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A Hesitant Fuzzy TOPSIS model to supplier performance evaluation

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Abstract
Supplier performance evaluation is a decision-making problem that involves quantitative and qualitative metrics. Although several models that allow the use of linguistic terms such as "low" and "high" to evaluate suppliers, none of them enables the application of linguistic expressions, which is especially useful when decision makers hesitates to express their evaluations. This study proposes a model based on the Hesitant Fuzzy TOPSIS method to support the supplier performance evaluation. A pilot application was carried out in an automotive company considering 8 suppliers and 10 criteria. When compared to previous similar approaches, the proposed model presented the following advantages: it enables the use of linguistic expressions to assess the supplier performance in each criterion; it groups suppliers with similar levels of performance to develop appropriate management actions; and does not limit the number of criteria and suppliers evaluated.

Keywords: supplier performance evaluation; hesitant fuzzy TOPSIS method; multicriteria decision-making; supply chain management.

Un modelo Hesitant Fuzzy TOPSIS para la evaluación del desempeño de los proveedores

Resumen
La evaluación del desempeño de proveedores es un problema de toma de decisiones que involucra métricas cuantitativas y cualitativas. Aunque existen varios modelos que permiten el uso de términos lingüísticos como "bajo" y "alto" para evaluar a los proveedores, ninguno de esos permite la aplicación de expresiones lingüísticas, lo cual es especialmente útil cuando los tomadores de decisiones dudan en expresar sus evaluaciones. Este estudio propone un modelo basado en el método Hesitant Fuzzy TOPSIS para apoyar la evaluación del desempeño de los proveedores. Se realizó una aplicación piloto en una empresa automotriz considerando 8 proveedores y 10 criterios. En comparación con los modelos similares anteriores, el modelo propuesto presenta las siguientes ventajas: permite el uso de expresiones lingüísticas para evaluar el desempeño del proveedor en cada criterio; agrupa a proveedores con niveles similares de desempeño para desarrollar acciones apropiadas; y no limita el número de criterios y proveedores evaluados.

Palabras clave: evaluación del desempeño del proveedor; método hesitant fuzzy TOPSIS; toma de decisiones multicriterios; gestión de la cadena de suministro.

1. Introduction

In the face of globalized markets, supply chain management emerges as a way to achieve competitive advantage, since it encourages the strengthening of relationships with suppliers to make them strategic partners of the purchasing company [1]. Supplier performance management has become a key process for many companies as it represents most of the spending for several organizations. Besides influencing the operating costs of the purchasing company, the supplier performance affects the quality of products, delivery times and, consequently, the satisfaction of the final customer [2].

Given the impact of supplier performance on the processes and products of purchasing companies, supplier performance evaluation has become a strategic process to manage supply chain operations [1,3]. This evaluation is carried out in at least two moments. During the supplier selection process, evaluation

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is performed to generate a ranking of alternatives that helps in choosing the most appropriate supplier for a given product or service. After contracting suppliers, evaluation and monitoring are made by observing the fulfillment of contractual obligations and analyzing the performance of suppliers in several metrics [4]. It aims to identify the metrics that perform below the pre-established goals, to support the development of continuous improvement plans and other supplier development practices [5].

The supplier performance evaluation has been approached in the literature as a decision-making problem based on multiple criteria, also called performance metrics or indicators [2]. A complicating factor in this evaluation is related to the difficulty of evaluating the performance of suppliers in qualitative and subjective criteria, such as trust, commitment to improving quality, supplier reputation, and collaboration [4]. Due to the lack of up-to-date information on some aspects of the supplier's performance, there are also several quantitative criteria whose evaluation process is inaccurate. In this context, several decision-making techniques suitable for uncertain scenarios have been developed and applied to support decisions related to supplier performance management [6]. Among these, techniques based on fuzzy set theory stand out since it is an approach derived from the area of artificial intelligence that allows decision makers to use linguistic terms such as "low", "medium", or "high" to quantify the performance of suppliers [2,6].

More recently, in order to support decision situations under uncertainty in which decision makers hesitate in choosing linguistic terms, techniques based on the Hesitant Fuzzy Linguistic Term Sets (HFLTS) have emerged [7]. One of them is called Hesitant Fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [8], whose operations combine the principles of the TOPSIS method with resources from HFLTS to allow alternatives to be evaluated based on linguistic expressions, such as "at least medium" or "between very high and excellent". Although the adoption of this technique has some potential use benefits, no studies applying Hesitant Fuzzy TOPSIS to evaluate the performance of suppliers were found in the literature. This fact is corroborated by the systematic review developed by [9], who did not find studies applying Hesitant Fuzzy techniques in this problem domain.

Given the above, this study proposes a multicriteria decision model based on the Hesitant Fuzzy TOPSIS method to support the evaluation of the suppliers' performance after contracting. A pilot application was carried out based on the linguistic judgments of two specialists from an automotive chain company, who evaluated the performance of eight suppliers based on seven criteria related to the cost and performance of operations. The research procedures adopted are detailed below.

2. Research procedures

Based on the study developed by [10], the present research is classified as normative axiomatic research based on computational modeling and simulation, since it uses quantitative models that include a set of variables representing a specific problem and that have causality among themselves, in order to provide an adequate solution. Regarding the methodological steps, this study is divided into:

i. Bibliographic review: in this stage, papers published in international journals on supplier performance evaluation, quantitative models to support supplier evaluation, and Hesitant Fuzzy TOPSIS were collected and analyzed. The collection of articles was carried out on the Web of Science, Emerald Insight, Scopus and IEEE-xplore databases using the keywords "supplier performance evaluation", "supplier performance assessment", and "Hesitant Fuzzy TOPSIS". From the analysis of the studies found, a mapping of the techniques and criteria used by the previous models was carried out, which helped in the development of a theoretical basis for the conception, modeling, and application of the proposed model;
ii. Computational modeling and simulation: this step involved the implementation and testing of two computational models, based on the equations of the Hesitant Fuzzy TOPSIS method [8]. The computational models were implemented using Microsoft Excel. While the first model includes the evaluation of criteria related to costs, the second is focused on the criteria related to the performance of operations;
iii. Pilot application: it was carried out in an automotive company based on the linguistic judgments of two specialists, who evaluated the performance of eight suppliers regarding seven criteria. The specialists were also consulted on the consistency of the results and the usability of the model. More details on the proposed model and its application are presented in section 4.

3. Supplier performance evaluation

The literature on supply chain management presents some theoretical models to deal with the performance evaluation of suppliers. In general, these models propose a set of steps to manage better the supplier base, including decision-making processes from selection to relationship management. One of them was proposed by Igarashi, De Boer and Fet [6], which structure the selection and evaluation processes in six main stages. The first five are regarding the selection and the last one to supplier performance evaluation after contracting. The first stage involves defining the needs of the organization, the products and / or services to be purchased and their specifications. The second stage, called formulation of criteria, consists of choosing the criteria or requirements that potential suppliers must meet. The third stage refers to the receipt of proposals prepared by suppliers. The fourth stage, named qualification, involves the analysis of the proposals to identify the suppliers that meet the minimum requirements of the contractor. In the fifth stage, the final selection takes place, that is, the final decision on contracting one or more suppliers that best meet the needs. After the contracting of suppliers, there is an assessment of the performance of suppliers, which aims to develop them by monitoring and analyzing results to enhance performance levels. Finally, the activities of each stage are reviewed and, if necessary, reformulated to suit further scenarios [6].

Glock et al. [1] proposed another theoretical model focused on supplier relationship management to align the organization's strategic planning with the management between buyer and supplier. This model includes the following activities: (1) identification of strategic suppliers; (2) assessing the performance of these suppliers based on multiple criteria; (3) identification of those requiring improvement; (4) implementation of supplier development programs or replacement of suppliers; (5) and continuous monitoring of performance. Therefore, this model is more comprehensive than that proposed by [6], since it considers the activities of supplier development and replacement.

As suggested by the theoretical models found in the literature [1,6], the set of criteria used to assess suppliers has a relevant role in the decision-making process. Table 1 presents a listing of the criteria used in some quantitative models to assess supplier performance. In general, supplier performance evaluation encompasses criteria related to financial and non-financial aspects and operational and strategic factors [4]. These criteria are commonly defined by specialists involved in the problem, considering the context and strategy of each company. In several of the quantitative models of supplier evaluation, such criteria are grouped into different dimensions that delimit the scope considered in the assessment, such as capabilities, willingness [11], cost, delivery performance [2], pricing policy, flexibility, and communication [12].

More recently, due to the concern with managing collaborative relationships in supply chains and the sustainability of operations, several qualitative criteria have been adopted. Some examples shown in Table 1 are: open communication, supplier profile, environmental contribution, support from top management for green supply practices, flexibility, commitment, governance, policy, and discrimination. The fact that many criteria are difficult to assess, as they have a subjective evaluation makes it necessary to use appropriate techniques to support group decisions in uncertain scenarios. The following section focuses on discussing some of the decision-making techniques.

3.1 Decision models for supplier performance evaluation

An important issue in the supplier performance evaluation is the choice of a quantitative method suitable to support the decision-making process. Several studies in the literature have proposed models to evaluate supplier performance based on multicriteria decision-making methods (MCDM) and computational intelligence techniques [1,6]. Based on the type of output provided by such models, they may be classified into two distinctive groups. The first group encompasses models that provide a ranking of suppliers according to their global performance, which is calculated considering individual scores on multiple criteria [13-15]. In this case, the ranking of suppliers is made only to identify the best and worst suppliers, without suggesting actions for their management. On the other hand, the second group includes models that propose a two-dimensional classification matrix, usually composed of four

Table 1.
Dimensions and criteria used to assess supplier performance.

Authors	Performance dimensions	Criteria
Rezaei and Ortt [11]	Capabilities	Price, delivery, quality, reserve capacity, geographical location and financial position.
	Willingness	Commitment to quality, open communication, willingness to share information, JIT principles, and long-term relationship.
Osiro et al. [4]	Market complexity	Barriers to entry and co-development of product specification.
	Item importance	Market concentration, product uniqueness, environmental contribution, alignment, and added value profile.
	Potential for partnership	Commitment to improving and reducing costs, and ease of communication.
Liou et al. [14]	Delivery performance	Delivery performance, delivery reliability, price performance, and problem resolution.
	Compatibility	Relationship, flexibility, and information sharing.
	Quality	Knowledge and skills, customer satisfaction, and deadline.
	Cost	Cost savings and flexibility.
	Risk	Loss of management control and information security.
Lima Junior and Carpinetti [2]	Cost	Sourcing costs, material costs, return costs, among others.
	Delivery performance	Orders delivered in full, deadline fulfillment, documentation accuracy, perfect condition, cycle time, and supplier risk.
Görener et al. [12]	Pricing policy	Pricing policy for spare parts and services, flexible pricing policy and quantity discount policy.
	Delivery	Waiting time, delivery time reliability, documentation for customs services, and delivery reliability.
	Flexibility	Flexible payment plans, return policy, emergency handling, and complaints feedback.
	Communication	Response time and customer support.
Luthra et al. [17]	Economic performance	Product price, product profit, product quality, flexibility, technological and financial capacity, production facilities and capacity, product delivery and service, lead time, and transportation cost.
	Environmental performance	Environmental management systems, ecological design and purchasing, green manufacturing, green management, green packaging and labeling, waste management and pollution prevention, environmental costs, environmental skills and innovation.
	Social factors	Occupational health and safety systems, employee rights, and stakeholder rights.
Santos et al. [18]	Capabilities	Product quality, packaging, delivery time, after-sales support, billing and order processing system, and delivery reliability.
	Potential for partnership	Communication, transparency, ethics, mutual respect and honesty, previous experience with the supplier, compliance and commitment to quality.

Source: The authors.

Table 2.
Quantitative techniques used in supplier performance evaluation.

Authors	Quantitative techniques	Application
Osiro et al. [4]	Fuzzy inference	Automotive company
Ho et al. [5]	IPA (Importance-Performance Analysis), DEMATEL	Computer industry
Rezaei and Ortt [11]	Fuzzy AHP	Chicken cutting Company
Dey et al. [3]	QFD and AHP	Carpet factory
Lima Junior and Carpinetti [2]	Fuzzy TOPSIS	Automotive company
Görener et al. [12]	Interval Type-2-Fuzzy AHP and Interval Type-2-Fuzzy TOPSIS	Aviation company
Luthra et al. [17]	AHP and VIKOR	Automotive industry
Santos et al. [18]	AHP and Fuzzy 2-Tuple	Pharmaceutical supply center
Liu et al. [19]	Fuzzy AHP and Fuzzy TOPSIS	Agrifood chain

Source: The authors.

quadrants, in which each axis represents a performance dimension. Each quadrant of the classification matrix suggests actions to be taken for supplier management. This categorization-based approach is adopted by [2-5,11,16-19]. Regarding the type of application, there are some studies based on simulated data, as well as real applications in which suppliers' scores are obtained through historical performance data or expert judgments. These real applications are more frequent in automotive companies.As shown in Table 2, some of the MCDM methods that have been applied in supplier performance evaluation include Decision Making Trial and Evaluation Laboratory - DEMATEL [11], Analytic Hierarchy Process - AHP [3], and VIseKriterijumska Optimizacija I Kompromisno Resenje - VIKOR [17]. These methods use a set of quantitative and qualitative criteria to evaluate the supplier performance, generally considering the relative weight of these criteria.

Computational intelligence methods, on the other hand, incorporate new abilities into supplier assessment models. Some examples are the models based on fuzzy inference that simulate the human reasoning process using decision rules adjusted through the knowledge of experts [4]. There are also some models based on the hybridization of techniques, such as Fuzzy AHP [11,12,19] and Fuzzy TOPSIS [2,12,19], which enable decision makers to use linguistic judgments such "low" and "medium" to evaluate the individual scores of the suppliers.

Although the models shown in Table 2 have made several contributions to the literature concerning supplier performance evaluation, they have some limitations related to features of the decision techniques adopted. Besides limiting the number of criteria and alternatives considered in the assessment, models based on comparative approaches such as AHP and Fuzzy AHP require a greater amount of judgments from decision makers as well as the execution of consistency tests. Also, none of the models found in the literature provide support for group decision situations in which decision makers hesitate in choosing linguistic terms. In this case, they may prefer to use two or more linguistic terms, as well as linguistic expressions to quantify the supplier score against a given criterion. The use of techniques based on Fuzzy Linguistic Hesitant Term Sets has the potential to overcome this limitation. However, no models of supplier performance evaluation based on such techniques were found.

3.2 Hesitant fuzzy linguistic term sets

Hesitant Fuzzy Linguistic Term Sets (HFLTS) is a recent extension of the Fuzzy Set Theory. It combines some fundamentals of hesitant fuzzy sets with fuzzy linguistic terms to deal with problems under uncertainty and hesitancy [7,8]. Some fundamental definitions are presented below.

3.2.1 Definition 1: HFLTS

Let $\mathbf{s}$ be a set of linguistic terms, where $\mathbf{s} = \{s_0, \ldots, s_g\}$, as shown in Fig. 1. $\mathbf{h_s}$ is a finite ordered subset of the consecutive linguistic terms of S. An empty HFLTS and a full HFLTS for a linguistic variable ϑ can be defined as follows [7,8]:

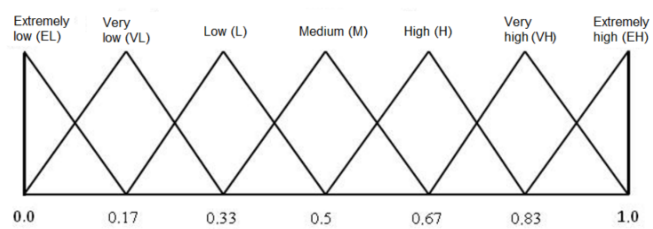

Figure 1. Set of seven linguistic terms.
Source: The authors.

1. HFLTS empty: $\mathbf{h_s}(\vartheta) = \{\ \}$
2. HFLTS full: $\mathbf{h_s}(\vartheta) = \mathbf{s}$

Beg and Rashid [8] highlight that any other HFLTS is formed by at least one linguistic term in $\mathbf{s}$.

Example 1. Considering $\mathbf{s}$ as the set of linguistic terms shown in Fig. 1, $\mathbf{s}$ = {s_0: Extremely Low (EL), s_1: Very Low (VL), s_2: Low (L), s_3: Medium (M), s_4: High (H), s_5: Very High (VH), s_6: Extremely High (EH)}, a subset of $\mathbf{s}$ can be expressed as $\mathbf{h_s}(\vartheta)$ = {s_1: Very Low (VL), s_2: Low (L), s_3: Medium (M), s_4: High (H), s_5: Very High (VH)}. Such subsets are used in the Hesitant Fuzzy TOPSIS method to represent the judgments of a decision maker regarding the scores of the alternatives in each criterion [8].

3.2.2 Definition 2: h_{s+} e h_{s-}

Let $\mathbf{s}$ be a set of linguistic terms, $\mathbf{s} = \{s_0, \ldots s_g\}$ and $\mathbf{h_s}$ be an HFLTS. The upper limit h_{s+} and the lower limit h_{s-} of $\mathbf{h_s}$ are represented as [7].

$$h_{s+} = \max(s_i) = s_j, s_i \in \mathbf{h_s} \text{ and } s_i \leq s_j \qquad \forall i; (1)$$

$$h_{s-} = \min(s_i) = s_j, s_i \in \mathbf{h_s} \text{ and } s_i \geq s_j \qquad \forall i. (2)$$

3.2.3 Definition 3: $\mathbf{env}(\mathbf{h_s})$

The envelope of an HFLTS, $\mathbf{env}(\mathbf{h_s})$, is a linguistic interval whose limits are calculated using the upper limit (max) and lower limit (min) of $\mathbf{h_s}$. Therefore, $\mathbf{env}(\mathbf{h_s}) = [h_{s-}, h_{s+}]$ [7].

Example 2. Let $\boldsymbol{s}$ = {$\boldsymbol{s_0}$: Extremely Low, $\boldsymbol{s_1}$: Very Low, $\boldsymbol{s_2}$: Low, $\boldsymbol{s_3}$: Medium, $\boldsymbol{s_4}$: High, $\boldsymbol{s_5}$: Very High, $\boldsymbol{s_6}$: Extremely High} be a set of linguistic terms, and $\boldsymbol{H_s}$ = {$\boldsymbol{s_4}$: High, $\boldsymbol{s_5}$: Very High, $\boldsymbol{s_6}$: Extremely High} an HFLTS of $\boldsymbol{s}$, then the envelope will be [8]:

$h_{s-} = \min$ (s_4: High, s_5: Very High, s_6: Extremely High)
$h_{s-} = s_4$: High
$h_{s+} = \max$ (s_4: High, s_5: Very High, s_6: Extremely High)
$h_{s+} = s_6$: Extremely High
$\mathbf{env}(\mathbf{h_s})$ = [s_4, s_6] = [s_4: High, s_6: Extremely High].

3.2.4 Definition 4: the transformation of linguistic expressions into HFLTS

Rodríguez et al. [20] proposed a function $e_{G_H}: ll \rightarrow \mathbf{h_s}$ to transform linguistic expressions into HFLTS ($\mathbf{h_s}$):

1) $e_{G_H}(s_i)$={s_i / $s_i \in \mathbf{s}$};
2) e_{G_H}(at most s_i)={s_j | $s_j \in \mathbf{s}$ and $s_j \leq s_i$};
3) e_{G_H}(lower than s_i)={s_j | $s_j \in \mathbf{s}$ and $s_j < s_i$};
4) e_{G_H}(at least s_i)={s_j | $s_j \in \mathbf{s}$ and $s_j \geq s_i$};
5) e_{G_H}(greater than s_i)={s_j | $s_j \in \mathbf{s}$ and $s_j > s_i$};
6) e_{G_H}(between s_i and s_j)={s_k | $s_k \in \mathbf{s}$ and $s_i \leq s_k \leq s_j$}.

3.2.5 Definition 5: the distance between two HFLTS

Let h_S^1 and h_S^2 be two HFLTS, with $\mathbf{env}(\mathbf{h_S^1}) = [s_p, s_q]$ and $\mathbf{env}(\mathbf{h_S^2}) = [s_{p'}, s_{q'}]$. Then, the distance between $\mathbf{h_S^1}$ and $\mathbf{h_S^2}$ is given by eq. (3) [8].

$$\mathrm{d}(\mathbf{h_S^1}, \mathbf{h_S^2}) = |q' - q| + |p' - p| \quad (3)$$

3.3 The hesitant fuzzy TOPSIS method

The Hesitant Fuzzy TOPSIS method adopted in this study was proposed by [8] to allow support for group decisions in situations under uncertainty and hesitation. It is based on the same principle as the TOPSIS method, which consists of prioritizing alternatives according to their proximity to the positive ideal solution (PIS) and the negative ideal solution (NIS). While the PIS is made up of the best scores achieved in each criterion, the NIS is made up of the worst scores. The steps of Hesitant Fuzzy TOPSIS method are detailed below [8]:

Step 1. Let $\tilde{\mathbf{X}} = [h_{Sij}^l]_{mxn}$ be a fuzzy decision matrix; $\mathbf{e} = \{e_1, e_2, \dots, e_k\}$ is the set of decision makers or specialists involved in the decision-making process; $\mathbf{a} = \{a_1, a_2, \dots, a_m\}$ is the set of alternatives evaluated; and $\mathbf{c} = \{c_1, c_2, \dots, c_n\}$ is the set of criteria used for assessing the alternatives. The performance of the alternative a_i in relation to criterion c_j is denoted as $\tilde{\mathbf{x}}_{\mathbf{ij}}$, in an aggregated matrix $\tilde{\mathbf{X}}$. The matrix $\tilde{\mathbf{X}} = [\tilde{\mathbf{x}}_{\mathbf{ij}}]$, with $\tilde{\mathbf{x}}_{\mathbf{ij}} = [s_{p_{ij}}, s_{q_{ij}}]$, is calculated by aggregating the opinions of decision makers $(\tilde{\mathbf{X}}^1, \tilde{\mathbf{X}}^2, \dots, \tilde{\mathbf{X}}^k)$, according to eq. (4) and (5) [8].

$$s_{pij} = \min\left\{\min_{l=1}^{k}\left(\max h_{Sij}^l\right), \max_{l=1}^{k}\left(\min h_{Sij}^l\right)\right\} \quad (4)$$

$$s_{qij} = \max\left\{\min_{l=1}^{k}\left(\max h_{Sij}^l\right), \max_{l=1}^{k}\left(\min h_{Sij}^l\right)\right\} \quad (5)$$

Step 2. Let $\Omega_{\boldsymbol{b}}$ be a collection of benefit criteria (i.e., the larger c_j, the greater preference) and $\Omega_{\boldsymbol{c}}$ be a collection of cost criteria (i.e. the smaller c_j, the greater preference). The PIS is represented as $\tilde{\mathbf{A}}^+ = (\tilde{\mathbf{v}}_1^+, \tilde{\mathbf{v}}_2^+ \dots, \mathbf{v}_n^+)$, and the NIS is defined as $\tilde{\mathbf{A}}^- = (\tilde{\mathbf{v}}_1^-, \tilde{\mathbf{v}}_2^- \dots, \tilde{\mathbf{v}}_n^-)$. Eq. (6) and (7) guide the composition of the SIP and SIN, respectively [8].

$$\tilde{\mathbf{A}}^+ = \left[\left(\left(\max_{l=1}^{k}\left(\max_i h_{Sij}^l\right)\right) | \, j \in \Omega_{\mathbf{b}}, \left(\min_{l=1}^{k}\left(\min_i h_{Sij}^l\right)\right) | \, j \, \varepsilon \, \Omega_{\mathbf{c}}\right)\right], \left(\left(\max_{l=1}^{k}\left(\max_i h_{Sij}^l\right)\right) | \, j \in \Omega_{\mathbf{b}}, \left(\min_{l=1}^{k}\left(\min_i h_{Sij}^l\right)\right) | \, j \, \varepsilon \, \Omega_{\mathbf{c}}\right) \quad (6)$$

$$\tilde{\mathbf{A}}^- = \left[\left(\left(\min_{l=1}^{k}\left(\min_i h_{Sij}^l\right)\right) | \, j \in \Omega_{\mathbf{b}}, \left(\max_{l=1}^{k}\left(\max_i h_{Sij}^l\right)\right) | \, j \, \varepsilon \, \Omega_{\mathbf{c}}\right)\right], \left(\left(\min_{l=1}^{k}\left(\min_i h_{Sij}^l\right)\right) | \, j \in \Omega_{\mathbf{b}}, \left(\max_{l=1}^{k}\left(\max_i h_{Sij}^l\right)\right) | \, j \, \varepsilon \, \Omega_{\mathbf{c}}\right) \quad (7)$$

Where $\tilde{\mathbf{v}}_\mathbf{j}^+ = [\mathbf{v_{pj}}, \mathbf{v_{qj}}]$, $\tilde{\mathbf{v}}_\mathbf{j}^- = [\mathbf{v_{pj}}, \mathbf{v_{qj}}]$ and $(j = 1,2, \dots, n)$.

Step 3. Construct the positive ideal separation matrix ($\mathbf{D}^+$) and negative ideal separation matrix ($\mathbf{D}^-$), which are defined according to eq. (8) and (9), respectively [8]:

$$\mathbf{D}^+ = \begin{pmatrix} \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{11}}, \tilde{\mathbf{v}}_1^+) & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{21}}, \tilde{\mathbf{v}}_2^+) & + & \cdots & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{1n}}, \tilde{\mathbf{v}}_\mathbf{n}^+) \\ \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{21}}, \tilde{\mathbf{v}}_1^+) & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{22}}, \tilde{\mathbf{v}}_2^+) & + & \cdots & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{2n}}, \tilde{\mathbf{v}}_\mathbf{n}^+) \\ \vdots & & \vdots & & \vdots & + & \vdots \\ \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{m1}}, \tilde{\mathbf{v}}_1^+) & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{m2}}, \tilde{\mathbf{v}}_2^+) & + & \cdots & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{mn}}, \tilde{\mathbf{v}}_\mathbf{n}^+) \end{pmatrix} \quad (8)$$

$$\mathbf{D}^- = \begin{pmatrix} \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{11}}, \tilde{\mathbf{v}}_1^-) & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{21}}, \tilde{\mathbf{v}}_2^-) & + & \cdots & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{1n}}, \tilde{\mathbf{v}}_\mathbf{n}^-) \\ \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{21}}, \tilde{\mathbf{v}}_1^-) & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{22}}, \tilde{\mathbf{v}}_2^-) & + & \cdots & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{2n}}, \tilde{\mathbf{v}}_\mathbf{n}^-) \\ \vdots & & \vdots & & \vdots & + & \vdots \\ \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{m1}}, \tilde{\mathbf{v}}_1^-) & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{m2}}, \tilde{\mathbf{v}}_2^-) & + & \cdots & + & \mathrm{d}(\tilde{\mathbf{x}}_{\mathbf{mn}}, \tilde{\mathbf{v}}_\mathbf{n}^-) \end{pmatrix} \quad (9)$$

Step 4. Calculate the relative closeness (rc) of each alternative to the ideal solution using eq. (10) [8]:

$$rc(a_i) = \frac{\mathbf{D_i^-}}{\mathbf{D_i^+} + \mathbf{D_i^-}}, i = 1,2, \dots, m, \quad (10)$$

Where $\mathbf{D_i^-} = \sum_{j=1}^{n} d(\tilde{\mathbf{x}}_{ij}, \tilde{\mathbf{v}}_j^-)$ and $\mathbf{D_i^+} = \sum_{j=1}^{n} d(\tilde{\mathbf{x}}_{ij}, \tilde{\mathbf{v}}_j^+)$.

Step 5. Classify all the alternatives a_i $(i = 1, 2, \ldots, m)$ according to $rc(a_i)$. The greater the $rc(a_i)$ value, the better the alternative a_i [8].

4. The proposed model to supplier evaluation

The model proposed by the present study to support supplier performance evaluation is based on [2,8]. It consists of three stages, as shown in Fig. 2. In steps 1 and 2, decision makers assess the suppliers' performance using the linguistic terms presented in Fig. 1, as well as the linguistic expressions presented in section 3.2.4. In step 1, using the computational model 1, suppliers are evaluated based on three criteria associated with the cost dimension: price, percentage of cost reduction and financial risk. In step 2, the same suppliers are evaluated concerning the delivery performance dimension based on four criteria: quality conformance, commitment to quality improvement, delivery in full on time, and speed of delivery problem resolution. The decision makers participating in the pilot application chose these decision criteria considering the needs of the company in which they operate. It is important to emphasize that these criteria are also used in other studies in the literature [4,8,16].

The output of step 2 is calculated using the computational model 2. In step 3, based on the performance achieved by each supplier in steps 1 and 2, they are categorized into a two-dimensional matrix, in which each quadrant represents a group of suppliers with a similar performance [2]. Each group indicates an action to be taken aiming to manage the company's supplier base better. According to the categorization result, action plans should be developed based on the following guidelines [2]:

i. Group I: suppliers positioned in this group are considered adequate. Once these suppliers have met the buyer's expectations in both performance dimensions, efforts should be focused on maintaining the buyer-supplier relationship. Also, they may become partners for the co-development of critical items;
ii. Group II: suppliers in this group have a high performance in operations, but they require cost reductions. The following steps can be taken: (1) identification of criteria related to costs in which the supplier presents underperformance; (2) identification of the causes of high costs; (3) negotiation of cost reduction targets with the supplier concerning each criterion; (4) creation, implementation, and monitoring of action plans aimed at cost reduction in the critical processes;
iii. Group III: suppliers classified in this group exhibits underperformance in operations, which indicates that they need improvements in some critical processes. Given this, the following actions are suggested: (1) identification of criteria that require improvements in their results; (2) investigation of the critical processes related to these metrics and the causes of poor performance; (3) formulation, implementation, and monitoring of programs aimed at the continuous improvement of the critical processes;
iv. Group IV: a supplier of this group needs to be replaced because they present unsatisfactory performance levels in both performance dimensions. Therefore, it is recommended to select a replacement supplier.

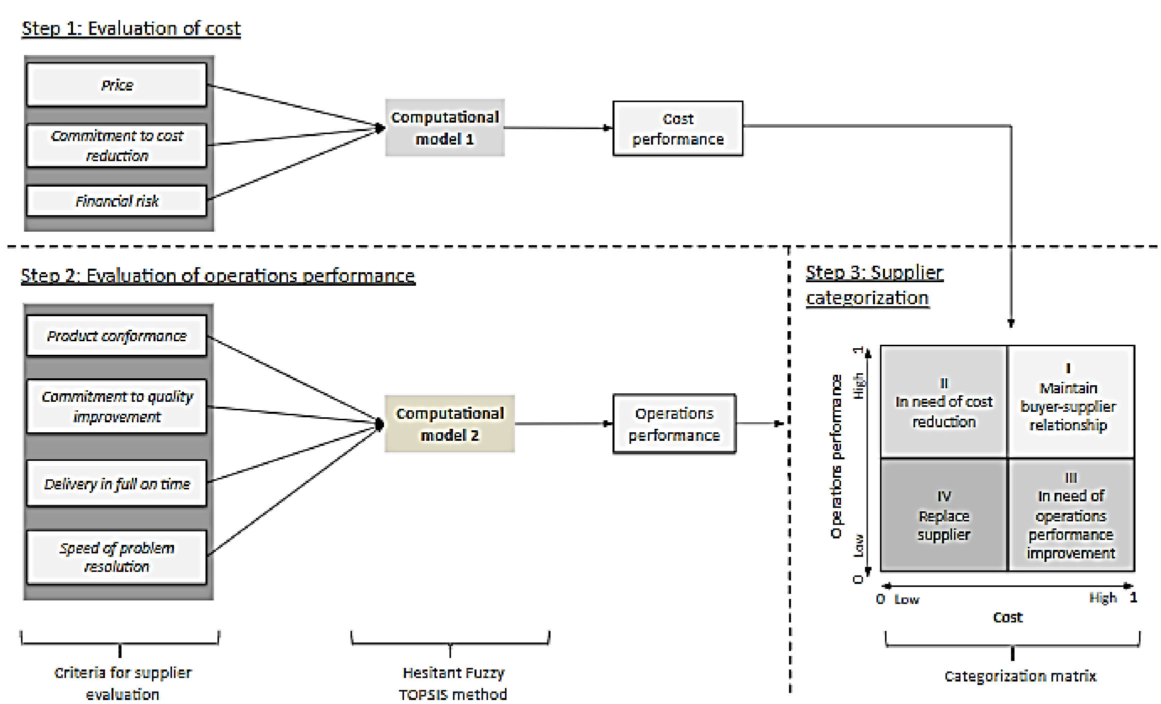

Figure 2. The proposed model to support the assessment of supplier performance.
Source: The authors.

Table 3.
Judgments of decision maker 1 regarding scores of the suppliers.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7
a_1	At most very low	At least very high	Between very low and low	At least high	At least very high	Extremely high	Extremely high
a_2	Extremely low	At least very high	Low	At least very high	At least high	At least very high	At least very high
a_3	Between very low and low	Very high	At most very low	High	High	Medium	Medium
a_4	Very low	Very high	Between low and medium	Between medium and high	Extremely high	Very high	Very high
a_5	Between extremely low and very low	Very high	Low	Low	Between medium and high	At least high	Greater than medium
a_6	Between very low and low	High	Between medium and high	At least very high	At least very high	At least very high	Greater than high
a_7	Between very low and low	At least very high	Between medium and high	Very high	Very high	Very high	Very high
a_8	Medium	Between medium and high	Very high	High	Extremely high	At least very high	At least very high

Source: The authors.

Table 4.
Judgments of decision maker 2 regarding scores of the suppliers.

	c_1	c_2	c_3	c_4	c_5	c_6	c_7
a_1	Extremely low	At most very low	At most very low	Extremely high	At least high	At least very high	Extremely high
a_2	Extremely low	Greater than high	Very high	Very high	At least very high	At least high	At least very high
a_3	Very low	Very high	Very high	Very high	High	High	Medium
a_4	At most very low	High	Between very low and low	Between medium and high	Medium	Very high	Very high
a_5	Very low	High	Medium	Low	Between very low and low	Between medium and high	Greater than medium
a_6	Between very low and low	Between high and very high	Between low and medium	Between medium and high	At least very high	At least very high	At least very high
a_7	Very low	Extremely high	Between medium and good	Between high and very high	Very high	Very high	Very high
a_8	Medium	Between medium and high	Between very low and low	High	High	Extremely high	At least very high

Source: The authors.

4.1 Application case

The proposed model was applied in a pilot case, based on real data, provided by specialists working in a car factory located in the state of São Paulo, Brazil. In this application, the judgments of two engineers who work in the evaluation and development of suppliers were considered. They assessed the performance of eight auto parts suppliers concerning the seven criteria shown in Fig. 2. The values of the weights of these criteria were considered equal.

Tables 3 and 4 present the judgments of these specialists regarding the scores of suppliers in the criteria related to cost. Tables 3 and 4 show judgments regarding the criteria of the operations performance. It is important to note that criteria c_1 and c_3 were modeled as cost criteria, that is, lower values on the scale of linguistic terms are used to indicate the best level of performance. The judgments shown in Tables 3 and 4 are presented in the form of linguistic terms and expressions. Tables 5 and 6 show these judgments converted into HFLTS. The aggregation of the linguistic judgments shown in Tables 5 and 6 was made using eq. (4) and (5). The results are shown in Table 7.

After aggregating the judgments of the decision makers, the positive ideal solution ($\widetilde{\mathbf{A}}^{+}$) and negative ideal solution ($\widetilde{\mathbf{A}}^{-}$) were defined for each of the seven criteria considered. For most of the criteria, eq. (6) was used to determine the values of $\widetilde{\mathbf{A}}^{+}$, while eq. (7) was applied to find the values of $\widetilde{\mathbf{A}}^{-}$. In the case of criteria c_1 and c_3, as these were modeled as cost criteria, eq. (7) was used to calculate $\widetilde{\mathbf{A}}^{+}$ while eq. (6) was applied to calculate $\widetilde{\mathbf{A}}^{-}$. Thus, for the criteria of model 1, we obtained $\widetilde{\mathbf{A}}^{+} = [[EL][EH][EL,VL]]$ and $\widetilde{\mathbf{A}}^{-} = [[M][M,H][M,H]]$. For the criteria of model 2, results are $\widetilde{\mathbf{A}}^{+} = [[EH][VH,EH][EH][EH]]$ and $\widetilde{\mathbf{A}}^{-} = [[VL][VL,L][M,H][M]]$.

Using the values of $\widetilde{\mathbf{A}}^{+}$ and $\widetilde{\mathbf{A}}^{-}$, as well as the values of Table 7, the distances from the positive ideal solution ($\mathbf{D}^{+}$) and negative ideal solution ($\mathbf{D}^{-}$) for each alternative were calculated. For the calculation of $\mathbf{D}^{+}$, eq. (3) and (8) were used. Eq. (3) and (9) were used to calculate $\mathbf{D}^{-}$. The following matrices exemplify the calculations of $\mathbf{D}^{+}$ and $\mathbf{D}^{-}$ performed by computational model 1.

Table 5.
Result of converting linguistic expressions to the HFLTS format (decision maker 1).

	c_1	c_2	c_3	c_4	c_5	c_6	c_7
a_1	[EL, VL]	[VH, EH]	[VL, L]	[VH, EH]	[H, VH, EH]	[VH, EH]	[EH]
a_2	[EL]	[VH, EH]	[L]	[VH, EH]	[VH, EH]	[H, VH, EH]	[VH, EH]
a_3	[VL, L]	[VH]	[EL, VL]	[VH]	[H]	[H]	[M]
a_4	[VL]	[VH]	[L, M]	[M, H]	[M, H]	[EH]	[VH]
a_5	[EL, VL]	[VH]	[L]	[VL]	[L]	[M, H]	[H, VH, EH]
a_6	[VL, L]	[H]	[M, H]	[M, H]	[VH, EH]	[VH, EH]	[VH, EH]
a_7	[VL, L]	[VH, EH]	[M, H]	[VH]	[VH]	[VH]	[VH]
a_8	[M]	[M, H]	[VL]	[H]	[H]	[EH]	[VH, EH]

Source: The authors.

Table 6.
Result of converting linguistic expressions to the HFLTS format (decision maker 2).

	c_1	c_2	c_3	c_4	c_5	c_6	c_7
a_1	[EL]	[VH, EH]	[VL, L]	[EH]	[H, VH, EH]	[VH, EH]	[EH]
a_2	[EL]	[VH, EH]	[L]	[VH]	[VH, EH]	[H, VH, EH]	[VH, EH]
a_3	[VL]	[VH]	[L]	[VH]	[H]	[H]	[M]
a_4	[EL, VL]	[H]	[VL, L]	[M, H]	[M]	[VH]	[VH]
a_5	[VL]	[H]	[M]	[L]	[VL, L]	[M, H]	[H, VH, EH]
a_6	[VL, L]	[H, VH]	[L, M]	[M, H]	[VH, EH]	[VH, EH]	[VH, EH]
a_7	[VL]	[EH]	[M, H]	[H, VH]	[VH]	[VH]	[VH]
a_8	[M]	[M, H]	[VL, L]	[H]	[H]	[EH]	[VH, EH]

Source: The authors.

Table 7.
Aggregated judgments matrices.

	Model 1				Model 2		
	c_1	c_2	c_3	c_4	c_5	c_6	c_7
a_1	[EL]	[VH, EH]	[VL]	[EH]	[H, VH, EH]	[VH, EH]	[EH]
a_2	[EL]	[VH, EH]	[VL, L]	[VH]	[VH, EH]	[H, VH, EH]	[VH, EH]
a_3	[VL]	[VH]	[VL]	[VH]	[H]	[H]	[M]
a_4	[VL]	[H, VH]	[L]	[M, H]	[M]	[VH, EH]	[H, VH, EH]
a_5	[VL, L]	[H, VH]	[L, M]	[VL, L]	[L]	[H, VH]	[H, VH, EH]
a_6	[VL, L]	[H]	[M]	[M, H]	[VH, EH]	[VH, EH]	[VH, EH]
a_7	[VL]	[EH]	[M, H]	[VH]	[VH]	[VH]	[VH]
a_8	[M]	[M, H]	[VL]	[H]	[H]	[EH]	[VH, EH]

Source: The authors.

Results yielded by computational model 2 for $\mathbf{D}^{+}$ are presented next. Due to the limited space in this article, values provided by model 2 for $\mathbf{D}^{-}$ were suppressed.

In both computational models, the values of the $rc(a_i)$ for each alternative were calculated using eq. (10). The results achieved by suppliers in the dimensions "cost" and "operations performance" were used to categorize them according to step 3 in Fig. 2. In this application, values below 0.5 were considered "low", while values equal to or greater than 0.5 are "high". Table 8 presents the values of $rc(a_i)$, the result of the categorization and the recommended guidelines for each supplier.

Fig. 3 represents the categorization results of suppliers according to the groups defined in Fig. 2. It can be noted that suppliers a_1, a_2, a_4, and a_7 were classified in group I, which indicates that they have been meeting the buyer's expectations. Suppliers a_6 and a_8 were positioned in group II because they reached high performance in operations, but they do not meet the expectations in terms of cost performance. Supplier a_3 was categorized in group III, as it reached good results in the cost dimension but presented low in operations. Supplier a_5 have low performance in both dimensions. Therefore, it is recommended to replace it.

The decision makers endorsed the results provided by the computational models. Also, they agree that supplier a_5 should be replaced, since it supplies routine items and, in this case, it may not be advantageous for the purchasing company to implement supplier development programs.

$$\mathbf{D}^{+}=\begin{bmatrix}0+0 & + & 0+1 & + & 0+1\\ 0+0 & + & 0+1 & + & 1+1\\ 1+1 & + & 1+1 & + & 0+1\\ 1+1 & + & 1+2 & + & 1+2\\ 1+1 & + & 1+2 & + & 2+2\\ 2+1 & + & 2+2 & + & 2+3\\ 1+1 & + & 0+0 & + & 3+3\\ 3+3 & + & 2+3 & + & 0+1\end{bmatrix}=\begin{bmatrix}2\\3\\5\\8\\9\\12\\8\\12\end{bmatrix}$$

$$\mathbf{D}^{-}=\begin{bmatrix}3+3 & + & 2+2 & + & 3+2\\ 3+3 & + & 2+2 & + & 2+2\\ 2+2 & + & 1+2 & + & 3+2\\ 2+2 & + & 1+1 & + & 2+1\\ 2+2 & + & 1+1 & + & 1+1\\ 1+2 & + & 0+1 & + & 1+0\\ 2+2 & + & 2+3 & + & 0+0\\ 0+0 & + & 0+0 & + & 3+2\end{bmatrix}=\begin{bmatrix}15\\14\\12\\9\\8\\5\\9\\5\end{bmatrix}$$

$$\mathbf{D}^{+}=\begin{bmatrix}0+0 & + & 0+1 & + & 0+1 & + & 0+0\\ 1+1 & + & 0+0 & + & 0+2 & + & 0+1\\ 1+1 & + & 2+1 & + & 2+2 & + & 3+3\\ 2+3 & + & 3+2 & + & 0+1 & + & 1+1\\ 4+5 & + & 4+3 & + & 2+3 & + & 0+2\\ 2+3 & + & 0+0 & + & 0+1 & + & 0+1\\ 1+1 & + & 1+0 & + & 1+1 & + & 1+1\\ 2+2 & + & 2+1 & + & 0+0 & + & 0+1\end{bmatrix}=\begin{bmatrix}2\\5\\15\\13\\23\\7\\7\\8\end{bmatrix}$$

4.2 Discussion of results

The results of the pilot application are somewhat similar to those found by the studies proposed by Lima Junior and Carpinetti [2], Osiro et al. [4], and Lima Junior et al. [21]. These studies also applied models based on fuzzy logic to assess suppliers of automotive companies and concluded that the vast majority of suppliers presented satisfactory performance, while a few suppliers required development programs and only one should be replaced.

When compared to other previous models to supplier performance evaluation, the proposed model has advantages such as:

Table 8.
Categorization results and suggested actions for each supplier

	$rc(a_i)$ - model 1	Classification (cost)	$rc(a_i)$ - model 2	Classification (operations performance)	Group	Recommended actions
a_1	0.88	High	0.93	High	I	Maintain relationship
a_2	0.82	High	0.83	High	I	Maintain relationship
a_3	0.71	High	0.48	Low	III	In need of cost reduction
a_4	0.53	High	0.55	High	I	Maintain relationship
a_5	0.47	Low	0.21	Low	IV	Replace supplier
a_6	0.29	Low	0.76	High	II	In need of operations performance improvement
a_7	0.53	High	0.76	High	I	Maintain relationship
a_8	0.29	Low	0.72	High	II	In need of operations performance improvement

Source: The authors.

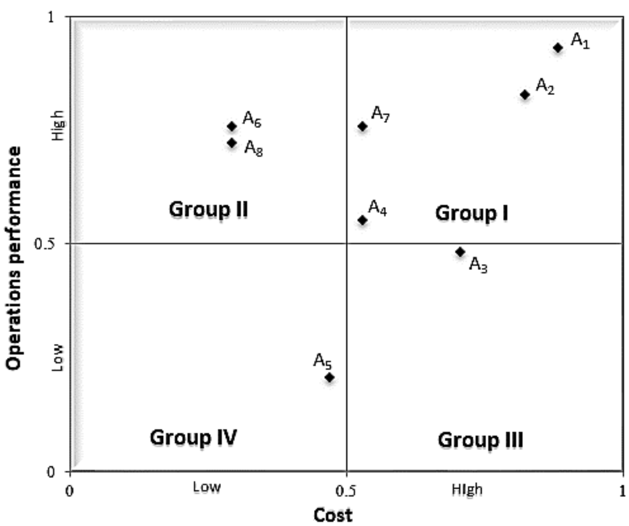

Figure 3. Categorization results of the evaluated suppliers.
Source: The authors.

i. Unlike all the previous models found in literature [2-5,11,12,17-19,21], it allows the decision makers to use linguistic expressions, or more than one linguistic term simultaneously, to evaluate the performance of a supplier in a given criterion;
ii. Another advantage is dealt with group decision-making employing aggregation of the subjective judgments of several decision makers. Thus, it enables the use of qualitative data converted into quantitative data to assess supplier performance;
iii. In contrast to models based on ordering suppliers [13-15], it allows indicating appropriate action plans for each group;
iv. Unlike approaches based on pairwise comparison [3,11,12,17-19], the proposed model allows using a not limited number of suppliers and criteria.

5. Conclusion

This study presented a decision model based on the Hesitant Fuzzy TOPSIS method to support supplier performance evaluation. A pilot case was developed to demonstrate and validate the use of the proposed model.

The proposed approach allows assessing suppliers on multiple criteria related to costs and performance of operations. The results achieved in each performance dimension are used to indicate actions to be taken by managers for the appropriate management of each group of suppliers. Thus, the proposed model allows managers to monitor the suppliers' performance and to identify which ones need development programs to reduce costs or to improve the operations performance. It also helps to identify which suppliers presents underperformance and therefore should be replaced. Furthermore, the use of linguistic terms and expressions allows greater flexibility to express the decision makers' judgments about the suppliers' performance, in addition to being more suitable to support decision-making processes under uncertainty and hesitation.

A limitation of the proposed model is that it does not make it possible to consider the criteria weights in linguistic format. It is due to a limitation of the Hesitant Fuzzy TOPSIS method [8]. In this sense, further studies may adapt this method to overcome this limitation. Other suggestions for further studies are: (1) to implement the model in the form of software with a graphical interface to test its usability by non-expert users; (2) to apply the proposed model in other purchasing companies to evaluate its adaptability in companies from different sectors; (3) to develop new decision models based on the Hesitant Fuzzy TOPSIS method to support the supplier sustainability assessment and the choice and evaluation of supplier development programs; (4) to compare the results of this study with other decision techniques based on Hesitant Fuzzy Linguistic Term Sets.

References

[1] Glock, C.H., Grosse, E.H. and Ries, J.M., Decision support models for supplier development: systematic literature review and research agenda, International Journal of Production Economics, 193, pp.798-812, 2017. DOI: 10.1016/j.ijpe.2017.08.025.
[2] Lima-Junior, F.R. and Carpinetti, L.C.R., Combining SCOR model and fuzzy TOPSIS for supplier evaluation and management, International Journal of Production Economics, 174, pp.128-141, 2016. DOI: 10.1016/j.ijpe.2016.01.023.
[3] Dey, P.K., Bhattacharya, A. and Ho, W., Strategic supplier performance evaluation: a case-based action research of a UK manufacturing organization, International Journal of Production Economics, 166, pp.192-214, 2015. DOI: 10.1016/j.ijpe.2014.09.021.
[4] Osiro, L., Lima-Junior, F.R. and Carpinetti, L.C.R., A Fuzzy logic approach to supplier evaluation for development, International Journal of Production Economics, 153, pp. 95-112, 2014. DOI: 10.1016/j.ijpe.2014.02.009.
[5] Ho, L.H., Feng, S.Y., Lee, Y.C. and Yen, T.M., Using modified IPA to evaluate supplier's performance: multiple regression analysis and DEMATEL approach, Expert Systems with Applications, 39(8), pp.

7102-7109, 2012. DOI: 10.1016/j.eswa.2012.01.034.
[6] Igarashi, M., De Boer, L. and Fet, A.M., What is required for greener supplier selection?. A literature review and conceptual model development, Journal of Purchasing & Supply Management, 19, pp. 247-263, 2013. DOI: 10.1016/j.pursup.2013.06.001.
[7] Rodriguez, R.M., Martinez, L. and Herrera, F., Hesitant fuzzy linguistic term sets for decision making, IEEE Transactions on Fuzzy systems, 20, pp.109-119, 2012. DOI: 10.1109/tfuzz.2011.2170076.
[8] Beg, I. and Rashid, T., TOPSIS for Hesitant Fuzzy linguistic term sets, International Journal of Intelligent Systems, 28, pp.1162-1171, 2013. DOI: 10.1002/int.21623.
[9] Xu, Z. and Zhang, S., An overview on the applications of the hesitant fuzzy sets in group decision-making: Theory, support and methods, Frontiers of Engineering Management, 6, pp.1-20, 2019.
[10] Bertrand, J.W.M. and Fransoo, J.C., Operations management research methodologies using quantitative modelling, International Journal of Operations & Production Management, 22(2), pp.241-264, 2002.
[11] Rezaei, J. and Ortt, R., Multi-criteria supplier segmentation using a fuzzy preference relations based AHP, European Journal of Operational Research, 225, pp.75-84, 2013. DOI: 10.1016/j.ejor.2012.09.037.
[12] Görener, A., Ayvaz, B., Kusakci, A.O. and Altinok, E., A. Hybrid Type-2 Fuzzy based supplier performance evaluation methodology: the Turkish Airlines technic case, Applied Soft Computing, 56, pp.436-445, 2017. DOI: 10.1016/j.asoc.2017.03.026.
[13] Aksoy, A. and Öztürk, N., Supplier selection and performance evaluation in just-in-time production environments, Expert Systems with Applications, 38(5), pp. 6351-6359, 2011. DOI: 10.1016/j.eswa.2010.11.104.
[14] Liou, J.J.H., Chuang, Y.C. and Tzeng, G.H., A Fuzzy integral-based model for supplier evaluation and improvement, Information Sciences, 266, pp. 199-217, 2014. DOI: 10.1016/j.ins.2013.09.025.
[15] Sahu, N.K., Datta, S. and Mahapatra, S.S., Green supplier appraisement in fuzzy environment, Benchmarking, 21, pp. 412-429, 2014. DOI: 10.1108/BIJ-06-2012-0042.
[16] Sarkar, A. and Mohapatra, P.K.J., Evaluation of supplier capability and performance: a method for supply base reduction. Journal of Purchasing and Supply Management, 12(3), pp.148-163, 2006.
[17] Luthra, S., Govindan, K., Kannan, D., Mangla, S. and Garg, C., An integrated framework for sustainable supplier selection and evaluation in supply chains, J. of Cleaner Production, 140, pp.1686-1698, 2017.
[18] Santos, L.F.D.O.M, Osiro, L. and Lima, R.H.P., A model based on 2-tuple fuzzy linguistic representation and Analytic Hierarchy Process for supplier segmentation using qualitative and quantitative criteria, Expert Systems with Applications, 79, pp. 53-64, 2017. DOI: 10.1016/j.eswa.2017.02.032.
[19] Liu, Y., Eckert, C., Yannou, G. and Petit, G., A fuzzy decision tool to evaluate the sustainable performance of suppliers in an agrifood value chain**, Computers & Industrial Engineering**, 127, pp.196-212, 2019.
[20] Rodríguez, R.M., Martínez, L. and Herrera, F., A group decision-making model dealing with comparative linguistic expressions based on hesitant fuzzy linguistic term sets, Information Sciences, 241, pp. 28-42, 2013.
[21] Lima Junior, F.R., Carvalho, G.M.R., Carpinetti, L.C.R., A methodology based on fuzzy inference and SCOR® model for supplier performance evaluation. Gestão & Produção, 23, pp. 515-534, 2016. DOI: 10.1590/0104-530x2625-15.

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