International Journal of Production Economics 202 (2018) 182–196

Contents lists available at ScienceDirect

International Journal of Production Economics

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

A group decision approach for supplier categorization based on hesitant fuzzy and ELECTRE TRI

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A R T I C L E I N F O

Keywords:
Supplier evaluation and categorization
Group decision
MCDM
ELECTRE TRI
Hesitant fuzzy

A B S T R A C T

Supplier evaluation and categorization is an important decision process in supplier management. It relies on judgements by multiple decision makers about the performance of a supplier on a set of criteria. Uncertainty of judgements, non-compensation between criteria and group decision are the main requirements of the decision process that have to be considered. However, none of the studies found in the literature presents a solution that contemplates all this requirements at the same time. Therefore, aiming to bridge this gap, this paper proposes an approach to supplier categorization based on the use of ELECTRE TRI combined with hesitant fuzzy. ELECTRE TRI is a non-compensatory multicriteria decision making method specific for categorization. Hesitant fuzzy is used prior to it to aggregate linguistic judgements of multiple decision makers. The decision process model is detailed and implemented in Matlab©. Analyses of the results of an illustrative case of application in the automotive industry show consistent categorization results, particularly using the pessimistic ELECTRE TRI categorization procedure. But, when there is too much discordance, negotiation techniques may be a better option. Also, test with different criteria weights showed no change in the categorization results, confirming the non-compensatory effect of the technique.

1. Introduction

Nowadays, manufacturing companies rely greatly on a pool of suppliers for providing materials and components used in their finished products. Therefore, managing the performance of suppliers and supporting their continuous improvement have become critical for companies to compete in the marketplace in criteria such as quality, cost, delivery and flexibility (Kuo et al., 2010; Nair et al., 2015; Saiz et al., 2014; Sanayei et al., 2008; Trent and Monczka, 2010; Zeydan et al., 2011).

Essential to supply management are the processes of supplier selection and development (Park et al., 2010). Supplier evaluation performed by multiple decision makers and based on multiple criteria is central for both processes. In supplier selection, multicriteria evaluation is carried out generally with the purpose of defining an ordered list of preferred suppliers. Sometimes a pre-selection or qualification step is performed with the aim of sorting candidate suppliers that can meet the minimum requirement in all considered criteria (De Boer et al., 2001). Several multicriteria decision making (MCDM) techniques, mostly for ranking, are proposed in the literature to deal with the problem of supplier selection (Chai et al., 2013; Ho et al., 2010; Simić et al., 2016; Ware et al., 2012).

After selection, in the course of supplying, evaluation of current suppliers helps the buying firm to take actions to better meet its supply needs. For example, it can induce development of its supplier or in to the worst case replace it (Hosseininasab and Ahmadi, 2015; Osiro et al., 2014; Rezaei and Ortt, 2012). The usual approach is to classify suppliers according the level of performance or in categories of performance in order to guide further actions (Araz et al., 2007; Guarnieri, 2014; Osiro et al., 2014; Wang, 2010). Therefore, in both instances, in the qualification stage in supplier selection as well as after selection, the evaluation process seeks to categorize suppliers by level of performance on the criteria. When the decision problem is one of categorization or sorting, this type of result should guide the choice of a proper technique (Roy and Słowiński, 2013). However, the literature presents many examples of application of techniques recommended for ranking in decision problems of categorization or sorting of suppliers (Arabzad et al., 2013; Lima-Junior and Carpinetti, 2016; Pattnaik, 2013; Rezaei and Ortt, 2013a; Sarkar and Mohapatra, 2006; Yu and Wong, 2015, 2014).

The uncertainty of judgements by decision makers is another important issue that have to be considered in the supplier evaluation process, either for selection or after selection. Judgements in the problem

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https://doi.org/10.1016/j.ijpe.2018.05.023
Received 25 July 2017; Received in revised form 1 March 2018; Accepted 20 May 2018
Available online 23 May 2018

of supplier evaluation are frequently rather uncertain, for several reasons: the nature of the judgement, for instance when evaluating the relative importance of different criteria; the vagueness intrinsic to the evaluation of qualitative criteria, for instance quality management capabilities; or the lack of complete information, for instance in the case of a completely new supplier.

Fuzzy set theory combined with MCDM techniques has been largely used to deal with uncertainty in supplier selection, as it provides an adequate mathematical formulation to linguistic terms that convey the uncertainty of judgement. Common hybridizations applied to supplier selection include fuzzy AHP (Analytic Hierarch Process), fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), fuzzy inference, fuzzy DEA among others (Chai et al., 2013; Ho et al., 2010).

Another issue is the multiplicity of decision makers in supplier evaluation. Group decision is usually the case in supplier relationship management, since several stakeholders from different areas such purchasing, product development, quality management and production are involved with the evaluation processes.

The literature presents several papers dealing with group decision making, including aggregation approaches or consensus (Alencar and Almeida, 2008; Costa et al., 2003; Leyva-López and Fernández-González, 2003; Macharis and Brans, 1998; Morais and De Almeida, 2012; Parreiras et al., 2012) voting (Hadi-Vencheh and Niazi-Motlagh, 2011; Liu and Hai, 2005), game theory (Leoneti, 2016), intuitionistic fuzzy sets (Boran et al., 2009; Izadikhah, 2012; Khaleie and Fasanghari, 2012; Liu, 2013; Wang and Xu, 2016; Wei et al., 2010; Yu, 2013a, 2012; Zeng, 2013), hesitant fuzzy (Darabi and Heydari, 2016; Gitinavard et al., 2016; Kahraman et al., 2016; Rodríguez et al., 2013; Wang and Xu, 2016; Xia et al., 2013; Yu et al., 2013) fuzzy 2-tuple (Baležentis and Baležentis, 2011; Chen and Ben-Arieh, 2006; Rao et al., 2016; Wang, 2010; Wei and Zhao, 2012), interval type-2 fuzzy sets (Liu et al., 2018; Qin et al., 2017a, 2017b), among others. However, most of these techniques are applied for ordering rather than categorization. Other techniques applied to categorization do not consider uncertainty, such as López and Ishizaka (2017), Masoumi et al. (2017), Palha et al. (2016), Chen et al. (2015), Morais et al. (2014), Kadziński et al. (2013), Cai et al. (2012), Jabeur and Martel (2007) and Damart et al. (2007). Some other techniques for categorization consider uncertainty in group decision such as Sun et al. (2017), Shen et al. (2016), Liu et al. (2015), Li et al. (2014), Chen et al. (2012), Li et al. (2009), Valls et al. (2009) and Dias and Clímaco (2000). However, they do not consider the possibility of hesitation by decision makers.

Fuzzy set techniques such as intuitionistic sets (Atanassov, 1986) hesitant fuzzy sets (Torra, 2010) and type-2 fuzzy sets (Zadeh, 1975) have been proposed to deal with situations in which information is incomplete or in which the decision makers have hesitation or additional imprecision in expressing their decision preferences. Using intuitionistic and type-2 fuzzy sets, imprecision or hesitation are defined in the parameterization process. In the intuitionistic fuzzy sets, the definition of the membership function considers a margin of error, given by the hesitation degree (Atanassov, 1986). In the type-2 fuzzy sets, the definition of the membership function considers some possibility distribution, given by the primary and secondary membership functions (Liu et al., 2018; Qin et al., 2017a). On the other hand, in the hesitant fuzzy sets (HFS), hesitation is not set in the definition of the membership functions. Using HFS, the decision maker can include more than one linguistic term in the universe of discourse to express hesitation of judgements. Therefore, the main motivation for proposing the use of HFS applied to group decision making is that a hesitant fuzzy set can include all the judgements of the decision group, avoiding aggregating preferences by averaging operations. The uncertainty of judgements by decision makers is another important issue that have to be considered in the supplier evaluation process, either for selection or after selection. Judgements in the problem of supplier evaluation are frequently rather uncertain, for several reasons: the nature of the judgement, for instance when evaluating the relative importance of different criteria; the vagueness intrinsic to the evaluation of qualitative criteria, for instance quality management capabilities; or the lack of complete information, for instance in the case of a completely new supplier.

However, although hesitant fuzzy is a sound technique to aggregate uncertain judgements, on its own it is not able to cope with the aim of categorization in supplier evaluation. A variant of the ELECTRE (*Elimination et Choix Traduisant la Realité* – Elimination and Choice Expressing the Reality) family of techniques, developed for categorization purpose is the ELECTRE TRI (Yu, 1992). ELECTRE also brings the benefit of non-compensation between criteria. However, ELECTRE TRI does not deal with group decision making; the inputs, that is, the scores of the alternatives as well as the weights of the criteria, given by a group of decision makers, have to be aggregated beforehand. Therefore, by combining this fuzzy set representation with ELECTRE TRI it is possible to use this technique in the context of group decision for categorization.

Considering the issues highlighted in the previous paragraphs, this paper proposes the use of ELECTRE TRI combined with hesitant fuzzy as an approach to deal with the decision problem of supplier qualification. Hesitant fuzzy is used prior to the ELECTRE TRI, to aggregate linguistic judgements of multiple decision makers, regarding weights of criteria and scores of alternatives, and transform them into values of a numerical scale to be used as inputs of the ELECTRE TRI method. Therefore, different from previous studies (Arabzad et al., 2013; Araz and Ozkarahan, 2007; Cao et al., 2014; Hallikas et al., 2005; Irfan et al., 2011; Kefer et al., 2016; Lima-Junior and Carpinetti, 2016; Lima Junior et al., 2013; Omurca, 2013; Osiro et al., 2015; Pattnaik, 2013; Rezaei and Ortt, 2013a, 2013b; Sarkar and Mohapatra, 2006; Sepulveda and Derpich, 2015; Wu and Barnes, 2012; Yu and Wong, 2015, 2014), this proposal can simultaneously contemplate the requirements of decision under uncertainty by a group of decision makers using a non-compensatory MCDM technique proper for categorization.

A descriptive quantitative approach was used as the research method (Bertrand and Fransoo, 2002). The techniques were implemented in Matlab©. An illustrative application was developed in the automotive industry so as to evaluate and discuss the proposal. The paper is organized as follows: Section 2 briefly revises the subject of supplier evaluation. Next, section 3, briefly presents fundamental concepts of fuzzy hesitant fuzzy set and aggregation operators in hesitant fuzzy. Section four presents the ELECTRE TRI method and section 5 details the proposal of integrating hesitant fuzzy to ELECTRE TRI in the context of supplier evaluation. Section 6 presents the illustrative application and discusses its results. Conclusions about this study and suggestions for further work are presented in Section 7.

2. Supplier evaluation for selection and development

Supplier evaluation is central to supplier selection and development, two major activities of purchasing management. The abundant number of review papers on the subject of supplier evaluation, especially supplier selection in the past decade also brings evidence of the importance of this subject to the academia (Agarwal et al., 2011; Chai et al., 2013; De Boer et al., 2001; Ho et al., 2010; Setak et al., 2012; Wetzstein et al., 2016). Understood as multicriteria decision processes, there are three aspects that are usually considered in the studies on the subject: process, criteria and techniques. Regarding supplier selection, De Boer et al. (2001) proposed an outstanding process reference model. It consists basically of four steps: problem definition, formulation of criteria, qualification and choice. The authors also consider variations along this process based on different purchasing situations: new suppliers for new products; new suppliers for the same product; same suppliers for modified products; and straight rebuy of routine or strategic/bottleneck items. The first step aims at defining the decision problem, which may be selecting new suppliers for a completely new or modified product, replacing suppliers of a current item or selecting suppliers for new items from the same set of suppliers. In the subsequent step, criteria formulation, the buyer should revise criteria already being used or deploy and weigh quantitative and qualitative decision criteria so as to guide the following steps. In the third step, of qualification, the main objective is to sort the initial set of suppliers between qualified and non-qualified ones based on a set of qualifying criteria. Implicit in this qualification step is the non-compensatory rule of the decision making process (De Boer et al., 2001; Lima Junior et al., 2013). This step is particular important in the selection of new suppliers. In the last step, the purpose is to define an ordered list of potential suppliers so as to make the final choices. Ranking is especially important in situations where there is usually a large set of potential suppliers. Wu and Barnes (2012), based on this framework, proposed an additional step aiming at given feedback to potential suppliers in their performance in the selection process.

Regarding supplier evaluation for development, the decision process involves basically categorization of suppliers into one or more performance dimensions so as to guide improvement actions. For instance, short-term performance and long term capability are the dimensions proposed by Sarkar and Mohapatra (2006) to categorize suppliers. Willingness and capability are the dimensions proposed by Rezaei and Ortt (2013a) to evaluate suppliers. Osiro et al. (2014) propose a model to evaluate suppliers based on the dimensions delivery performance and potential for partnership. Lima-Junior and Carpinetti (2016) propose a supplier evaluation model based on the metrics of the SCOR (Supply Chain Operation Reference) model. Other authors propose supplier evaluation models based on the overall performance (Araz et al., 2007; Omurca, 2013).

Implicit in the supplier evaluation decision process are the criteria used in the process. Defining the set of evaluation criteria and their relative importance is also another topic of relevance discussed in the literature. A study conducted by Dickson in the sixties identified quality, delivery and performance history are the three most important criteria. Further studies confirmed the importance of these criteria (Kannan and Tan, 2006; Verma and Pullman, 1998; Weber et al., 1991). More recently, some studies propose criteria for evaluating environmental performance (Büyüközkan and Çifçi, 2012; Darabi and Heydari, 2016; Gitinavard et al., 2016; Kannan et al., 2013; Khaleie et al., 2012; Rao et al., 2016; Nia et al., 2016). Kahraman et al. (2003) proposed organizing the criteria into four groups: supplier's profile, product performance, service performance and cost performance. Table 1 presents a summary of criteria commonly cited by recent publications. Some criteria are quantifiable such as conformance to quality and delivery. But even for criteria of quantitative nature, for completely new suppliers, there is no way of quantifying performance and therefore it should be judged considering other evidences. Other criteria are judgmental by nature such as reputation and commitment to quality. In the selection process, some criteria can be considered for qualification of new suppliers; for instance, quality certification and financial health. For current suppliers, evaluation may depend on supply history; for instance, performance level higher than the minimum requirement in criteria such as ability to problem resolution and flexibility.

Decision making techniques applied to supplier evaluation include a great variety of techniques, especially in supplier selection; in general the techniques are grouped as multicriteria techniques, mathematical programming, stochastic programming and artificial intelligence techniques (Ho et al., 2010; Wetzstein et al., 2016). Most of the studies propose the use of techniques for ordering alternatives. Multicriteria techniques in combination with fuzzy set theory have been largely proposed to deal with the uncertainty of the decision problem (Simić et al., 2016). Table 2 presents some studies found in the literature applied to supplier evaluation in qualification or after selection. Most of the studies propose a fuzzy hybridization to deal with the uncertainty in the decision problem. Yu and Wong (2014, 2015), Arabzad et al. (2013) and Rezaei and Ortt (2013b) propose the use of fuzzy TOPSIS, TOPSIS and fuzzy AHP, techniques that are used for ranking.

Another aspect of the decision problem in supplier evaluation that impacts the choice of technique is the need of a non-compensatory approach such that a good performance in one criterion does not compensate a poor performance in another criterion. Sepulveda and Derpich (2015) and Araz and Ozkarahan (2007) use PROMETHE (Preference Ranking Organization Method for Enrichment Evaluations) and ELECTRE, non-compensatory MCDM techniques. Lima Junior et al. (2013) and Osiro et al. (2014) use fuzzy inference within a non-compensatory decision process.

Finally, the adequacy to support group decision making is still

Table 1
Supplier selection and evaluation criteria.

Criteria	References
Quality	Amid et al. (2006), Araz et al. (2007), Boran et al. (2009), Kirytopoulos et al. (2010), Park et al. (2010), Kuo et al., 2010, Büyüközkan and Çifçi (2012), Lin et al. (2011), Khaleie et al. (2012), Yayla et al. (2012), Huang and Hu (2013), Kannan et al. (2013), Wang et al. (2013), Yue and Jia (2013), Zhang et al., 2016, Lima Junior et al. (2013), Kar (2014), Xu and Shen (2014), Yue (2014), Li et al., 2014, Darabi and Heydari (2016), Nia et al., 2016, Rao et al. (2016), Kefer et al. (2016).
Delivery	Araz et al. (2007), Sanayei et al. (2008), Kirytopoulos et al. (2010), Boran et al. (2009), Park et al. (2010), Kuo et al., 2010, Liao and Kao (2010), Büyüközkan and Çifçi (2012), Lin et al. (2011), Khaleie et al. (2012), Yayla et al. (2012), Kannan et al. (2013), Yue and Jia (2013), Zhang et al., 2016, Kar (2014), Yue (2014), Li et al., 2014, Darabi and Heydari (2016), Nia et al., 2016, Rao et al. (2016), Kefer et al. (2016).
Price/cost	Amid et al. (2006), Sanayei et al. (2008), Kirytopoulos et al. (2010), Boran et al. (2009), Park et al. (2010), Wang (2010), Liao and Kao (2010), Kuo et al., 2010, Lin et al. (2011), Büyüközkan and Çifçi (2012), Khaleie et al. (2012), Yayla et al. (2012), Huang and Hu (2013), Kannan et al. (2013), Wang, 2010, Shen et al., 2016, Yue and Jia (2013), Zhang et al., 2016, Kar (2014), Xu and Shen (2014), Li et al., 2014, Darabi and Heydari (2016), Nia et al., 2016, Rao et al. (2016), Gitinavard et al. (2016).
Production/process capacity	Amid et al. (2006), Sanayei et al. (2008), Kirytopoulos et al. (2010), Kuo et al., 2010, Büyüközkan and Çifçi (2012), Huang and Hu (2013), Kannan et al. (2013), Huang and Hu (2013), Kar (2014), Shen et al., 2016, Yue (2014).
Technology management/ ability/capability	Araz et al. (2007), Feng et al. (2011), Park et al. (2010), Khaleie et al. (2012), Huang and Hu (2013), Kannan et al. (2013), Kar (2014), Xu and Shen (2014), Darabi and Heydari (2016).
Financial position/capability	Araz et al. (2007), Amin and Razmi (2009), Kirytopoulos et al. (2010), Feng et al. (2011), Kuo et al., 2010, Wang (2010), Büyüközkan and Çifçi (2012), Kar (2014), Nia et al., 2016.
Reputation	Amin and Razmi (2009), Kirytopoulos et al. (2010), Feng et al. (2011), Liao and Kao (2010), Lin et al. (2011), Khaleie et al. (2012), Huang and Hu (2013), Wang, 2010, Xu and Shen (2014), Shen et al., 2016, Rao et al. (2016).
Flexibility/response to changes	Araz et al. (2007), Kuo et al., 2010, Wang (2010), Büyüközkan and Çifçi (2012), Yue and Jia (2013).
Environment issues	Büyüközkan and Çifçi (2012), Khaleie et al. (2012), Kannan et al. (2013), Darabi and Heydari (2016), Nia et al., 2016, Gitinavard et al. (2016), Rao et al. (2016).
Relationship	Araz et al. (2007), Amin and Razmi (2009), Boran et al. (2009), Feng et al. (2011), Büyüközkan and Çifçi (2012), Lin et al. (2011), Zhang et al., 2016, Wang, 2010, Xu and Shen (2014), Rao et al. (2016).
Service level	Amid et al. (2006), Liao and Kao (2010), Huang and Hu (2013), Yue and Jia (2013), Wang, 2010, Shen et al., 2016.
Management	Araz et al. (2007), Park et al. (2010), Khaleie et al. (2012), Huang and Hu (2013), Xu and Shen (2014).
Geographic location	Kuo et al., 2010, Lin et al. (2011).
Historical performance	Yu and Wong (2015).
Technical performance	Xu and Shen (2014), Shen et al., 2016.

Table 2
Multi-criteria techniques applied for supplier qualification, supplier selection or supplier classification.

Citation	Purpose	Addressed Issues	Techniques		
			Qualification	Final Selection	Classification
Kefer et al. (2016)	Classification and Final Selection	Uncertainty and categorization	–	Modified ELECTRE II[a]	Fuzzy Multicriteria ABC Model (based on Euclidian distance)[b]
Yu and Wong (2015)	Qualification and Final Selection	Uncertainty	Fuzzy TOPSIS[a]		
Yu and Wong (2014)	Qualification	Uncertainty	Fuzzy TOPSIS[a]		
Sepulveda e Derpich (2015)	Classification	Categorization	–	–	ELECTRE and FlowSort
Cao et al. (2014)	Qualification	Qualification	Multi-objective Optimization Model solved by NGA II algorithm (non-dominated sorting genetic algorithm)[c]	MAS (multi-agent system)[c]	–
Lima Junior et al. (2013)	Qualification and Final Selection	Qualification, uncertainty and categorization	Fuzzy Inference (using non-compensatory rules for sorting)[b]		
Wu and Barnes (2011)	Classification	–	–	–	–
Arabzad et al. (2013)	Classification (of items) and Final Selection	–	–	TOPSIS[a]	DEA (data envelopment analysis)
Pattnaik (2013)	Classification	Uncertainty	–	–	fuzzy supplier selection algorithm (FSSA)[a]
Irfan et al. (2011)	Classification	Categorization	–	–	Projected clustering-based algorithm combined with Linear Weighted Model (LWM)[b]
Hallikas et al. (2005)	Classification	Categorization	–	–	Cluster analysis[b]
Araz and Ozkarahan (2007)	Final Selection and Classification	Categorization	–	PROMETHEE sorting (PROMSORT)[b]	PROMETHEE methods[a]
Omurca (2013)	Final Selection and Classification	Uncertainty and categorization	–	–	hybridization of fuzzy c-means (FCM) and rough set theory (RST)[b]
Sarkar and Mohapatra (2006)	Qualification	Qualification and uncertainty	Fuzzy Set Approach[a]	–	–
Rezaei and Ortt (2013a)	Classification	Uncertainty	–	–	Fuzzy AHP (Analytic Hierarchy Process)[a]
Rezaei and Ortt (2013b)	Classification	Qualification and uncertainty	–	–	Fuzzy rule-based (fuzzy inference)[b]
Osiro et al. (2014)	Classification	Uncertainty and categorization	–	–	Fuzzy Inference (using pattern classification) combined with the simple fuzzy grid limitation[b]
Lima Junior and Carpinetti (2016)	Classification	Uncertainty and categorization	–	–	Fuzzy TOPSIS[a] and categorization using two-dimensional grid

[a] The result is a rank of *k*-best alternatives.
[b] The result is the categorization of alternatives into predefined categories.
[c] The result is a choice of one or few alternatives.

another issue to be considered. Multiple actors from different functional areas are involved in the decision making process (De Boer et al., 1998) and consequently it is desirable that the techniques used in supplier evaluation be adequate to combine different judgements of multiple decision makers. Several studies have been published in the last decade that propose the use of fuzzy sets as intuitionistic and hesitant applied to group decision making. Hesitant fuzzy set (HFS) is convenient to describe a group of decision makers' judgement, especially when they are somehow independent (Yu et al., 2016). This may explain why hesitant fuzzy has been quite explored as a technique to group decision making (Ai et al., 2014; Chai and Ngai, 2015; Fahmi et al., 2016; Kahraman et al., 2016; Shan et al., 2016; Wang and Xu, 2016; Yu et al., 2016; Zhang et al., 2016).

Searching the Scopus and Web of Science databases using the string ("group decision" AND (categorization OR sorting)) led to the studies presented in Table 3. It shows few studies about categorization techniques in group decision-making. In addition, most of the studies do not deal with the uncertainty. Among the studies that considers uncertainty only one deals with hesitation (Shen et al., 2016). However it applies intuitionistic fuzzy, which does not allow hesitation in the judgements by the decision makers as is the case of hesitant fuzzy. Thus, the use of this technique in group decision-making adds to the literature an approach that takes into account hesitation in the judgements besides uncertainty.

3. Hesitant fuzzy applied to group decision making

Group decision making is understood as a process where two or more specialists with different knowledge and preferences are involved in the judgement of some objects with the purpose of reaching a collective decision (Rodríguez et al., 2013). Fuzzy set generalizations such as Atanossov intuitionistic and hesitant fuzzy sets have been proposed to deal with the problem of group decision making (Ai et al., 2014). Hesitant fuzzy set has become lately a quite often technique applied to the problem of supplier selection due its ability to deal with uncertainty and aggregation of judgements (Chai et al., 2013; Kahraman et al., 2016; Zhang and Wei, 2013).

A hesitant fuzzy set (HFS) E in a fixed set X is a function that when applied to X returns a subset of [0, 1]. Mathematically, it is represented as in equation (1).

Table 3
Results of the literature search using the key-words "group decision" and "categorization or sorting".

Reference	Group Decision Making Technique	Does the technique deals with uncertainty and hesitation?
Scopus		
López and Ishizaka 2017	Group Analytic Hierarchy Process Sorting (GAHPSort)	No
Masoumi et al. (2017)	Analytic Hierarchy Process and Multi-Criteria Optimization and Compromise Solution	No
Sun et al. (2017)	Multigranulation fuzzy decision-theoretic rough set	Only uncertainty
Shen et al. (2016)	Intuitionistic fuzzy for group decision making	It deals with uncertainty, considers hesitation, but does not allow the decision maker to evaluate using various linguistic terms. The hesitancy degree is defined in the linguistic scale.
Liu et al. (2015)	Consensus	In this paper, the uncertainty refers to imprecise evaluations of alternatives.
Chen et al. (2015)	MAGDM analysis method based on error propagation and vertical projection distance.	No
Morais et al. (2014)	SMAA-TRI	No
Kadziński et al. (2013)	UTAGMS GROUP and UTADISGMS GROUP	No
Cai et al. (2012)	RINCON algorithm	No
Chen et al. (2012)	Hybrid of the dominance-based rough set approach (DRSA) and the Dempster–Shafer (DS) theory	Only uncertainty
Li et al. (2009)	A rough set approach and linguistic computing	Only uncertainty
Jabeur and Martel (2007)	Ordinal sorting method for group decision-making	No
Damart et al. (2007)	ELECTRE TRI method implemented on the Decision Support System IRIS	No
Web of Science		
Palha et al. (2016)	ROR-UTADIS method	No
Li et al. (2014)	Cloud model and VIKOR method	It deals with uncertainty and fuzziness caused by the experts' subjective perception and experience. But does not allow the decision maker to evaluate using various linguistic terms.
Valls et al. (2009)	ClusDM method	Deal with imprecise information, but does not allow the decision maker to evaluate using various linguistic terms.
Damart et al. (2007)	ELECTRE TRI with e optimization tools	It deals with uncertainty, considers discordance, but does not allow the decision maker to evaluate using various linguistic terms.

$$\tilde{E} = \{\langle x, \tilde{h}_{\tilde{E}}(x) | x \in X \rangle\}, \tag{1}$$

where, called a hesitant fuzzy element (HFE), is a set of values in [0, 1] of the element x in X, and a HFS is a set of HFEs. By means of HFS, decision makers are able to express their judgements using one or more linguistic terms. For instance, a linguistic expression for a judgement can be of the type between medium and high, equal or lower than medium, equal or greater than high, as illustrated in Fig. 1 (Rodriguez et al., 2012).

Based on the HFE definitions proposed by Torra (2010), Xia and Xu (2011) defined some operations in order to obtain a collective hesitant fuzzy aggregation of preferences. Given the HFEs h, h_1 e h_2, the following operations are defined as in equations (2)–(5).

$$\tilde{h}^{\lambda} = \left(\cup_{\gamma \epsilon \tilde{h}}\{\gamma^{\lambda}\}\right) \tag{2}$$

$$\lambda\tilde{h} = \left(\cup_{\gamma \epsilon \tilde{h}}\left\{1-(1-\gamma)^{\lambda}\right\}\right) \tag{3}$$

$$\tilde{h}_1 \oplus \tilde{h}_2 = \left(\cup_{\gamma_1 \epsilon \tilde{h}_1, \gamma_2 \epsilon \tilde{h}_2}\{\gamma_1+\gamma_2-\gamma_1\gamma_2\}\right) \tag{4}$$

$$\tilde{h}_1 \otimes \tilde{h}_2 = \cup_{\gamma_1 \epsilon \tilde{h}_1, \gamma_2 \epsilon \tilde{h}_2}\{\gamma_1\gamma_2\} \tag{5}$$

Yu, 2013a, pointing some drawbacks of the traditional HFS proposed the Triangular Fuzzy Hesitant Fuzzy Set (TFHFS), an extend of the HFS. The definition of TFHFS follows the same properties of the HFS, however the function $\tilde{f}_{\tilde{E}}(x)$ returns triangular fuzzy values. It is denoted by:

$$\tilde{E} = \{x, \tilde{f}_{\tilde{E}}(x) | x \in X\}, \tag{6}$$

where the set of triangular fuzzy numbers $(\tilde{f}_{\tilde{E}}(x))$ expresses the possible membership degree of the element $x \in X$ to the set $\tilde{E}$. The Triangular Fuzzy Hesitant Fuzzy Element (TFHFE) is represented as:

$$\tilde{f}_{\tilde{E}}(x_i) = \left\{\left(\tilde{\xi}^L, \tilde{\xi}^M, \tilde{\xi}^U\right) | \tilde{\xi} \epsilon \tilde{f}_{\tilde{E}}(x_i)\right\} \tag{7}$$

where $\tilde{\xi}$ is a triangular fuzzy number (TFN), $\tilde{\xi}^L$, $\tilde{\xi}^M$ and $\tilde{\xi}^U$ are respectively the lower, middle and upper values of the TFN.

Xia and Xu (2011) proposed several aggregation operators, including the Hesitant Fuzzy Weighted Average Operator (HFWA) and the Hesitant Fuzzy Weighted Geometric Operator (HFWG). Following this, Yu, 2013b proposed aggregation operators for TFHFE. A Triangular Fuzzy Hesitant Weighted Averaging (TFHFWA) operator is defined as in equation (8).

$$\begin{aligned} TFHFWA(\tilde{f}_1, \tilde{f}_2, \ldots, \tilde{f}_n) &= \oplus_{j=1}^{n}(w_j\tilde{f}_j) \\ &= \left\{\left(1-\prod_{j=1}^{n}\left(1-\tilde{\xi}^L\right)^{w_j}, 1-\prod_{j=1}^{n}\left(1-\tilde{\xi}^M\right)^{w_j}, 1 - \prod_{j=1}^{n}\left(1-\tilde{\xi}^U\right)^{w_j}\right) \middle| \tilde{\xi}_1 \in \tilde{f}_1,\ \tilde{\xi}_2 \in \tilde{f}_2, \ldots,\ \tilde{\xi}_n \in \tilde{f}_n\right\}, \end{aligned} \tag{8}$$

where $w = (w_1, w_2, \ldots, w_n)$ is the weight vector such that $w_j > 0$, $\sum_{j=1}^{n} w_j = 1$.

In the same way, a Triangular Fuzzy Hesitant Fuzzy Weighted Geometric (TFHFWG) is defined as in equation (9):

$$\begin{aligned} TFHFWG(\tilde{f}_1, \tilde{f}_2, \ldots, \tilde{f}_n) &= \oplus_{j=1}^{n}(w_j\tilde{f}_j) \\ &= \left\{\left(\prod_{j=1}^{n}\left(\tilde{\xi}^L\right)^{w_j}, \prod_{j=1}^{n}\left(\tilde{\xi}^M\right)^{w_j}, \prod_{j=1}^{n}\left(\tilde{\xi}^U\right)^{w_j}\right) \middle| \tilde{\xi}_1 \in \tilde{f}_1, \tilde{\xi}_2 \in \tilde{f}_2, \ldots, \tilde{\xi}_n \in \tilde{f}_n\right\} \end{aligned} \tag{9}$$

4. ELECTRE TRI

ELECTRE TRI is a technique pertaining to the ELECTRE family of outranking methods. It assigns alternatives to predefined and ordered categories (Certa et al., 2017; Figueira et al., 2005; Ishizaka and Nemery, 2013; Mousseau et al., 2000). It presents several features: it does not allow for compensation between criteria; it accepts heterogeneity of scales and qualitative scales of some criteria (Figueira et al., 2013;

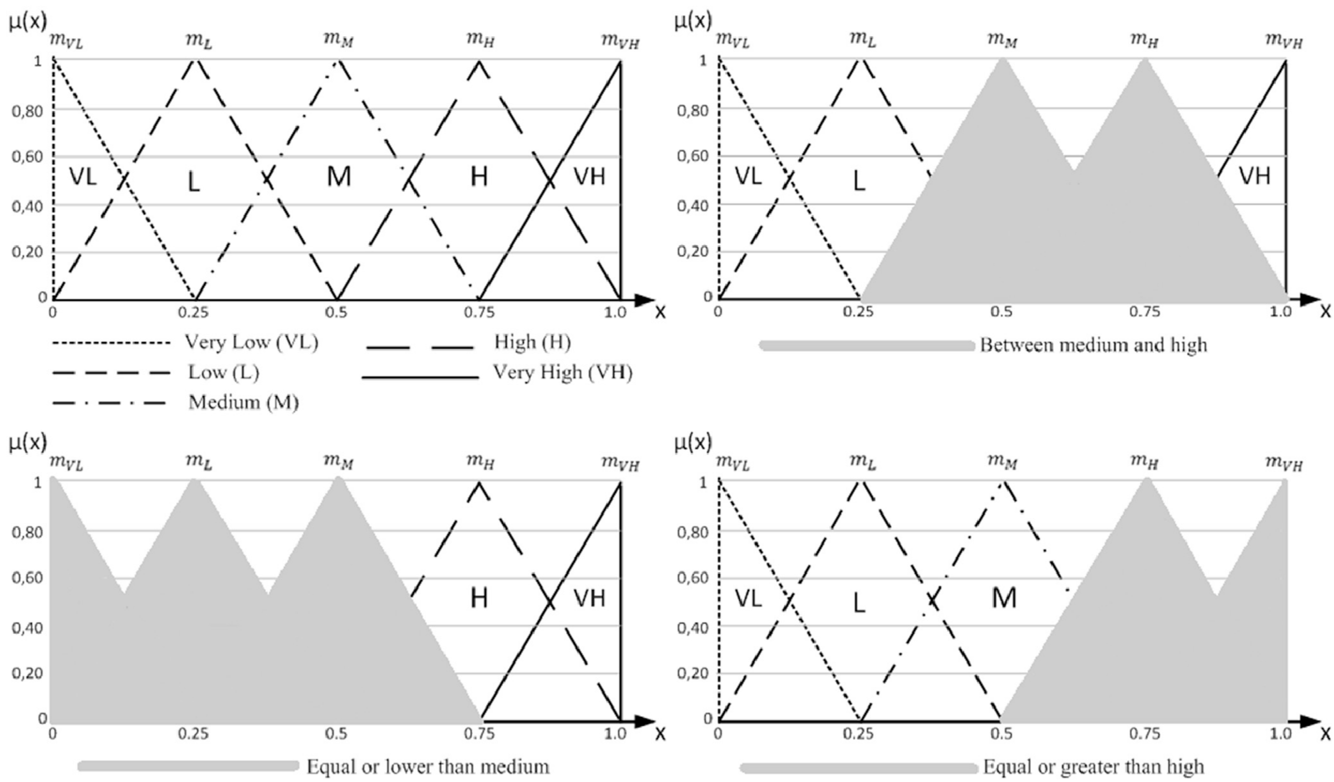

Fig. 1. Linguistic expressions for the judgements of the decision makers.

Guarnieri, 2014). All these characteristics make it suitable to the problem of supplier evaluation. It has been applied to different categorization problems (Certa et al., 2017; Figueira et al., 2011; Fontana and Cavalcante, 2013; Szajubok et al., 2006).

In the ELECTRE TRI method, the ordered categories are defined with lower and upper limits adjusted for each criteria being considered. As in Fig. 2, for each criterion $C_j (j = 1, 2, \ldots, n)$, the category CT_{h+1} will be limited by a lower limit b_h and an upper limit b_{h+1}.

The assignment of an alternative a into a category CT_{h+1} results from the comparison of the alternative with the limits $b_h (h = 1, 2, \ldots, p)$. Comparisons are based on an outranking relation S (Mousseau et al., 2001; Roy, 1991). To validate that aSb_h or b_hSa, ELECTRE TRI uses the credibility index $\sigma(a, b_h)$ and $\sigma(b_h, a)$. The credibility index $\sigma(a, b_h)$ is calculated as in equation (10).

$$\sigma(a, b_h) = c(a, b_h) \times \prod_{j=1}^{n} \frac{1 - d_j(a, b_h)}{1 - c(a, b_h)}, \tag{10}$$

where $c(a, b_h)$ is the comprehensive concordance index and $d_j(a, b_h), j = 1, 2, \ldots, n$, are the discordance indices. The comprehensive concordance index $c(a, b_h)$ is calculated as in equation (11).

$$c(a, b_h) = \frac{\sum_{j=1}^{n} W_j \times c_j(a, b_h)}{\sum_{j=1}^{n} W_j}, \tag{11}$$

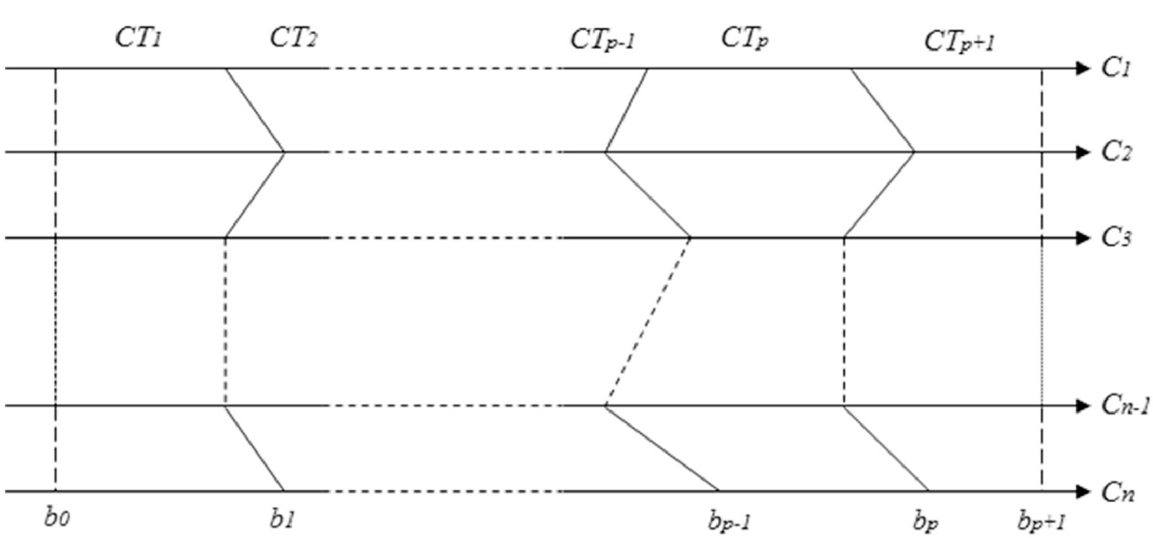

Fig. 2. Definition of categories using limit profiles.

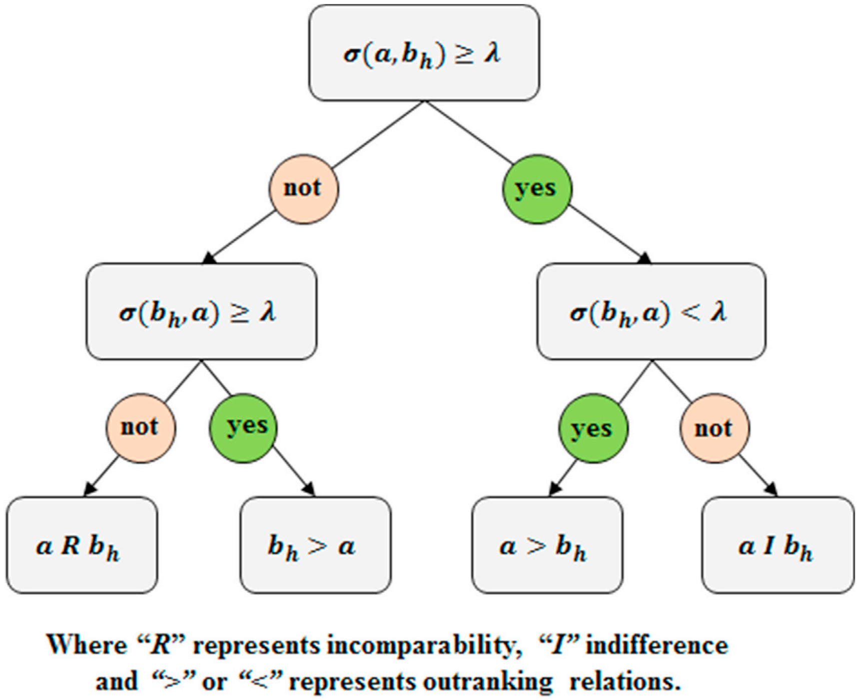

Fig. 3. Definition of the binary relations $\succ$, I and R (Certa et al., 2017).

where W_j is the weight of the criteria C_j and $c_j(a, b_h)$ is the partial concordance index ($j = 1, 2, \ldots, n$), which is computed as in equation (12).

$$c_j(a,b_h) = \begin{cases} 0 \text{ if } g_j(b_h) - g_j(a) \geq p_j(b_h) \\ 1 \text{ if } g_j(b_h) - g_j(a) \leq q_j(b_h) \\ \dfrac{p_j(b_h) + g_j(a) - g_j(b_h)}{p_j(b_h) - q_j(b_h)}, \text{otherwise} \end{cases}, \tag{12}$$

where $g_j(a)$ is the evaluation of alternative a on the criterion C_j, $g_j(b_h)$ is the value of the limit b_h for the criteria C_j. The parameters $p_j(b_h)$ and $q_j(b_h)$ are respectively the predefined preference and indifference threshold indices for the criterion C_j and limit b_h.

The discordance indices $d_j(a, b_h)$, $j = 1, 2, \ldots, n$, is calculated as in equation (13).

$$d_j(a,b_h) = \begin{cases} 0 \text{ if } g_j(b_h) - g_j(a) \leq p_j(b_h) \\ 1 \text{ if } g_j(b_h) - g_j(a) > v_j(b_h) \\ \dfrac{g_j(b_h) - g_j(a) - p_j(b_h)}{v_j(b_h) - p_j(b_h)}, \text{otherwise} \end{cases}, \tag{13}$$

where $v_j(b_h)$ is the veto threshold for the criterion C_j and limit b_h, also a predefined parameter.

Once the credibility indices $\sigma(a, b_h)$ and $\sigma(b_h, a)$ are calculated, to determine the preference relation between a and b_h, the following rules are used, as illustrated in Fig. 3 (based on a predefined cutting level $\lambda \in [0.5, 1]$):

a) If $\sigma(a, b_h) \geq \lambda$ and $\sigma(b_h, a) \geq \lambda$, aSb_h and b_hSa, then a is indifferent in relation to b_h (aIb_h);
b) If $\sigma(a, b_h) \geq \lambda$ and $\sigma(b_h, a) < \lambda$, aSb_h and not b_hSa, then a is preferred in relation to b_h (aSb_h);
c) If $\sigma(a, b_h) \geq \lambda$ and $\sigma(b_h, a) \geq \lambda$, b_hSa and not aSb_h, then b_h is preferred in relation to a (b_hSa);
d) If $\sigma(a, b_h) \geq \lambda$ and $\sigma(b_h, a) < \lambda$, aSb_h and b_hSa do not hold, then a is incomparable in relation to b_h (aSb_h).

After application of these rules to determine the preference relations, two assignment procedures are used, as follows (Certa et al., 2017; Mousseau et al., 2001):

- The pessimistic (or conjunctive) procedure:
  a) Compare successively each alternative a with the limits $b_i (i = p, p-1, \ldots, 1)$
  b) Assign the alternative a to the highest category CT_h such that aSb_{h-1}.
- The optimistic (or disjunctive) procedure:
  a) Compare successively each alternative a with the limits b_i ($b_i(i = 1, 2, .., p)$;
  b) Assign the alternative a to the lowest category CT_h such that $b_h \succ a$.

It is interesting to note that, using the pessimistic procedure, when $\lambda = 1$, assignment of an alternative a to a category CT_h only happens if $g_j(a)$ equal or exceeds $g_j(b_h)$ for each criterion (Mousseau et al., 2000). On the other, when using the optimistic procedure, when $\lambda = 1$, an alternative a will be assigned to a category CT_h only when $g_j(b_h)$ exceeds $g_j(a)$ for at least one criterion (Mousseau et al., 2000).

5. ELECTRE TRI with hesitant fuzzy for group decision

The proposed group decision approach for supplier categorization is illustrated in Fig. 4. It comprises two phases: hesitant fuzzy aggregation of individual judgements and categorization of alternatives. The steps in these phases are as follow:

Although it uses the mathematical definitions of Triangular Hesitant Fuzzy, including its aggregation operators, the method proposed in this paper suggests modifications in relation to the usual aggregation, which has the goal of ordering the alternatives. In addition, the method allows the use of different weights for the decision makers in each criterion, besides the elicitation of weights of each criterion, which is not verified

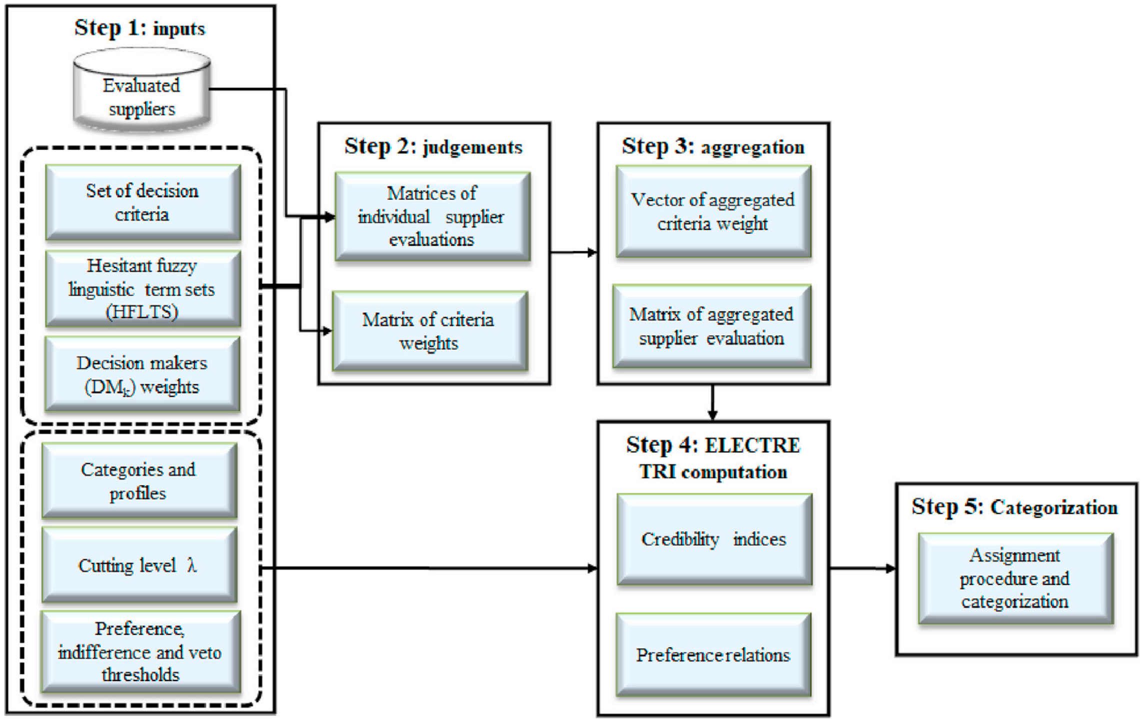

Fig. 4. Proposed group decision approach for hesitant fuzzy aggregation of individual judgements and ELECTRE TRI supplier categorization.

in any article that uses the Hesitant Fuzzy. Elicitation is important when the criteria and weights of the criteria are not clearly known.

5.1. Step 1: inputs

The evaluated suppliers are given by $A_i = (i = 1, 2, \ldots, m)$, which are evaluated by the decision makers $DM_k(k = 1, 2, \ldots, d)$ in each of the n criteria $C_j(j = 1, 2, \ldots n)$. The linguistic terms used for weighting criteria and evaluating alternatives and respective triangular fuzzy sets are presented in Figs. 5 and 6 with indication of the middle vertices of the fuzzy sets. The possible hesitant linguistic expressions are presented in Table 4.

In step 1, the ELECTRE TRI parameters are also defined, which include the categories CT_{h+1}, the profiles $b_h(h = 1, 2, \ldots, p)$, the cutting level λ and the thresholds: preference, $p_j(b_h)$, indifference, $q_j(b_h)$ and veto, $v_j(b_h)$.

5.2. Step 2: judgements

Each decision maker DM_k judges the weights of the criteria C_j and the performance of the alternatives using the linguistic expressions of Table 5. As a result, the matrices of criteria weights and individual alternative evaluations are built. The matrix in 14 represents criteria weight judgements $\tilde{f}_{wjk} \in [0, 1]$.

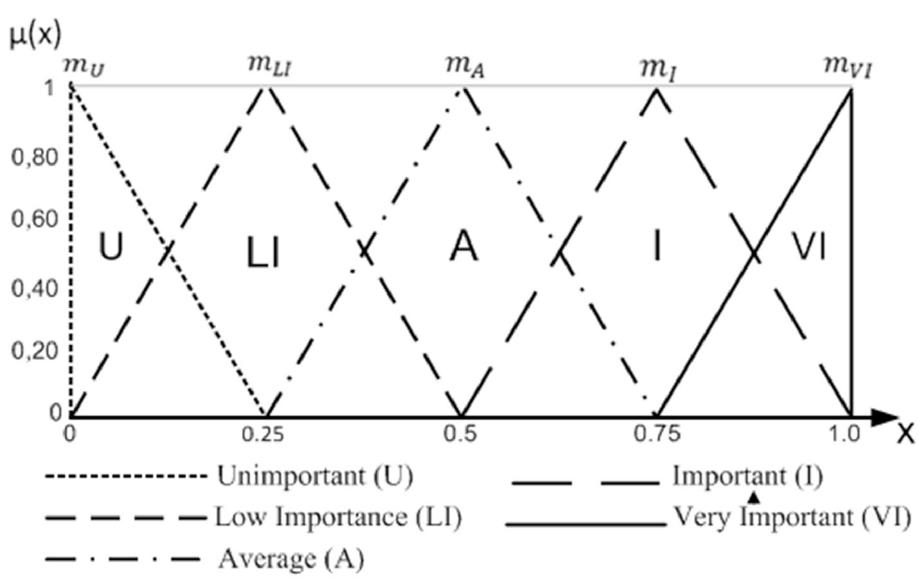

Fig. 5. Linguistic terms for criteria weight evaluation.

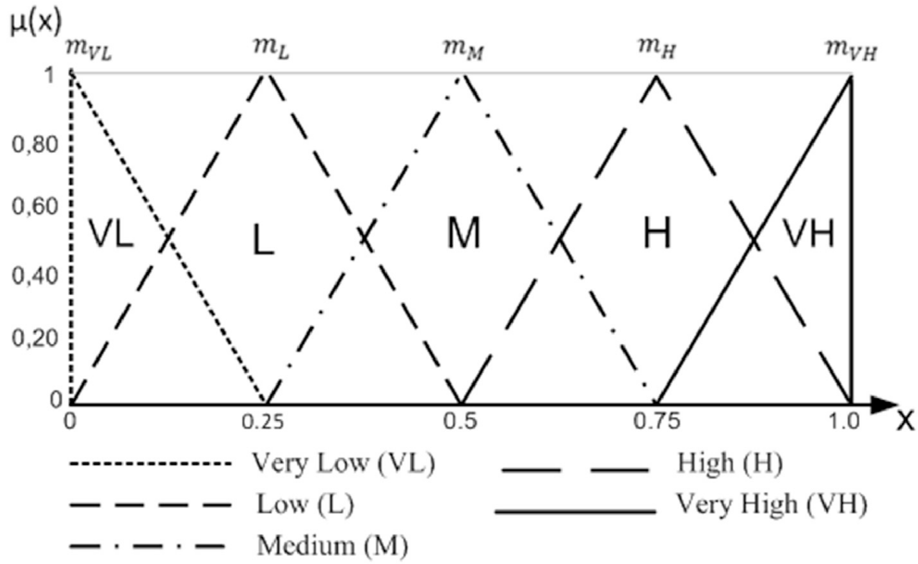

Fig. 6. Linguistic terms for alternative performance evaluation.

Table 4
Hesitant linguistic expressions and hesitant terms set (Fig. 5).

Hesitant linguistic expressions	Example of application	Hesitant terms set	Middle vertices
Unimportant or very low	Specific evaluation	U or VL	(0.0, 0.0, 0.25)
Low Importance or low		LI or L	(0.0, 0.25, 0.5)
Average or medium		A or M	(0.25, 0.5, 0.75)
Important or high		I or H	(0.5, 0.75, 1.0)
Very Important or very high		VI or VH	(0.75, 1, 1)
"Equal or lower than …" or "at most …"	"Equal or lower than average" or "Equal or lower than medium"	U, LI, A VL, L, M	(0.0, 0.0, 0.25) (0.0, 0.25, 0.5) (0.25, 0.5, 0.75)
"Equal or greater than …" or "at least …"	"Equal or greater than important" or "equal or greater than high"	I, VI H, VH	(0.5, 0.75, 1.0) (0.75, 1, 1)
"Between … and …"	"Between low importance and important" or "between low and high"	LI, A, I L, M, H	(0.0, 0.25, 0.5) (0.25, 0.5, 0.75) (0.5, 0.75, 1.0)

Table 5
Judgements of criteria importance using linguistic expressions.

Criteria	Decision Makers		
	DM$_1$	*DM*$_2$	*DM*$_3$
C_1: Quality Management	Important	Equal or greater than important	–
C_2: Problem Resolution	Between important and very important	Equal or greater than important	Important
C_3: Delivery	Equal or greater than important	Important	Equal or greater than important

$$\begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{cccc} DM_1 & DM_2 & \ldots & DM_d \end{array} \\ \begin{pmatrix} \tilde{f}_{w_{11}} & \tilde{f}_{w_{12}} & \cdots & \tilde{f}_{w_{1d}} \\ \tilde{f}_{w_{21}} & \tilde{f}_{w_{22}} & \cdots & \tilde{f}_{w_{2d}} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{f}_{w_{n1}} & \tilde{f}_{w_{n2}} & \cdots & \tilde{f}_{w_{nd}} \end{pmatrix} \end{array} \tag{14}$$

The matrix in 15 represents the individual alternative evaluations $\tilde{f}_{A_{ijk}}(j = 1, 2, \ldots, n; k = 1, 2, \ldots, d)$ of the k decision makers in regard to alternative $A_i = (i = 1, 2, \ldots, m)$.

$$A_i = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{cccc} DM_1 & DM_2 & \ldots & DM_d \end{array} \\ \begin{pmatrix} \tilde{f}_{A_{i11}} & \tilde{f}_{A_{i12}} & \cdots & \tilde{f}_{A_{i1d}} \\ \tilde{f}_{A_{i21}} & \tilde{f}_{A_{i22}} & \cdots & \tilde{f}_{A_{i2d}} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{f}_{A_{in1}} & \tilde{f}_{A_{in2}} & \cdots & \tilde{f}_{A_{ind}} \end{pmatrix} \end{array} \tag{15}$$

5.3. Step 3: aggregation of judgements

First, the aggregation of the criteria weights is based on the triangular fuzzy hesitant fuzzy weighted average operator, $TFHFWA_{C_j}$, for criterion $C_j, j = 1, \ldots, n$ as in equation (16), where w_k denotes the weights of the decision makers and $\tilde{f}_{wjk}$ represents the hesitant elements as in matrix 14.

$$\begin{aligned} TFHFWA_{C_j}\left(\tilde{f}_{w_{j1}}, \tilde{f}_{w_{j2}}, \ldots, \tilde{f}_{w_{jd}}\right) &= \overset{d}{\underset{k=1}{\oplus}} \left(w_k \tilde{f}_{w_{jk}}\right) \\ &= \Big\{ \Big(1 - \textstyle\prod_{k=1}^{d} \left(1 - \tilde{\xi}^{L}\right)^{w_k}, 1 \\ &\quad - \textstyle\prod_{k=1}^{d} \left(1 - \tilde{\xi}^{M}\right)^{w_k}, 1 \\ &\quad - \textstyle\prod_{k=1}^{d} \left(1 - \tilde{\xi}^{U}\right)^{w_k}\Big) \Big| \tilde{\xi}_1 \\ &\quad \in \tilde{f}_{w_1}, \tilde{\xi}_2 \in \tilde{f}_{w_2}, \ldots, \tilde{\xi}_n \in \tilde{f}_{w_n} \Big\}, \end{aligned} \tag{16}$$

The results of aggregation are normalized so as to obtain $W_{C_j}(j = 1, 2, \ldots n)$, where $\sum_1^n W_{C_j} = 1$.

The aggregation of the decision maker evaluations for each alternative A_i is also based on the TFHFWA indicated in equation (17) where w_k also denotes the weights of the decision makers and $\tilde{f}_{A_{ijk}}$ represents the hesitant elements as in matrix 15.

$$TFHFWA_{A_i}\left(\tilde{f}_{A_{ij1}}, \tilde{f}_{A_{ij2}}, \ldots, \tilde{f}_{A_{ijd}}\right) = \mathop{\oplus}_{k=1}^{d} \left(w_k \tilde{f}_{A_{ijk}}\right) = \left\{\left(1 - \prod_{k=1}^{d}\left(1 - \tilde{\xi}^{L}\right)^{w_k}, 1 - \prod_{k=1}^{d}\left(1 - \tilde{\xi}^{L}\right)^{w_k}, 1 - \prod_{k=1}^{d}\left(1 - \tilde{\xi}^{L}\right)^{w_k}\right) \middle| \tilde{\xi}_1 \in \tilde{f}_{A_{ij1}}, \tilde{\xi}_2 \in \tilde{f}_{A_{ij2}}, \ldots, \tilde{\xi}_n \in \tilde{f}_{A_{ijn}}\right\} \quad (17)$$

The aggregation of the judgements of the decision makers regarding the evaluation of each alternative results in a matrix with the criteria C_j in the column and the alternatives A_i in the lines which, together with the normalized weight vector W_j, are used as input to the ELECTRE TRI procedure in the next step.

5.4. Step 4: ELECTRE TRI computation

Let $g_j(a)$ be the evaluation of alternative A on the criterion C_j resulted from the aggregation procedure (based on equation (17)) in the previous step. The ELECTRE TRI method starts by calculation of the partial concordance index, $c_j(a, b_h)$, $(j = 1, 2, \ldots, n)$ which is computed as in equation (12); $g_j(b_h)$ is the value of the limit b_h for the criteria C_j, defined in step 1; also defined in step 1 are $p_j(b_h)$ and $q_j(b_h)$, respectively the preference and indifference threshold indices for the criterion C_j and limit b_h. Next, discordance indices $d_j(a, b_h), j = 1, 2, \ldots, n$, is calculated as in equation (13), where $v_j(b_h)$ is the veto threshold for the criterion C_j and limit b_h, also predefined in step 1. The credibility index $\sigma(a, b_h)$ is then calculated as in equation (10). Then, the rules illustrated in Fig. 3 are applied to define the preference relations between alternatives and category profiles.

5.5. Step 5: supplier categorization

Based on the preference relations between alternatives and category profiles, defined in the previous step, the procedures described in section 4 were applied to define the supplier categories in the pessimistic and optimistic scenarios. The decision makers have to finally decide the supplier status based on the pessimistic and optimistic categorizations.

6. Illustrative application case

The illustrative case is based on a decision process of a manufacturer in the automotive supply chain that evaluates its current suppliers on a regular basis and classifies them as certified or premium suppliers when they achieve and sustain high performance in some criteria. Otherwise, they are categorized in two other categories: approved or disqualified. The criteria used to evaluate the suppliers are: C_1 - quality management; C_2 - cost reduction and C_3 - delivery. Three decision makers of different functional areas are involved in this evaluation process: DM_1 – Production; DM_2 - Quality; and DM_3 - Purchasing. To illustrate the application of this proposal, the steps in section 5 were followed, as described next.

6.1. Step 1: inputs

The specialists were asked to evaluate the same six suppliers using linguistic expressions as in Table 4. They were also asked to judge the relative importance of each criterion, also using linguistic expressions as in Table 4. The weight of each decision maker varies depending on the criterion, as presented in Table 5. However, the criterion C_1 was evaluated only by DM_1 and DM_2. The parameters of the ELECTRE TRI were also defined in this step as follows:

- The limits between the categories for each criterion were defined based on the preferences of the decision makers. Therefore, the profiles of the categories are $b_1 = \{0.85, 0.80, 0.75\}$, limiting the categories CT_1 (premium supplier) and CT_2 (approved) and; $b_2 = \{0.70, 0.60, 0.60\}$, limiting the categories CT_2 and CT_3 (disqualified);
- The choice of the threshold parameters were made based on an estimation of the opinions of the decision makers regarding indifference, veto and preference in the alternative evaluation for each criterion: preference $p_j(b_h) = \{0.05, 0.05, 0.05\}$, indifference $q_j(b_h) = \{0.02, 0.03, 0.03\}$ and veto $v_j(b_h) = \{0.1, 0.1, 0.1\}$;
- The cutting level $\lambda = 1$, following suggestion by Mousseau et al. (2000).

6.2. Step 2: judgements

Table 5 presents the linguistic expressions of the decision makers used to judge the importance of the criteria. Table 6 presents the transformation of these expressions in TFHFSs based on the fuzzy numbers of the linguistic term sets in Fig. 5. The judgements of the alternatives by the decision makers are presented in Tables 7 and 8, based on the linguistic

Table 6
TFHFSs of judgements in Table 4.

Criteria	Decision Makers			Decision Marker Weight		
	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
C_1: Quality Management	(0.5,0.75,1)	(0.5,0.75,1) (0.75,1,1)	–	0.4	0.6	–
C_2: Problem Resolution	(0.5,0.75,1) (0.75,1,1)	(0.75, 1.00)	(0.5,0.75,1)	0.4	0.3	0.3
C_3: Delivery	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1)	(0.5,0.75,1) (0.75,1,1)	0.4	0.2	0.4

Table 7
Performance evaluation of suppliers using linguistic expressions.

Suppliers	C_1: Quality management		C_2: Problem Resolution			C_3: Delivery		
	DM_1	DM_2	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
A_1	$\geq$ M	$\geq$ M and $\leq$ H	H	$\geq$ H	$\geq$ H and $\leq$ VH	$\geq$ M and $\leq$ H	M	$\geq$ M and $\leq$ H
A_2	$\geq$ L and $\leq$ M	$\leq$ M	M	$\geq$ M and $\leq$ H	H	$\geq$ H	$\geq$ H and $\leq$ VH	$\geq$ H
A_3	$\geq$ H and $\leq$ VH	H	$\geq$ H	$\geq$ H and $\leq$ VH	H	VH	$\geq$ M and $\leq$ H	$\geq$ M
A_4	L	$\leq$ L	$\leq$ M	$\leq$ L	M	$\geq$ M	$\geq$ M and $\leq$ H	M
A_5	H	VH	$\geq$ H and $\leq$ VH	$\geq$ H	$\geq$ H	VH	$\geq$ H and $\leq$ VH	H
A_6	$\geq$ H	$\geq$ H and $\leq$ VH	H	$\geq$ M and $\leq$ H	$\geq$ M	H	$\geq$ M and $\leq$ H	$\geq$ M and $\leq$ H

Table 8
TFHFSs of judgements in Table 6 about performance evaluation of suppliers.

Suppliers	C_1: Quality management		C_2: Problem Resolution			C_3: Delivery		
	DM_1	DM_2	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
A_1	(0.25,0.50,0.75) (0.5,0.75,1) (0.75,1,1)	(0.25,0.50,0.75) (0.5,0.75,1)	(0.5,0.75,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.25,0.50,0.75) (0.5,0.75,1)	(0.25,0.50,0.75)	(0.25,0.50,0.75) (0.5,0.75,1)
A_2	(0,0.25,0.5) (0.25,0.50,0.75)	(0,0,0.25) (0,0.25,0.5) (0.25,0.50,0.75)	(0.25,0.50,0.75)	(0.25,0.50,0.75) (0.5,0.75,1)	(0.5,0.75,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1) (0.75,1,1)
A_3	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.75,1,1)	(0.75,1,1)	(0.25,0.50,0.75) (0.5,0.75,1)	(0.25,0.50,0.75) (0.5,0.75,1) (0.75,1,1)
A_4	(0,0.25,0.5)	(0,0,0.25) (0,0.25,0.5)	(0,0,0.25) (0,0.25,0.5) (0.25,0.50,0.75)	(0,0,0.25) (0,0.25,0.5)	(0.25,0.50,0.75)	(0.25,0.50,0.75) (0.5,0.75,1) (0.75,1,1)	(0.25,0.50,0.75) (0.5,0.75,1)	(0.25,0.50,0.75)
A_5	(0.5,0.75,1)	(0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1)
A_6	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1)	(0.25,0.50,0.75) (0.5,0.75,1)	(0.25,0.50,0.75) (0.5,0.75,1) (0.75,1,1)	(0.5,0.75,1)	(0.25,0.50,0.75) (0.5,0.75,1)	(0.25,0.50,0.75) (0.5,0.75,1)

expressions in Table 4 and fuzzy term sets in Fig. 6.

6.3. Step 3: aggregation of judgements

The judgements of the decision makers in Tables 6 and 8 were aggregated using the Triangular Fuzzy Hesitant Fuzzy Weighted Average (TFHFWA) operator as in equations (16) and (17). Table 9 presents the aggregation results.

6.4. Step 4: ELECTRE TRI computation

In this step, the ELECTRE TRI credibility indices were calculated based on equations (10)–(13) for each alternative in comparison to the profiles b1 and b2. Table 10 presents the credibility indices and the preference relations defined based on the procedure illustrated in Fig. 3. "*R*" represents incomparability, "*I*" indifference and ">" or "" outranking relations.

6.5. Step 5: categorization

Based on the preference relations in Table 10 and the procedures in section 4, the suppliers were categorized as presented in Table 11.

Table 9
Aggregation of judgements of criteria weights and supplier's performance.

	C1	C2	C3
W_j	0,324	0337	0,338
A1	0,727	0866	0,631
A2	0,396	0660	0,894
A3	0,828	0919	0,904
A4	0,233	0388	0,703
A5	0,918	0894	0,912
A6	0,878	0766	0,703

Table 10
Credibility indices and preference relations.

	$\sigma(a,b_h)$		$\sigma(b_h,a)$		Preference Relations
	b_1	b_2	b_1	b_2	
A_1	0	1	0,69	0	$A_1 > b_2$ and A_1Rb_1
A_2	0	0	0	0	A_2Rb_2 and A_2Rb_1
A_3	0,97	1	0	0	$A_3 > b_2$ and A_3Rb_1
A_4	0	0	1	0	A_4Rb_2 and $b_1 > A_4$
A_5	1	1	0	0	$A_5 > b_2$ and $A_5 > b_1$
A_6	0,65	1	0,91	0	$A_6 > b_2$ and A_6Rb_1

7. Discussion of results

Analyzing the categorization results in Table 11, it can be seen a great difference in the categorization results depending on the procedure. For instance, supplier A_2 was categorized as premium in the optimistic procedure and disqualified in the pessimistic one. It happens due to incomparability. Supplier A_2 is incomparable to both profiles, thus the optimistic procedure assigned the alternative for the best class, while the pessimistic procedure assigned the alternative for the worst category. As for the other suppliers, except supplier A_5, the change in category happened for the same reason of incomparability. Therefore, for the purpose of supplier categorization, the pessimistic procedure would be more adequate. In general, when the cutting level $\lambda = 1$, the pessimistic procedure insures that the performance of an alternative in each criterion is at least equal to the lower profile of the category in which the alternative has been assigned. Table 12 shows the categorization results when the cutting level is reduced to λ=*0,9*. It can be seen that alternative A_3 is

Table 11
Result of the ELECTRE TRI categorization.

	Pessimistic Procedure	Optimistic Procedure
CT_1: Premium supplier	A_5	A_1, A_2, A_3, A_5, A_6
CT_2: In need of improvement	A_1, A_3, A_6	A_4
CT_3: Disqualified	A_2, A_4	–

Table 12
Result of the ELECTRE TRI categorization with $\lambda = 0{,}9$.

	Pessimistic Procedure	Optimistic Procedure
CT_1: Premium supplier	A_5, A_3	A_1, A_2, A_3, A_5
CT_2: In need of improvement	A_1, A_6	A_4, A_6
CT_3: Disqualified	A_2, A_4	–

Table 13
Result of the ELECTRE TRI categorization varying criteria weights, $W_j = \{0.5, 0.2, 0.3\}$.

	Pessimistic Procedure	Optimistic Procedure
CT_1: Premium supplier	A_5	A_1, A_2, A_3, A_5, A_6
CT_2: In need of improvement	A_1, A_3, A_6	A_4
CT_3: Disqualified	A_2, A_4	–

Table 14
Performance evaluation of suppliers with modified judgement of decision maker DM_2.

Suppliers	C_1: Quality management		C_2: Problem Resolution			C_3: Delivery		
	DM_1	DM_2	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
A_1	≥ M	VH	H	VH	≥ H and ≤ VH	≥ M and ≤ H	VH	≥ M and ≤ H
A_2	≥ L and ≤ M	≥ H	M	H	H	≥ H	VH	≥ H
A_4	L	VH	≤ M	≥ H	M	≥ M	VH	M

Table 15
Credibility indices, preference relations and categorization of alternatives with modified judgement of decision maker DM_2.

	$\sigma(a,b_h)$		$\sigma(b_h,a)$		Preference Relations	Categorization (pessimistic)	Categorization (pessimistic with original data)
	b_1	b_2	b_1	b_2			
A_1	1	1	0	0	$A_1 > b_2$ and $A_1 > b_1$	CT_1	CT_2
A_2	0	1	0	0	$A_2 > b_2$ and A_2Rb_1	CT_2	CT_3
A_4	0	1	0	0	$A_4 > b_2$ and A_4Rb_1	CT_2	CT_3

assigned at the highest category (in the pessimistic procedure) even though the performance of the alternative A_3 in criterion C_1 is close but below the profile b_1.

Another test was performed varying the weights of the criteria so as to confirm the non-compensatory effect of the ELECTRE TRI method. Table 13 presents the categorization results using the weights $W_j = \{0.5, 0.2, 0.3\}$ for criteria C_1 to C_3, with $\lambda = 1{,}0$ and keeping constant all the other parameters. As it can be seen, the categorization remained the same although the significant change in the weights of criteria C_1 and C_2.

To evaluate the effect of discordance of judgements between the decision makers, first the judgements of decision maker DM_2 was intentionally modified in the direction of better evaluations of alternatives A_1, A_2 and A_4, which were initially evaluated by all the decision makers as having poor to medium performance. Table 14 presents the modified judgements of DM_2. Table 15 the categorization of these alternatives in comparison with the initial categorization as in Table 11. Again, the cutting level was set to $\lambda = 1{,}0$ and the other parameters were kept the same. Because of an increase on the scores of the alternatives given by DM_2 in each criterion, the categorization of alternatives A_1, A_2 and A_4 changed to one category above, which demonstrates the sensitivity of the method to variations in the judgement. Following that, another modification on the original was made so as to introduce even more discordance between judgements. Table 16 presents the modified judgements of DM_1 and DM_2. In this case, the data of decision maker DM_1 was altered so as to attribute poorer evaluations to alternatives A_1, A_2 and A_4. As a result of these changes, the categorization of alternatives A_1 and A_2 were kept the same when compared to the initial categorization as in Table 11. As for alternative A_4, it changed to CT_2 because of the highly positive judgement of decision maker DM_2 in comparison with the original data of this alternative. The result of this test suggest that when there is excess of discordance, group decision techniques such as aggregation of judgements may not be the best approach to group decision making. (See Table 17)

8. Conclusion

This study proposed and tested a MCDM decision model to supplier categorization that combines ELECTRE TRI and hesitant fuzzy as an approach to deal with categorization of suppliers either in the process of qualification for selection or in evaluation of the portfolio of suppliers. It fulfills several important characteristics of this decision process:

- The uncertainty of judgements due to the qualitative nature of some criteria or due to the possible lack of complete information and also due to the uncertainty implicit in the judgements about the relative importance of criteria;
- The hesitation of the multiple decision makers involved in the evaluation of the importance of criteria and performance of the alternatives;
- The importance of a non-compensatory multicriteria decision process for the purpose of categorization.
- judgements as a consequence of the aggregation of judgements by multiple decision makers;

Although numerous previous researches have explored the use of multicriteria decision making techniques in supplier evaluation, none of the studies propose a decision model that addresses all these issues.

The illustrative case has showed consistent categorization results, especially using the pessimistic ELECTRE TRI assignment procedure. The

Table 16
Performance evaluation of suppliers with modified judgement of decision makers DM_1 and DM_2.

Suppliers	C_1: Quality management		C_2: Problem Resolution			C_3: Delivery		
	DM_1	DM_2	DM_1	DM_2	DM_3	DM_1	DM_2	DM_3
A_1	≤ M	VH	L	VH	≥ H and ≤ VH	≥ L and ≤ M	VH	≥ M and ≤ H
A_2	L	≥ H	L	H	H	≥ M and ≤ H	VH	≥ H
A_4	L	VH	≤ L	≥ H	M	L	VH	M

Table 17
Credibility indices, preference relations and categorization of alternatives with modified judgement of decision maker DM_1 and DM_2.

	$\sigma(a,b_h)$		$\sigma(b_h,a)$		Preference Relations	Categorization (pessimistic)	Categorization (pessimistic with original data)
	b_1	b_2	b_1	b_2			
A_1	0,03	1	0,65	0	$A_1 > b_2$ and A_1Rb_1	CT_2	CT_2
A_2	0	0	0	0	A_2Rb_2 and A_2Rb_1	CT_3	CT_3
A_4	0	1	1	0	$A_4 > b_2$ and $b_1 > A_4$	CT_2	CT_3

test with different criteria weights showed no change in the categorization results, confirming the non-compensatory effect of the ELECTRE TRI method as already pointed by Figueira et al. (2013) and Guarnieri (2014). The tests with intentionally modified data to force discordance of judgements between the decision makers also led to consistent results. However, although the coherency of results, analysis of the judgements and the resulting categorization suggests that when there is excess of discordance, negotiation techniques may be a better option. The test also demonstrated that reducing the ELECTRE TRI cutting level causes the weakening the categorization rules as already demonstrated by other studies (Certa et al., 2017; Mousseau et al., 2000; Mousseau and Slowinski, 1998). Changes to the ELECTRE TRI threshold parameters allow additional flexibility to the categorization process. Sensitivity analysis of these parameters have already been performed and discussed by other studies (Certa et al., 2017; Dias et al., 2002; López, 2005; Mousseau et al., 2000; Mousseau and Slowinski, 1998; The and Mousseau, 2002).

As a further research, it is suggested to explore other techniques in combination with ELECTRE TRI and compare their results with the proposal presented in this study. For instance, fuzzy DELPHI, a technique for building consensus can be combined with ELECTRE TRI so as to mitigate the problem of discordance between the decision makers. Other possibility is the comparison of the proposed method with other techniques that consider hesitation and imprecision such as intuitionistic fuzzy sets and type-2 fuzzy sets.

Acknowledgments

Authors thank FAPESP (2016/14618-4), and CAPES for supporting this research project.

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