the same time, it can be seen in graphs (f) and (k) that when problem resolution is high, delivery performance will always be high no matter the level of price. Moreover, when problem resolution is high, delivery performance will be high even for medium level of delivery reliability and quality of conformance, as shown in graphs (c) and (i). The same analysis was made for all the inference systems, confirming their sensitivity and consistency.

6. Conclusion

This paper presented a method for evaluation of suppliers for development planning that bases its decision process on analyzing the gap between real and expected supplier performance according to the item category. The method is able to identify critical items aiming at proposing directives for managing and developing suppliers for leverage, bottleneck and strategic items. Evaluation of suppliers is made on the basis of short-term delivery performance and long-term potential for partnership. Unlike the previous studies, both of these dimensions of supplier evaluation contribute to identify potential partners in the development or co-development of critical items. It also helps to identify suppliers in need of attention or suppliers that should be replaced.

The fuzzy set theory is suitable for dealing with the vagueness intrinsic to qualitative factors of suppliers' evaluation, as well as imprecise weighing of different factors by different decision makers. The proposed method applies fuzzy inference combined with the simple fuzzy grid method as a procedure for pattern classification so as to categorize items and suppliers. Unlike other techniques used for supplier evaluation, this is particularly useful for supplier categorization using linguistic classes. Thus, the proposed techniques bring several advantages to the evaluation process, as follows:

- Unlike other approaches that combine fuzzy set theory with multicriteria decision making methods, the base of rules of a fuzzy inference system is designed grounded on *if–then* scenarios devised by specialists, therefore modeling human reasoning. This knowledge about the problem domain is then captured and kept in the system.
- Classes of supplier performance and items can be represented by fuzzy numbers, allowing for subjectivity of the decision makers.
- The number of potential suppliers simultaneously evaluated is unlimited, unlike comparative approaches such as AHP, ANP,

Table 17
Crisp values of inputs and output of FIS 2 for sensitivity tests.

Test	**Criteria**			**Importance of purchase**
	Environmental contribution	Core competency	Value-added profile	
1	0.00	0.00	0.00	1.00
2	0.00	0.00	5.00	1.00
3	0.00	0.00	10.00	1.00
4	0.00	6.00	0.00	1.00
5	0.00	6.00	5.00	2.60
6	0.00	6.00	10.00	9.00
7	0.00	10.00	0.00	1.00
8	0.00	10.00	5.00	8.95
9	0.00	10.00	10.00	9.00
10	6.00	0.00	0.00	1.00
11	6.00	0.00	5.00	2.60
12	6.00	0.00	10.00	7.40
13	6.00	6.00	0.00	1.00
14	6.00	6.00	5.00	2.60
15	6.00	6.00	10.00	9.00
16	6.00	10.00	0.00	1.00
17	6.00	10.00	5.00	8.95
18	6.00	10.00	10.00	9.00
19	10.00	0.00	0.00	1.00
20	10.00	0.00	5.00	2.60
21	10.00	0.00	10.00	9.00
22	10.00	6.00	0.00	1.01
23	10.00	6.00	5.00	9.00
24	10.00	6.00	10.00	9.00
25	10.00	10.00	0.00	8.95
26	10.00	10.00	5.00	9.00
27	10.00	10.00	10.00	9.00

Table 16
Performance gap analysis.

Supplier	Item category	Evaluated performance (x, y)	Expect performance (x, y)	Directives for action plans
S_1	Bottleneck	High, medium	High, medium Medium, high Medium, medium	Sustain relationship
S_2	Bottleneck	Medium, medium	High, medium Medium, high Medium, medium	Sustain relationship
S_3	Strategic	High, high	High, high	Sustain relationship
S_4	Leverage	High, medium	Medium, medium Low, high Low, medium	Support new development programs
S_5	Noncritical	–	–	–
S_6	Leverage	Medium, high	Medium, medium Low, high Low, medium	Support new development programs
S_7	Noncritical	–	–	–
S_8	Strategic	High, medium	High, high	Develop follow up program
S_9	Noncritical	–	–	–
S_{10}	Leverage	High, high	Medium, medium Low, high Low, medium	Allocate strategic items
S_{11}	Noncritical	–	–	–
S_{12}	Noncritical	–	–	–
S_{13}	Leverage	Medium, medium	Medium, medium Low, high Low, medium	Sustain relationship
S_{14}	Bottleneck	Medium, low	High, medium Medium, high Medium, medium	Develop follow up program
S_{15}	Strategic	High, high	High, high	Sustain relationship
S_{16}	Noncritical	–	–	–
S_{17}	Leverage	Medium, medium	Medium, medium Low, high Low, medium	Sustain relationship
S_{18}	Bottleneck	Medium, high	High, medium Medium, high Medium, medium	Sustain relationship
S_{19}	Leverage	Low, low	Medium, medium Low, high Low, medium	Replace supplier
S_{20}	Noncritical	–	–	–

(x, y): (potential for partnership, delivery performance).

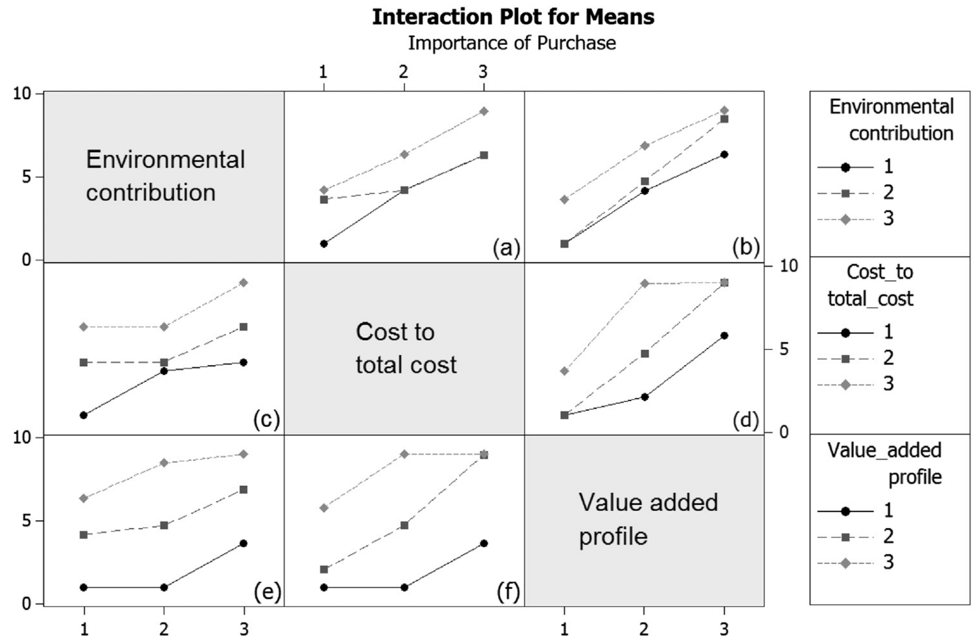

Fig. 9. Interaction effects of the input variables of the FIS of importance of purchase.

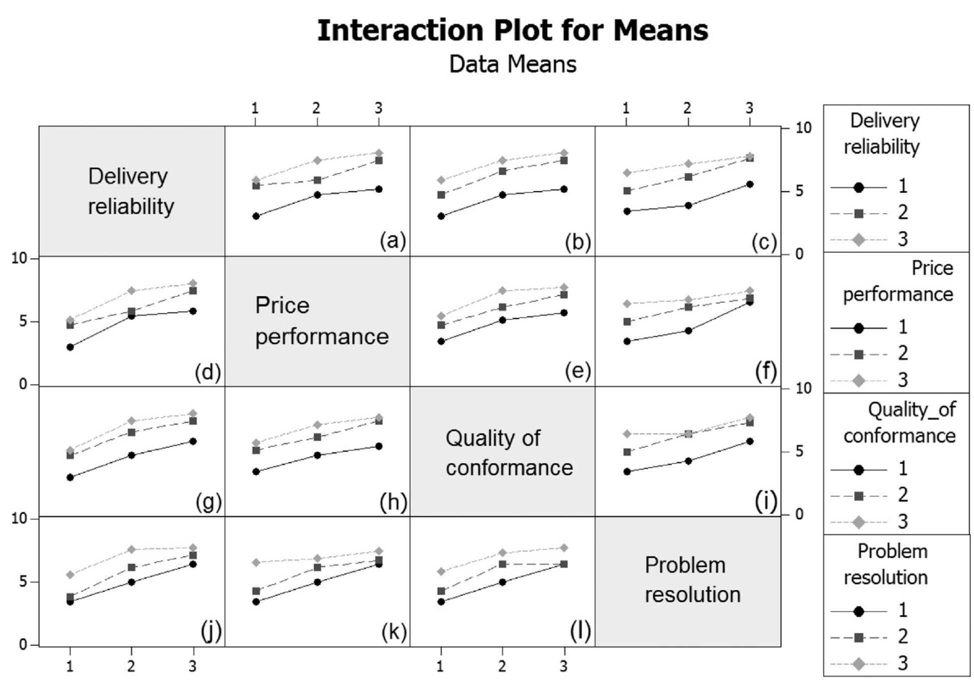

Fig. 10. Interaction effects of the input variables of the FIS of delivery performance.

fuzzy AHP and fuzzy ANP, in which the number of alternatives is limited by the human ability to simultaneous comparative judgment.

- Using linguistic terms as an indication of supplier performance is more appropriate to give feedback to suppliers in the evaluation process.
- The possibility of choosing different operators such as *t*-norms, *s*-norms and defuzzification operators brings flexibility to the system.

In this particular pilot application, it validated some decisions already made by the decision makers as well as it helped them in reviewing some supplier development action plans. For instance, suppliers S_4, S_6 and S_{10} were identified as potential partners in the development or co-development of critical items. On the other hand, the evaluation process indicated the need of replacing supplier S_{19}. In addition, the decision makers involved in the pilot application reported that the adoption of the proposed method brings objectivity and consistency to the decision process, supporting discussion and consensus building through the decision making process. Although there is an effort to incorporate into the system the knowledge and experience of the specialist, once this is done, there is no need to switch between crisp numbers and linguistic terms. The decision maker will only assess the suppliers using crisp values, which will then be fuzzified.

The sensitivity analysis using factorial design has shown no significant interaction effects between the criteria within the inference systems. Analysis has also revealed the relative importance of the criteria implicit in the decision rules. The pilot application of the proposed method has also shown that it is a learning process that is dependent on factors such as

- the choices of criteria for item and supplier classification in the evaluation models;
- parameters of the inference system such as linguistic terms and inference rules; and
- knowledge of the decision makers regarding evaluation of items and suppliers.

A limitation of the proposed method is that the inclusion of a new criterion increases exponentially the number of decision rules of an inference system. In the pilot application case, the first, third and fourth inference systems were built with four criteria, leading to 81 rules each. The inclusion of a new criterion in any of these systems would generate a set of 243 rules, which would imply in a greater effort and degree of difficulty to define the classes of the consequents of the decision rules. However, it is in general a good practice to work with a limited number of criteria since it facilitates the process of collecting and maintaining the supplier data base. Otherwise, when there is a need to work with a large number of criteria, it is possible to organize the inference systems in a cascade mode, so as to reduce the number of criteria in each inference system.

Further research can explore other fuzzy operators, as well as the use of approaches such as 2-tuple representation (Herrera and Martínez, 2000). Other further research can explore application of the Takagi–Sugeno (Pedrycz and Gomide, 2007) technique to define the base of rules from past experiences of supplier evaluation. It can be combined with a fuzzy rule generation procedure proposed by Nozaki et al. (1996) to define the consequent class using numerical data.

Acknowledgments

Authors thank FAPESP (SãoPaulo State Science Foundation) and CAPES for supporting the research project and the anonymous reviewers for their helpful contributions.

References

Amindoust, A., Ahmed, S., Saghafinia, A., Bahreininejad, A., 2012. Sustainable supplier selection: a ranking model based on fuzzy inference system. Appl. Soft Comput. J. 12 (6), 1668–1677.
Araz, C., Ozkarahan, I, 2007. Supplier evaluation and management system for strategic sourcing based on a new multicriteria sorting procedure. Int. J. Prod. Econ. 106 (2), 585–606.
Awasthi, A., Chauhan, S.S., Goyal, S.K., 2010. A fuzzy multicriteria approach for evaluating environmental performance of suppliers. Int. J. Prod. Econ. 126 (2), 370–378.
Bai, C., Sarkis, J., 2011. Evaluating supplier development programs with a grey based rough set methodology. Expert Syst. Appl. 38 (11), 13505–13517.
Baskarahan, V., Nachiappan, S., Rahman, S., 2012. Indian textile suppliers' sustainability evaluation using the grey approach. Int. J. Prod. Econ. 135 (2), 647–658.
Bensaou, M., 1999. Portfolios of buyer-supplier relationships. Sloan Manag. Rev. 40 (4), 35–44.
Bertrand, J.W.M., Fransoo, J., 2002. Operations management research methodologies using quantitative modeling. Int. J. Oper. Prod. Manag. 22 (2), 241–264.
Blome, C., Schoenherr, T., Eckstein, D., 2014. The impact of knowledge transfer and complexity on supply chain flexibility: a knowledge-based view. Int. J. Prod. Econ. 147, 307–316, http://dx.doi.org/10.1016/j.ijpe.2013.02.028.
Bojadziev, G., Bojadziev, M., 2007. Fuzzy Logic for Business. Word Scientific, Finance and Management, Singapore.
Castellano, G., Fanelli, A.M., 1999. Modeling fuzzy classification systems with compact rule base. In: Proceedings of the International Conference on Computational Intelligence for Modeling, Control and Automation.
Çelebi, D., Bayraktar, D., 2008. An integrated neural network and data envelopment analysis for supplier evaluation under incomplete information. Expert Syst. Appl. 35 (4), 1698–1710.
Chai, J., Liu, J.N.K., Ngai, E.W.T., 2013. Application of decision-making techniques in supplier selection: a systematic review of literature. Expert Syst. Appl. 40 (10), 3872–3885.
Chen, C., 2006. Stability conditions of fuzzy systems and its application to structural and mechanical systems. Adv. Eng. Softw. 37 (9), 624–629.
Chen, C., 2010. Application of fuzzy-model-based control to nonlinear structural systems with time delay: an LMI method. J. Vib. Control 16 (11), 1651–1672.
Chen, C., Lin, C., Huang, S., 2006. A fuzzy approach for supplier evaluation and selection in supply chain management. Int. J. Prod. Econ. 102 (2), 289–301.
Chen, C., Lin, J., Lee, W., Chen, C., 2010. Fuzzy control for an oceanic structure: a case study in time-delay TLP system. J. Vib. Control 16 (1), 147–160.
Chen, Y.-J., 2011. Structured methodology for supplier selection and evaluation in a supply chain. Inf. Sci. 181 (9), 1651–1670.
Chin, K.S., Yeung, I-K., Pun, K.F., 2006. Development of an assessment system for supplier quality management. Int. J. Qual. Reliab. Manag. 23 (7), 743–765.
De Boer, L., Labro, E., Morlacchi, P., 2001. A review of methods supporting supplier selection. Eur. J. Purch. Supply Manag. 7 (2), 75–89.
Dekkers, R., Chang, C.M., Kreutzfeldt, J., 2013. The interface between "product design and engineering" and manufacturing: a review of the literature and empirical evidence. Int. J. Prod. Econ. 144 (2), 316–333.
Dubois, D., Prade, H., Testermale, C., 1988. Weighted fuzzy pattern matching. Fuzzy Sets Syst.—Math. Model. 28 (3), 313–331.
Duda, R.O., Hart, P.E., Stork, D.G., 2000. Pattern Classification, 2nd ed.. Wiley-Interscience, New York.
Dyer, J.H., Cho, D.S., Chu, W., 1998. Strategic supplier segmentation: the next "best practice" in supply chain management. Calif. Manag. Rev. 40 (2), 57–77.
Frayret, J.-M., D'Amours, S., Venkatadri, U., Montreuil, B., 1998. An approach to model and manage cost-risk trade-off in networked manufacturing. In: Proceedings of the International Conference of Management and Networked Enterprises, Montreal, Canada.
García, N., Puente, J., Fernández, I., Priore, P., 2013. Supplier selection model for commodities procurement. Optimised assessment using a fuzzy decision support system. Appl. Soft Comput. 13, 1939–1951.
Govindan, K., Kannan, D., Haq, A.N., 2010. Analyzing supplier development criteria for an automobile industry. Ind. Manag. Data Syst. 110 (1), 43–62.
He, Y., Lai, K.K., Sun, H., Chen, Y., 2014. The impact of supplier integration on customer integration and new product performance: the mediating role of manufacturing flexibility under trust theory. Int. J. Prod. Econ. 147, 260–270, http://dx.doi.org/10.1016/j.ijpe.2013.04.044.
Herrera, F., Martínez, L., 2000. A 2-tuple fuzzy linguistic representation model for computing with words. IEEE Trans. Fuzzy Syst. 8 (6), 746–752.
Ho, W., Xu, X., Dey, P.K., 2010. Multi-criteria decision making approaches for supplier evaluation and selection: a literature review. Eur. J. Oper. Res. 202 (1), 16–24.
Hsu, C.W, Kuo, R.J., Chiou, C.Y., 2013. A multi-criteria decision-making approach for evaluating carbon performance of suppliers in the electronics industry. Int. J. Environ. Sci. Technol., http://dx.doi.org/10.1007/s13762-013-0265-5
Inemek, A., Matthyssens, P., 2011. Enhancing supplier performance in buyer–supplier relationships: the roles of supplier assessment, buyer assistance and supplier involvement in product development. In: Proceedings of the EUROMA Conference, Cambridge, UK.
Ishibuchi, H., Nozaki, K., Tanaka, H., 1992. Distributed representation of fuzzy rules and its application to pattern classification. Fuzzy Sets Syst. 52 (1), 21–32.
Ishibuchi, H., Nozaki, K., Tanaka, H., 1993. Efficient fuzzy partition of pattern space for classification problems. Fuzzy Sets Syst. 59 (3), 295–304.
Jain, V., Tiwari, M.K., Chan, F.T.S., 2004. Evaluation of the supplier performance using an evolutionary fuzzy-based approach. J. Manuf. Technol. Manag. 15 (8), 735–744.
Kahraman, C., 2008. Fuzzy Multicriteria Decision Making—Theory and Applications with Recent Developments. Springer Science, Turkey.
Kannan, V.R., Tan, K.C., 2002. Supplier selection and assessment: their impact on business performance. J. Supply Chain Manag. 38 (4), 11–21.
Katsikeas, C.C., Paparoidamis, N.G., Katsikea, E., 2004. Supply source selection criteria: the impact of supplier performance on distributor performance. Ind. Mark. Manag. 33 (8), 755–764.
Keskin, G.A., Ilhan, S., Özkan, C., 2010. The Fuzzy ART algorithm: a categorization method for supplier evaluation and selection. Expert Syst. Appl. 37 (2), 1235–1240.
Kraljic, P., 1983. Purchasing must become supply management. Harv. Bus. Rev. 61 (5), 109–117.
Krause, D.R., 1997. Supplier development: current practices and outcomes. Int. J. Purch. Mater. 33 (1), 12–19.
Lee, A.H.I, Chan, H.-J., Huang, C.-Y., 2009. An evaluation model of buyer–supplier relationships in high-tech industry—the case of an electronic components manufacturer in Taiwan. Comput. Ind. Eng. 57 (4), 1417–1430.
Lee, D.M., Drake, P., 2010. A portfolio model for component purchasing strategy and the case study of two South Korean elevator manufacturers. Int. J. Prod. Res. 48 (22), 6651–6682.
Lima, F.R., Osiro, L., Carpinetti, L.C.R., 2013. A fuzzy inference and categorization approach for supplier selection using compensatory and non-compensatory decision rules. Appl. Soft Comput. 13 (10), 4133–4147.
Lin, J., Chen, C., Peng, C., 2012. Potential hazard analysis and risk assessment of debris flow by fuzzy modeling. Nat. Hazards 64 (1), 273–282.
Lin, M., Chen, C., 2010. Application of fuzzy models for the monitoring of ecologically sensitive ecosystems in a dynamic semi-arid landscape from satellite imagery. Eng. Comput. 27 (1), 5–19.

Lin, R., 2009. An integrated FANP–MOLP for supplier evaluation and order allocation. Appl. Math. Model. 33 (6), 2730–2736.

Liu, K., Ko, C., Fan, C., Chen, C., 2012. Combining risk assessment, life cycle assessment and multi-criteria decision analysis to estimate environmental aspects in EMS. Int. J. Life Cycle Assess. 17 (7), 845–862.

Luzzini, D., Caniato, F., Ronchi, S., Spina, G., 2012. A transaction costs approach to purchasing portfolio management. Int. J. Oper. Prod. Manag. 32 (9), 1015–1042.

Mamdani, E.H., Assilian, S., 1975. An experiment in linguistic synthesis with a fuzzy logic controller. Int. J. Man–Mach. Stud. 7 (1), 1–13.

Montgomery, D.C., 1991. Design and Analysis of Experiments. Wiley, New York.

Nellore, R., Söderquist, K., 2000. Portfolio approaches to procurement: analyzing the missing link to specifications. Long Range Plan. 33 (2), 245–267.

Nguyen, C.H., Pedrycz, W., Duong, T.L., Tran, T.S., 2012. A genetic design of linguistic terms for fuzzy rule based classifiers. Int. J. Approx. Reason. 54 (1), 1–21.

Nozaki, K., Ishibuchi, H., Tanaka, H., 1996. Adaptive fuzzy rule-based classification systems. IEEE Trans. Fuzzy Syst. 4 (3), 238–250.

Ohdar, R., Ray, P.K., 2004. Performance measurement and evaluation of suppliers in supply chain: an evolutionary fuzzy-based approach. J. Manuf. Technol. Manag. 15 (8), 723–734.

Olsen, R.F, Ellram, L.M., 1997. A portfolio approach to supplier relationships. Ind. Mark. Manag. 26 (2), 101–113.

Olugu, E.U., Wong, K.Y., 2012. An expert fuzzy rule-based system for closed-loop supply chain performance assessment in the automotive industry. Expert Syst. Appl. 39 (1), 375–384.

Omurca, S.I., 2013. An intelligent supplier evaluation, selection and development system. Appl. Soft Comput. 13 (1), 690–697.

Pagell, M., Wu, Z., Wasserman, M.E., 2010. Thinking differently about purchasing portfolios: an assessment of sustainable sourcing. J. Supply Chain Manag. 46 (1), 57–73.

Park, J., Shin, D., Chang, T.W., Park, J., 2010. An integrative framework for supplier relationship management. Ind. Manag. Data Syst. 110 (4), 495–515.

Pedrycz, W., 1990. Fuzzy sets in pattern recognition: methodology and methods. Pattern Recognit. 23 (1–2), 121–146.

Pedrycz, W., Gomide, F., 2007. Fuzzy Systems Engineering—Toward Human-Centric Computing. Wiley, New Jersey.

Pedrycz, W., Kwak, K., 2006. Linguistic models as a framework of user-centric system modeling. Trans. Syst., Man Cybern. 36 (4), 727–745.

Pitchipoo, P., Venkumar, P., Rajakarunakaran, S., 2013. Fuzzy hybrid decision model for supplier evaluation and selection. Int. J. Prod. Res. 51 (13), 1–17.

Prajogo, D., Chowdhury, M., Yeung, A.C. L., Cheng, T.C.E., 2012. The relationship between supplier management and firm's operational performance: a multi-dimensional perspective. Int. J. Prod. Econ. 136 (1), 123–130.

Rezaei, J., Ortt, R., 2013a. Multi-criteria supplier segmentation using a fuzzy preference relations based AHP. Eur. J. Oper. Res. 225 (1), 75–84.

Rezaei, J., Ortt, R., 2013b. Supplier segmentation using fuzzy logic. Ind. Mark. Manag. 42 (4), 507–517.

Saaty, T.L., 1990. The Analytic Hierarchy Process. RWS Publications, Pittsburgh

Sarkar, A., Mohapatra, P.K.J., 2006. Evaluation of supplier capability and performance: a method for supply base reduction. J. Purch. Supply Manag. 12 (3), 148–163.

Schmitz, J., Platts, K.W., 2004. Supplier logistics performance measurement: indications from a study in the automotive industry. Int. J. Prod. Econ. 89 (2), 231–243.

Schoenherr, T., et al., 2012. Research opportunities in purchasing and supply management. Int. J. Prod. Res. 50 (16), 4556–4579.

Shih, K.-H., Hung, H.-F., Lin, B., 2009. Supplier evaluation model for computer auditing and decision-making analysis. Kybernetes 38 (9), 1439–1460.

Shirinfar, M., Haleh, H., 2011. Supplier selection and evaluation by fuzzy multi-criteria decision making methodology. Int. J. Ind. Eng. Prod. Res. 22 (4), 271–280.

Talluri, S., Sarkis, J., 2002. A model for performance monitoring of suppliers. Int. J. Prod. Res. 40 (16), 4257–4269.

Toni, A., Nassimbeni, G., 2001. A method for the evaluation of suppliers' co-design effort. Int. J. Prod. Econ. 72 (2), 169–180.

Tuzkaya G., Ozgen A., Ozgen D., Tuzkaya, U. R. Environmental performance evaluation of suppliers: A hybrid fuzzy multi-criteria decision approach, Int. J. Environ. Sci. Tech., 6 (3), 477–490.

Wang, S., 2008. Applying 2-tuple multigranularity linguistic variables to determine the supply performance in dynamic environment based on product-oriented strategy. IEEE Trans. Fuzzy Syst. 16 (1), 29–39.

Wu, C., Barnes, D., 2011. A literature review of decision-making models and approaches for partner selection in agile supply chains. J. Purch. Supply Manag. 17 (4), 256–274.

Yao, Y., Kohli, R., Sherer, S.A, Cederlund, J., 2013. Learning curves in collaborative planning, forecasting, and replenishment (CPFR) information systems: an empirical analysis from a mobile phone manufacturer. J. Oper. Manag. 31 (6), 285–297, http://dx.doi.org/10.1016/j.jom.2013.07.004.

Zadeh, L.A., 1965. Fuzzy sets. Inf. Control 8 (3), 338–353.

Zadeh, L.A., 1973. Outline of a new approach to the analysis of complex systems and decision processes. IEEE Trans. Syst., Man Cybern. 3 (1), 28–44.

Zeydan, M., Çolpan, C., Çobanoğlu, C., 2011. A combined methodology for supplier selection and performance evaluation. Expert Syst. Appl. 38 (3), 2741–2751.

Zimmermann, H.J., 1991. Fuzzy Set Theory and its Applications. Kluwer Academic, Massachussets.